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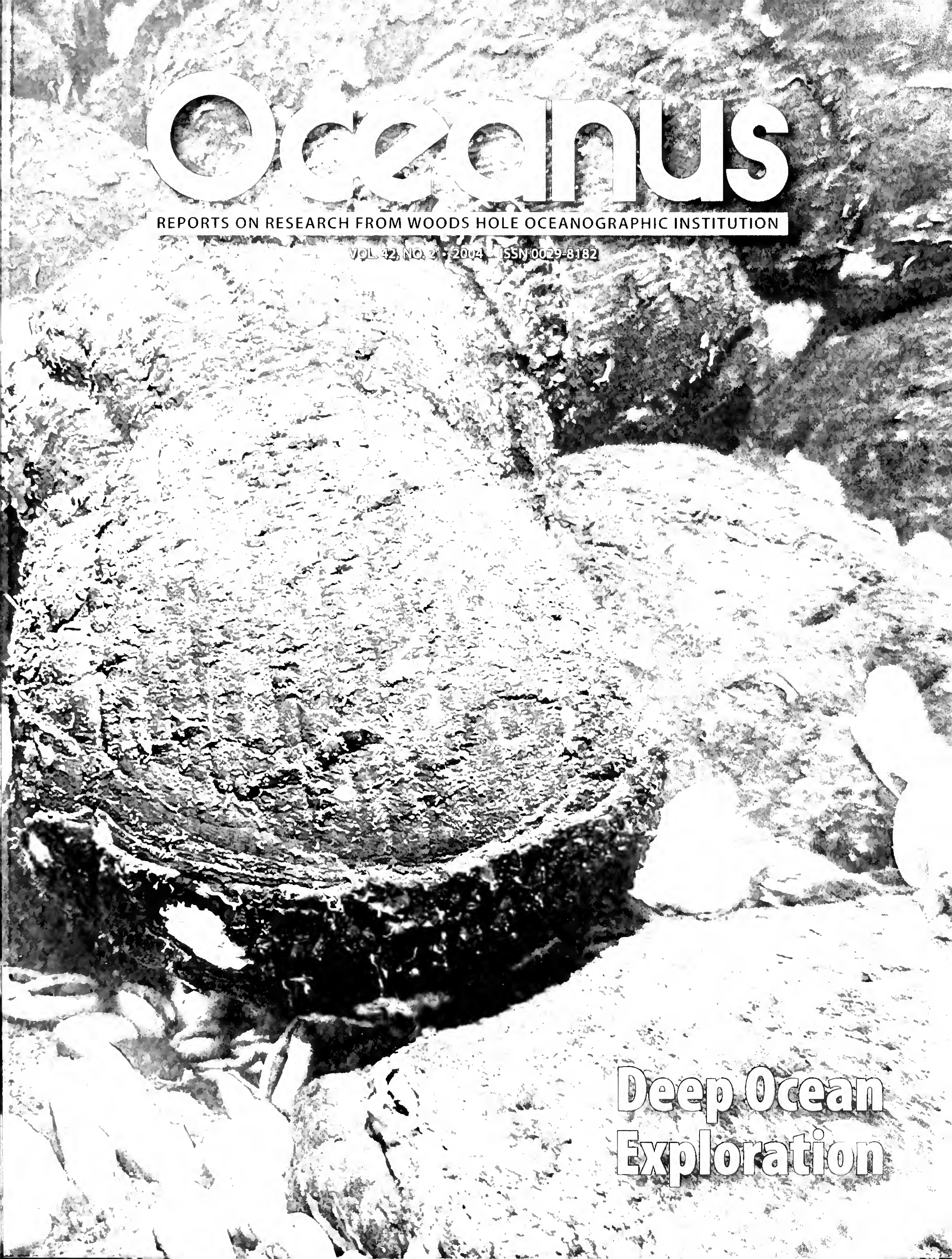

Deep Ocean Exploration

The Deep Ocean Ex

Investigating Earth's dynamic processes

This may sound like heresy, but for some of us at Woods Hole Oceanographic Institution, the ocean is a bit of a nuisance. All that lovely blue water can get in the way.

The ocean is a barrier that impedes our ability to understand how our planet works. It conceals powerful and fascinating forces that are constantly shaping and reshaping Earth's surface in ways that really make our planet unique.

Earth is not cold, dead, and static. Its surface is hot. It's moving. It's constantly changing. But just a half-century ago, we were largely unaware of our planet's extraordinary dynamism because it primarily occurred in a place where we couldn't easily observe it.

The ongoing, fundamental forces that forge our planet—that generate earthquakes and volcanoes; that perpetually create and destroy Earth's crust; that rip apart continents and smash them into one another; that create mountains like the Himalayas and island chains like Hawaii; that open and close ocean basins; that forge mineral deposits and generate oil and gas; and that brew chemical cauldrons that sustain rich communities of life in the sunless depths—most of this action occurs beneath the oceans.

Water is a blessing that supports life on Earth, but it is a dreadful medium for exploration. It is largely impenetrable to light, so we can't see through it. We can't view most of Earth's surface with a telescope, as we can with Mars. Flying vehicles through the viscous medium of water, under conditions of crushing pressure and complete darkness, poses daunting technical challenges.

Although we have fully mapped the waterless surfaces of Venus, Mars, and the moon in detail, we have mapped only 5 percent of the entire seafloor at the same resolution. Just 50 years ago, we were as ignorant about our home planet as we were about our solar system nearly 500 years ago—before the astronomer Copernicus told us that the Earth revolved around the sun, rather than vice versa.

Since then we have learned that the seafloor is not some vast, placid beach. In the 1950s and 1960s, we discovered that the globe is encircled by an active volcanic mountain chain. It bisects the ocean floor and stretches continuously for more than 75,000 kilometers (45,000 miles)—more than five times the length of the Andes, Rocky, and Himalayan mountains combined. Over millions of years, this mid-ocean ridge system continually spews lava, creating new ocean crust that repaves most of the planet's surface.

The seafloor is also rife with deep trenches, where old, cold ocean crust sinks back into Earth's interior and is recycled. At both ridges and trenches, volcanism and earthquakes are rampant. Indeed, about 80 percent of volcanic and seismic activity on Earth occurs under the sea.

Fueled by heat emanating from Earth's core, the engine that drives much of this activity is the mantle—the layer of our

ploration Institute

planet between the crust and core. At the high temperatures and pressures found within Earth's mantle, solid rocks can deform. (Think about how a blacksmith heats iron to a temperature just below its melting point to bend and shape a horseshoe.) Solid rocks within Earth's mantle can flow, with hot buoyant material rising and cold, dense material sinking.

This convection drives the motions of our planet's thin, rigid outer layer, which is broken into Earth's great tectonic plates. The plates move apart and together, continually (albeit slowly) changing the face of the planet. The continents atop the plates are carried along as passive riders.

In some cases, we are learning that the rending and collisions of continents have led to changes in the circulation of the oceans, or the atmosphere, or chemicals cycling among the Earth, ocean, and atmosphere. All of these, in turn, can spawn changes in Earth's climate.

Susan Humphris, the first Director of the WHOI Deep Ocean Exploration Institute, peers through an Alvin *viewport before the sub descends to the seafloor.*

In the late 1970s, the surprising discovery of life thriving at deep-sea hydrothermal vents revolutionized our concepts of where and how life can exist. An abundance of life flourishes in conditions we had considered too extreme, supported by chemicals created by processes occurring within the planet itself. More recently, we have seen evidence that previously unimagined and potentially huge communities of microbial life reside deep *within* the Earth. These discoveries have fundamentally changed our perspective on the origins of life on Earth and redirected our approaches to searching for extraterrestrial life.

Unforeseen discoveries—such as plate tectonics and chemosynthetic deep-sea life—have transformed our understanding of Earth. But oceanography is a very young science. The oceans remain a frontier.

Dramatic advances in deep-submergence vehicles and technologies now provide the potential for unprecedented access to the oceans and seafloor—and unprecedented discovery. New robotic systems and oceanographic instruments are being developed to remain in the oceans for long periods—to go beyond learning what's down there and begin to make inroads into learning more about what's *going on* down there.

That is the mission of the Deep Ocean Exploration Institute at Woods Hole Oceanographic Institution: to investigate Earth's dynamic processes by exploring the frontier where they are occurring. We journey into uncharted waters—or more precisely, *under* them—to reveal the history and natural engineering of the planet we call home.

—*Susan Humphris*

Susan Humphris is Chair of the WHOI Geology and Geophysics Department. She was the first Director of the WHOI Deep Ocean Exploration Institute, serving from 2000 until June 2004, when she was succeeded by Dan Fornari.

Composite photo, above: IMAX film by William Reeve and Stephen Low, Stephen Low Productions

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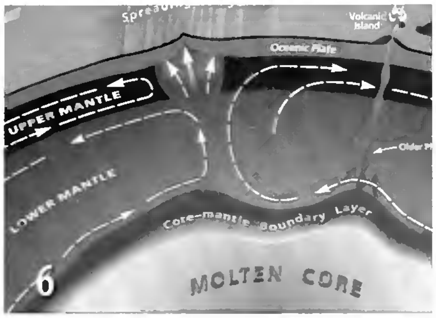

Motion in the Mantle: The Engine that Drives the Earth

Emerging Ocean Technology: New Windows into the Oceans and Earth

Creating the Seafloor: The Formation of New Ocean Crust

Earthquakes and Volcanoes: Linking the Engine to Earth's Movements

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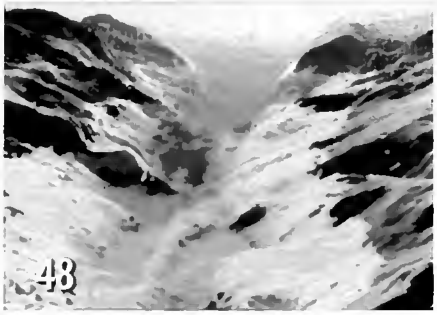
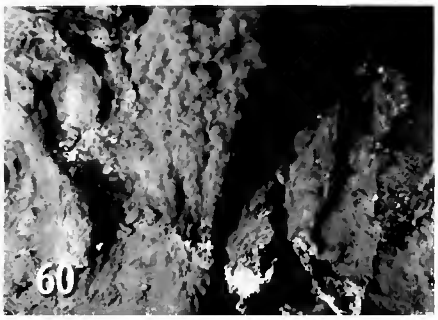
COVER: A striated tongue of basalt lava—extruded from the seafloor like toothpaste from a tube—lies atop older lava at the Galápagos Spreading Center 1,668 meters (5,463 feet) below the surface of the Pacific Ocean. In 2002, scientists diving in *Alvin* discovered an extensive community of giant clams up to 1 foot long (*Calpytogena magnifica*) thriving on low-temperature hydrothermal fluids venting from cracks in seafloor lava. (With grateful acknowledgement to David Metz of Canon, Inc.-USA and George Moss for the loan of a Canon EOS 1D digital camera system used in *Alvin* to take these high-resolution photographs) Photo credit: Tim Shank, and the *Alvin* Deep Submergence Operations Group





Earth-Ocean Interactions:
Where the Solid and Liquid Earths Meet

Life on Earth:
The Co-evolution of Life and the Planet

Shifting Continents and Climates:
How Earth Dynamics Change the Climate

WOODS HOLE OCEANOGRAPHIC INSTITUTION
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The Engine that

Motion in the Mantle

New tools and techniques reveal the inner workings of our planet

By Robert Detrick, Senior Scientist and Vice President for Marine Facilities and Operations
Woods Hole Oceanographic Institution

Poets and philosophers have celebrated the timelessness of the land around us for eons, but the solid Earth is actually a very dynamic body. Great tectonic plates are in constant motion at Earth's surface.

Earthquakes and volcanic eruptions are manifestations of these movements on human time scales. But over millions of years, the movements of Earth's tectonic plates rearrange the face of the Earth. They cause continents to rift and drift, creating entirely new ocean basins. Collisions between plates squeeze ancient oceans until they disappear and produce majestic mountain ranges such as the Alps and Himalayas.

Like an auto mechanic who has to look "under the hood" to see the engine that powers your car, geologists need to look deep within Earth's interior to understand the tremendous underlying forces that build and shape Earth's surface. We are now beginning to comprehend and describe the role that the Earth's mantle plays in driving changes on the planet we live on.

Hot, flowing rocks

Earth's mantle is the solid, rocky interior of our planet that extends from the base of the crust all the way down to Earth's core, about 2,900 kilometers (1,800 miles) below the surface. Although they are solid, the rocks in Earth's mantle can deform and flow by viscous creep over long time periods. At first glance, this might seem odd; after all, the rocks we find on Earth's surface are cold and brittle, and they fracture or break if they are deformed. On a large scale, this same process causes earthquakes.

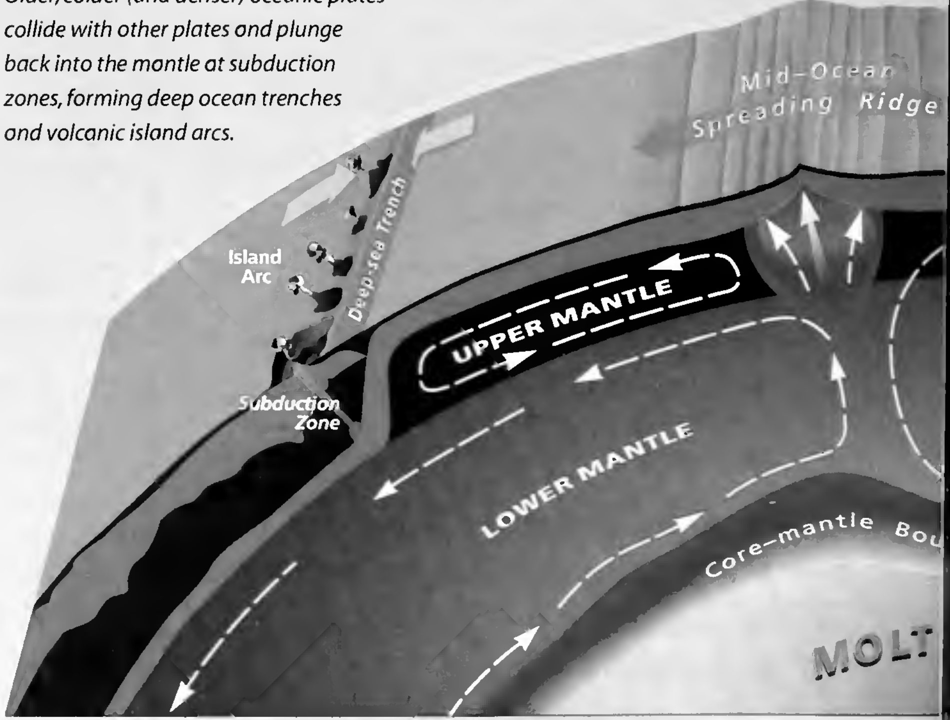
But as any blacksmith knows, when a hard, brittle material like iron is heated to a temperature just below its melting point, it becomes malleable. Similarly, given enough time, at the high temperatures and pressures found within Earth's interior, mantle rocks can deform and flow like

Continued on page 11

Is the mantle one big p

At mid-ocean ridges, mantle rock rises, melts, and erupts to form new oceanic crust and volcanic

Older, colder (and denser) oceanic plates collide with other plates and plunge back into the mantle at subduction zones, forming deep ocean trenches and volcanic island arcs.



The underlying "flow" of rocks in the mantle drives geological phenomena at Earth's surface, ranging from earthquakes and volcanoes to the creation of mountains and oceans. As any blacksmith knows, when a hard, brittle material like iron is heated to temperatures just below its melting point, it becomes malleable. Similarly, the high

Drives the Earth

Conduits Into Earth's Inaccessible Interior

Hot plumes from deep within the planet bring up telltale chemical clues about the mantle

By Stan Hart, Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Jules Verne wrote about a way to journey to the center of the Earth, but unfortunately, we haven't found it yet. So we really don't know what happens deep inside our planet.

Earth's interior has yielded its secrets only gradually over the past few decades. Yet it contains evidence about how our planet originally formed some 4.6 billion years ago. And it holds clues to the processes that shape the surface of the Earth—from the benign processes that produce things we covet (ore and mineral deposits) to the disruptive processes we yearn to predict and avoid (great earthquakes and volcanic eruptions).

We get glimpses of Earth's interior from mountain-building processes that occasionally thrust rocks to the surface from depths as great as 95 kilometers (60 miles). Volcanic eruptions sometimes bring up rocks from depths of 200 kilometers (125 miles). But Earth's rocky mantle continues down for another inaccessible 2,690 kilometers to the core-mantle boundary at 2,890 kilometers (1,800 miles). Nor will we ever directly view Earth's metallic core, which extends another 3,481 kilometers (2,163 miles) down to Earth's center.

Plumes that form islands

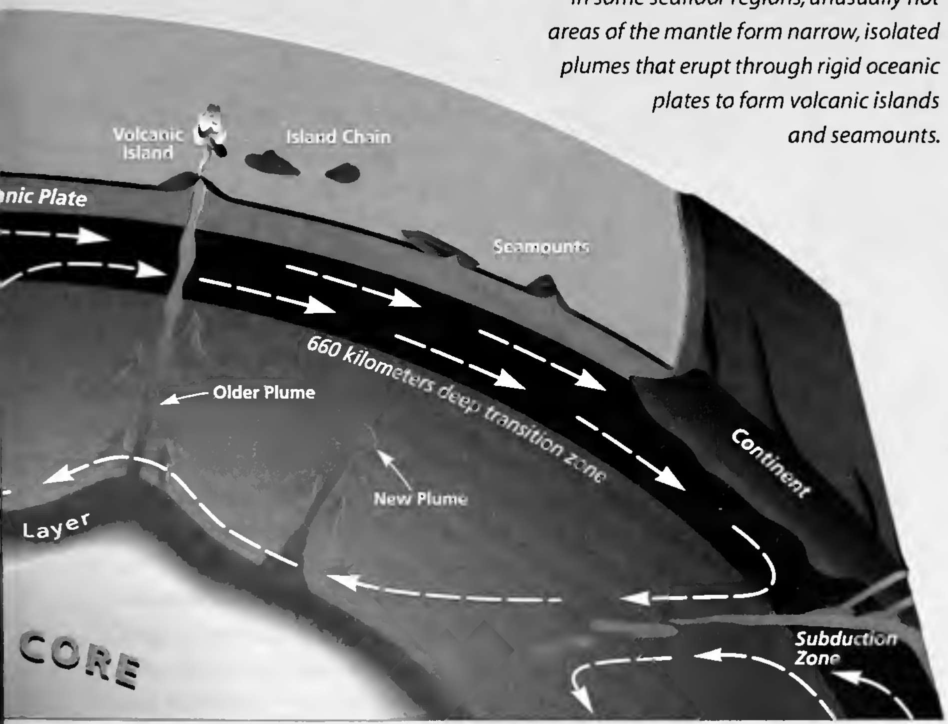
One way to probe the deep Earth is remote sensing, using seismic waves generated by earthquakes. (See "Listening Closely to 'See' into the Earth," page 16.) By studying the varying speeds at which these waves travel through rocks, we can infer a great deal about the rocks' chemical composition and their varying temperatures in different regions of the mantle. Still, the technique is indirect, and unfortunately, waves sometimes travel at similar velocity through rocks with different chemistry, providing ambiguous clues.

A more promising trail was blazed in 1972 when Jason Morgan of Princeton University proposed the "mantle plume" hypothesis. Mantle rocks are hot enough to be in slow but constant motion. But

or is it double-decked?

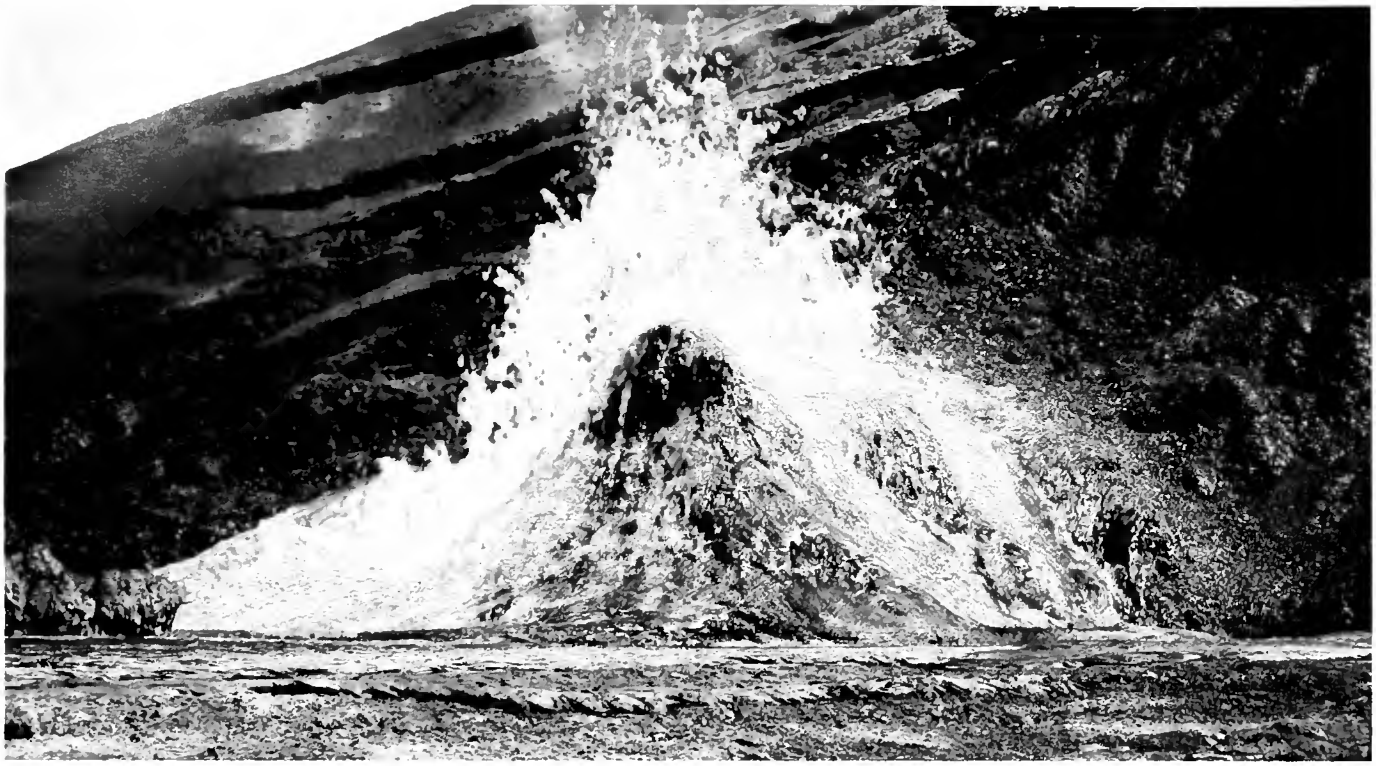
mountain chains. Newly created seafloor crust spreads outward from the ridges.

In some seafloor regions, unusually hot areas of the mantle form narrow, isolated plumes that erupt through rigid oceanic plates to form volcanic islands and seamounts.



temperatures and pressure within Earth's mantle deform rocks so that they can flow like a slowly moving liquid. Hot materials rise and cold materials sink in circular convection cells. Scientists are pursuing evidence to determine if the entire mantle convects (right side of diagram), or if the mantle is two-tiered (left side of diagram).

Jayne Doucette, WHOI Graphic Services



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A FOUNTAIN OF CLUES—Lava erupting on volcanic islands such as Hawaii is brought to the surface by narrow plumes of hot, buoyant rock originating in the mantle. The volcanic rocks contain chemical "fingerprints" that reveal their age, source, and formation—giving geochemists clues to the inner workings of the mantle.

occasionally, unusually hot areas can form upwelling plumes. On the scale of the entire mantle, these plumes are narrow (with a width-to-height ratio similar to a 6-inch strand of spaghetti). But these plumes can be vast—plume "heads" can reach an estimated 500 to 1,000 kilometers (310 to 620 miles) in diameter.

Plumes start at the bottom of the Earth's mantle and carry material near to Earth's surface—a trip that takes tens of millions of years. As these deep mantle rocks approach 50 miles from the surface, decreasing pressure allows them to partially melt. The melts, or magmas, may leak through the overlying cold rigid surface layer, or plate, to form volcanoes.

Most islands in the oceans are composed of volcanic rock derived from such plumes, as best we can tell. This seems like a promising avenue to reveal what lies at the bottom of the mantle. All we have to do is travel to island paradises and bring home volcanic rocks for analysis.

But, alas, it's not that easy. Mantle rocks are chemically altered during the melting processes, and scientists have spent the last 20 years trying to reliably unravel these processes. Furthermore, only the mantle rocks that actually melted end up in labs—what's left behind? And finally, we're not sure all plumes come from the bottom of the mantle.

Where do plumes come from?

Seismology provides our best way to detect plumes and map their sources, but the evidence is inconclusive. There are two schools of thought on the origins of plumes, the "layered mantle" school and the "whole mantle" school.

"Layerists" claim that the mantle has two layers. Below 660 kilometers (410 miles), pressure and temperature conditions cause mineralogical changes in rocks. The deeper rocks are denser, and do not "flow" in the same way shallower rocks do. As a result, rocks above and below the 660-kilometer "boundary" convect separately. In this model, plumes arise solely from the bottom of the top layer. Virtually nothing from the deepest parts of the mantle ever comes near the surface.

"Wholists," on the other hand, maintain that plumes come from the bottom of the mantle (1,800 miles deep), at the boundary of Earth's core. Heat from the core disturbs the overlying mantle, leading to plume formation. If accurate, this model gives hope that we will someday understand the chemistry of the deepest mantle (and if we're very lucky, of the outer core, provided some core material occasionally mixes into rising plumes).

"Fingerprinting" volcanic rocks

To explore the origin of plumes, geochemists analyze rocks from ocean volcanoes formed by plumes. They use a form of isotopic fingerprinting.

The rocks contain traces of long-lived radioactive isotopes left over from the initial building of our solar system. These elements have known half-lives—the time required for one-half of a quantity of "parent" isotopes to decay into more stable "daughter" isotopes.

We can calculate the rock's age by measuring the relative amounts of remaining radioactive parent and its daughter products. And we can determine the "parent" rocks from which the specimen originally descended (or more accurately in this case, "ascended"). In this way, we can trace a rock specimen's lineage.

If the mantle convected in a single unit, it would produce volcanic rocks with a single homogeneous chemistry. A two-tiered mantle would produce, at most, two types of rocks. But, once again, the solution is not easy. Our analyses point to more chemical diversity in the mantle.

Pedigree and mongrel rocks

We have identified four "lineages" of plumes, and mixtures thereof. Some oceanic islands appear to be virtually pure species. Most are just mongrels.

The purebred ocean island rocks have been given particular labels. Rocks from Pitcairn Island, of HMS *Bounty* fame, are labeled "EM1" (Enriched Mantle 1). Rocks from Samoa, of "Coming of Age" fame, are "EM2" (Enriched Mantle 2). Rocks from Mangaia, in the Cook/Austral chain, are called "HIMU" (High "Mu," from the Greek symbol "μ," which represents a uranium/lead ratio). Rocks from mid-ocean spreading ridges, which are fed from the shallow upper mantle, are "DMM" (Depleted Mid-ocean ridge basalt Mantle).

Note that even these purebred island rocks show some crossbreeding. For example, specimens from Vailulu'u and Malumalu, two newly discovered undersea volcanoes in Samoa, show both the purest EM2 yet sampled, as well as a variety of less pure offspring. An unexplained curiosity is that all of the purebred islands are in the Southern Hemisphere.

Some of the well-known "mongrel" islands are Hawaii, Tahiti, and the Galápagos, Azores, and Canary Islands. Hawaii is notable for being both the largest of all mantle plumes (as measured by total volcanic output over the millennia) and by far the most intensively studied by geochemists.

Recycled crust

The history of these purebred mantle rock species has been the subject of controversy for decades. Were they born when the Earth was born, somehow escaping mixing in the constantly convecting mantle? Are they primordial, homogenous, and once-pristine mantle rock species that have been contaminated by injections of rock from Earth's surface (as argued by Albrecht Hofmann of Max-Planck Institut für Chemie and William M. White of Cornell University in 1982)?

The rigid plates of rock that cover Earth's surface ultimately plunge back into the mantle—in the great subduction zones that border the Pacific Ocean and elsewhere. These plates carry ocean crust and its veneer of accumulated sediment into the mantle—sometimes deeply. This crust and sediment reintroduce chemicals into the mantle, which can confound our analyses.

For example, oceanic crust, during its millions of years of exposure to seawater, sequesters naturally radioactive uranium from the oceans. When this crust is subducted into the deep mantle, the uranium in it would decay, over a billion years, into significant accumulations of uranium's daughter isotope, lead-206. This ancient oceanic crust material, heated up again in the deep mantle, might once again become buoyant—and thus a new plume is born! Rocks from this plume would have a high (and highly misleading) ratio of lead-206—the same fingerprint that typically distinguishes HIMU rocks.

Over millions of years, ocean crust also accumulates an overlying veneer of sediments containing rubidium, uranium, and

Albrecht W. Hofmann

HOT OFF THE VOLCANO—Shielding his face with an asbestos glove, WHOI geochemist Stan Hart uses a rock hammer to collect freshly erupted lava from Kilauea Volcano in Hawaii. The lava, orginating from the mantle, provides chemical clues to the inner workings of the Earth.

lead from non-mantle sources. After subduction, hibernation in the mantle, and rejuvenation as a new plume, rocks containing recycled sediment material could contain "enriched" isotopic signatures that can confound our ability to trace the rocks' ultimate source in the mantle.

The "recycling" proposed by Hofmann and White must occur, and it explains many aspects of the chemical "zoo" we observe in mantle rocks. Nevertheless, there is no unanimity whatsoever in the geochemical community as to whether this model, or any of its amended versions, is the "real" scenario.

Deep Earth odyssey

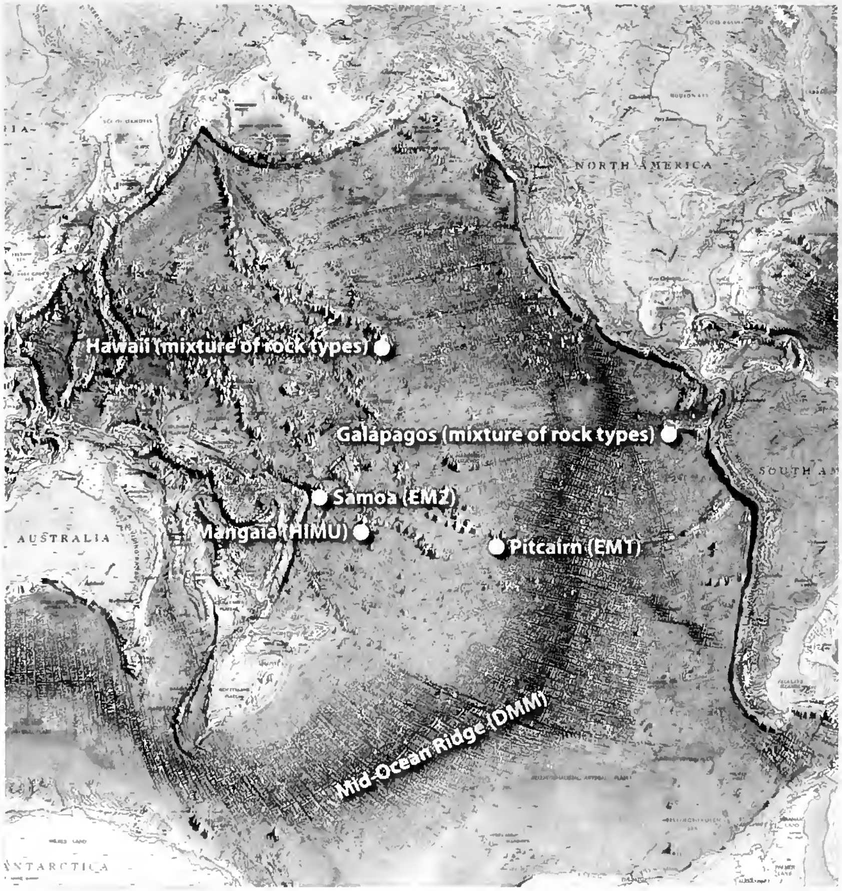
In 2004, here is the current state of our knowledge about the mantle. We know that Earth's mantle is convecting, but we don't know whether it is whole-mantle or layered convection. We are virtually certain that plumes exist, but don't know with certainty where they originate. We know Earth's mantle is not chemically homogeneous, but rather a chemical zoo with at least four purebred species and a bewildering pack of mongrels. We don't know where any of these species come from, nor can we trace the pedigrees of the purebreds.

Given that it's taken four decades of concerted effort to get this far, why are we optimistic and excited? Because in recent years, major links have formed among the fields of geochemistry, seismology, rock physics, and convection modeling. All these fields have also profited from the development of incredible new technologies that are allowing us to circumvent roadblocks that have stymied our scientific research for years.

Scientists must converse across disciplines more than ever. We need, each of us, to become broader—Renaissance scholars, as it were. We need to maintain access to cutting-edge technologies and continue to hone new ones. Then, possibly, an article on Earth's mantle written a decade from now will contain the answers to the questions that linger in this one.

Volcanic islands, like dogs, can be pedigrees or mutts

By analyzing radioactive isotopes in rocks from various volcanic islands, geochemists have determined that all islands are not alike. Most islands are made of mixtures of many rock types. But some islands are primarily composed of one of four chemically distinct rock types: EM1 (Enriched Mantle 1), EM2 (Enriched Mantle 2), HIMU (High "Mu," from the Greek symbol μ); and DMM (Depleted Mid-ocean ridge basalt Mantle). These chemical distinctions provide clues to understand the underlying mantle plumes that create the islands.



World Ocean Floor Map by Bruce Heezen and Marie Tharp, 1977

Rhea Waldman, WHOI

Stan Hart was born and raised in Lynn, Mass., a liability mitigated by living on the border of Lynn Woods, a many-square-mile tract of forest, granite ledges, and a pristine lake (the town water supply). Though prohibited, fishing in this water became an early passion; incessant roaming in the woods was permitted both by parents and town law. Undergraduate years were spent commuting to MIT, rock climbing the cliffs of New Hampshire, four-event skiing with the MIT Ski Team, and working summers in the Appalachian Mountain Club hut system. These outdoor leanings led to a switch of major from chemistry to geology (the first course in organic chemistry helped). A wonderfully stimulating year at Cal Tech, a master's degree in geochemistry, and daughter No. 1 cemented Stan's career path. He was wooed back to the gentility of MIT for a Ph.D., followed by a postdoc (and 14 more years!) at the Department of Terrestrial Magnetism, Carnegie Institution of Washington. Hart was called back to MIT for the retirement of his Ph.D. advisor, and he professored there for 14 years before opting for the more rural life of Falmouth for daughter No. 2 and son No. 1. He passed the 15-year mark at WHOI in 2004, and his climbing and skiing fervors have morphed into an addiction for running. His predispositions for travel and research are being satisfied by intensive study of the many volcanoes of Samoa (the youngest of which is still under water, and in active eruption).

Continued from page 6

a slowly moving fluid, even though they would appear solid to us. (See "Peering into the Crystal Fabric of Rocks," page 57.) These movements are gradual in human terms (a few centimeters a year), but over a hundred million years, mantle rocks can move thousands of kilometers.

The energy that drives this movement is heat within the Earth, which comes from two main sources. One is the residual heat left over from the formation of our planet 4.6 billion years ago. The radioactive decay of naturally occurring chemical elements in the Earth—most notably uranium, thorium, and potassium—also releases energy in the form of heat.

These two sources of heat warm Earth's mantle and cause it to rise and sink, much like soup in a pot on a stove. Material heated from below gets hotter and rises. It reaches the surface, releases its heat, becomes colder and denser, and sinks again.

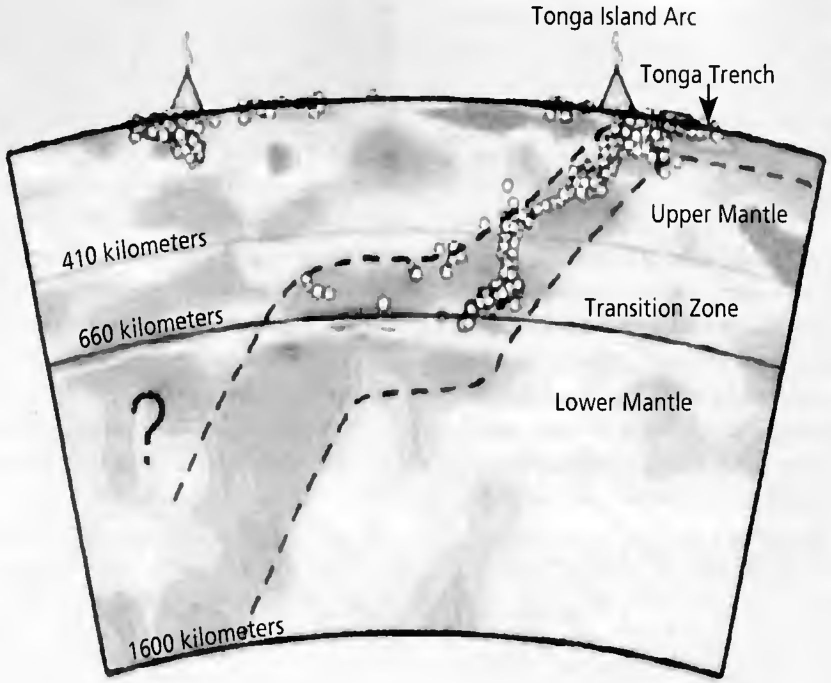
Ocean trenches and ridges

The motion of tectonic plates, and all of their associated volcanic and earthquake activity, are believed to be the surface manifestation of similar thermal convection occurring in Earth's mantle. The rigid outer layer of our planet, called the lithosphere, is the cold, top boundary of convection cells in the mantle. Two features of the ocean floor are the results of this active process.

At ocean trenches, old, cold, and dense lithosphere sinks back into the hotter mantle below, dragging surface plates along with it. The continents are carried along by these moving surface plates, producing the continental drift that, for instance, rifted and separated Africa and South America.

Beneath ocean spreading centers, two plates are moving apart. Hot, buoyant, solid mantle flows upward. It begins to melt as it reaches shallower areas where pressures are lower. That leads to volcanic activity that forms new ocean crust along the great mid-ocean ridge system.

A 'CAT scan' of Earth's interior



Seismic tomography is the geophysical analog of a medical CAT scan.

Seismalogists measure the speed of seismic waves generated by large earthquakes (white circles) that propagate through the mantle. They can then map temperature variations in the mantle, because seismic waves travel more slowly though hotter regions (yellow and red) and faster through colder regions (green).

The green region here marks the slab of old oceanic plate plunging back into the mantle at the Tonga Trench in the South Pacific Ocean.

Adapted from R. D. van der Hilst, "Complex morphology of the subducted lithosphere in the mantle beneath the Tonga Trench," in *Nature* Vol 374, 1995

In addition to this plate-scale flow, plumes of hot material can rise at various places from within the convecting mantle to form ocean island volcanoes or "hotspots" such as Hawaii. Indeed, convection currents in the mantle are responsible for most of the volcanic and tectonic processes that we see at Earth's surface.

A double-decked mantle?

Mantle convection is the "engine" that drives our dynamic Earth. But since scientists cannot directly observe the workings of this engine, they have debated the exact mechanisms of this convection for more than half a century.

For example, does convection occur over the entire mantle at once, creating a huge pot of essentially the same soup? Or is it layered—with separate convection cells occurring in an "upper mantle" (extending from near the surface to a depth of about 660 kilometers, or 410 miles) and in an underlying "lower mantle" (with denser rocks under higher pressure)?

This second scenario would result in two chemically distinct reservoirs in the mantle that almost never mix, like oil and water. The first model would seem to require a more compositionally uniform, well-mixed mantle. Two lines of evidence give contrasting answers to the question.

Lavas erupted at mid-ocean ridges and at oceanic islands have different compositions of trace elements and noble gases. (See "Conduits Into Earth's Inaccessible Interior," page 7.) This strongly suggests that distinct geochemical reservoirs exist in the mantle, and seems to favor a layered convection model with different mantle compositions in the upper and lower mantle.

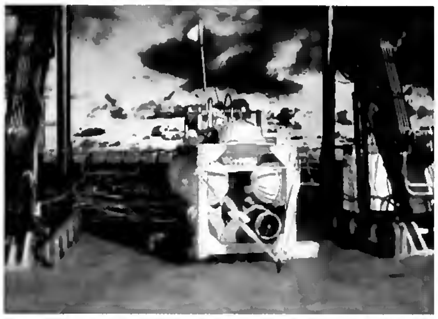
Geophysical 'CAT scans'

In the mid-1990s, however, seismologists studied how seismic waves generated by large earthquakes propagated in the mantle and made a startling discovery. Using a technique called seismic tomography—the geophysical analog of a medical CAT scan—they were able to map variations in the speed of the seismic waves traveling through the mantle. We can infer temperature variations in the mantle from this, because seismic waves travel more slowly through hotter regions and faster through colder regions.

The seismic tomographic images showed that in some cases, cold tectonic plates sink to depths of only about 600 to 700 kilometers—near the base of the upper mantle. In other cases, they sink more than halfway into the lower mantle. These results clearly show that the density contrast (of lighter and denser rocks) at the base of the upper mantle is not a barrier to mixing between the upper and lower mantle.

How can we then explain the evidence for distinct reservoirs in the mantle? In other words, why isn't our mantle soup well-mixed?

This vexing question is unresolved. Some scientists have proposed that there are "unstirred" blobs of material floating in the mantle that have persisted throughout most of geologic history. Others have suggested that a dense, poorly mixed region exists in the lower 1,000 kilometers of the mantle. This region is chemically distinct and rich in heat-producing elements, and it generates flow into "hotspot" areas.



Robert Detrick, WHOI

An ocean-bottom seismometer on R/V Ewing *awaits deployment to the seafloor during a 1997 experiment in the Pacific Ocean to elucidate how magma chambers feed magma to overlying mid-ocean ridges.*

Other unanswered questions

There are other puzzling questions about how the mantle convection engine works. For example, seismic tomography studies of the shallow mantle beneath oceanic spreading centers reveal a broad region of slow seismic velocities. This suggests the presence of partially melted material across an area of several hundred kilometers. Yet volcanic activity at mid-ocean ridges occurs over remarkably narrow zones just a few kilometers wide. We don't know how melting produced over such a broad region in the mantle can be focused into such a narrow zone of eruptive activity at the seafloor. (See "Unraveling the Tapestry of Ocean Crust," page 40.)

Another major debate centers around the origin of hotspot volcanic centers such as Hawaii and Iceland. Some researchers argue that hotspots are caused by rising plumes of hot mantle material originating in the "unstirred" reservoir just above the Earth's core. Others think that processes occurring in the uppermost mantle cause some hotspots. Answering such questions will require the integration of data from seismology, geochemistry, and mineral physics with fluid-dynamical modeling of mantle convection.

New tools to look into the Earth

This is a particularly exciting time for studies of the oceanic upper mantle. Advances in ocean-bottom seismic instrumentation now make it possible to record high-quality seismic data from earthquakes at sites over the two-thirds of the planet covered by water. (See "Listening Closely to 'See' into the Earth," page 16.)

Advances in geochemical and petrological studies over the past decade, including new analytical and sampling techniques, are defining important new limits on the mantle conditions that produce melting.

And in recent years we've seen tremendous increases in the affordability and speed of computer systems, improved numerical techniques, and a growing understanding of the complex processes of melting and viscous flow.

These advances are allowing the development of the first global-scale, self-consistent, three-dimensional models of mantle convection that can explain our surface observations of tectonic plate motions, gravity, and topography. These studies will lead to much more complete understanding of mantle convection.

Like the auto mechanic at your local garage, we are finally "lifting the hood" to view Earth's engine and the forces that drive changes on the face of the Earth.

Tom Kleindinst, WHOI

Bob Detrick, a marine geophysicist, became Vice President for Marine Facilities and Operations at WHOI in 2004. As a young boy, Detrick's family vacations to Colorado from his hometown of Pittsburgh sparked a lifelong interest in geology and a love of mountains and world travel. In 1970 he came to Woods Hole as a Summer Student Fellow and was captivated by the adventure and challenge of studying the geology of the seafloor. As first a Joint Program Student and later as a scientific staff member, Detrick has spent nearly 20 years at WHOI and participated in more than 30 different oceanographic research cruises. His research interests encompass marine seismology, ocean crustal structure and tectonics, especially along mid-ocean ridges, and mantle dynamics. In his new position, Detrick will be responsible for developing and implementing a strategy for integrating WHOI ships, vehicle systems (manned submersible, remotely operated vehicles, and autonomous underwater vehicles) and ocean observatories to provide researchers at WHOI with unmatched access to the sea.

If Rocks Could Talk. . .

The ion microprobe extracts hidden clues about our planet's history and evolution

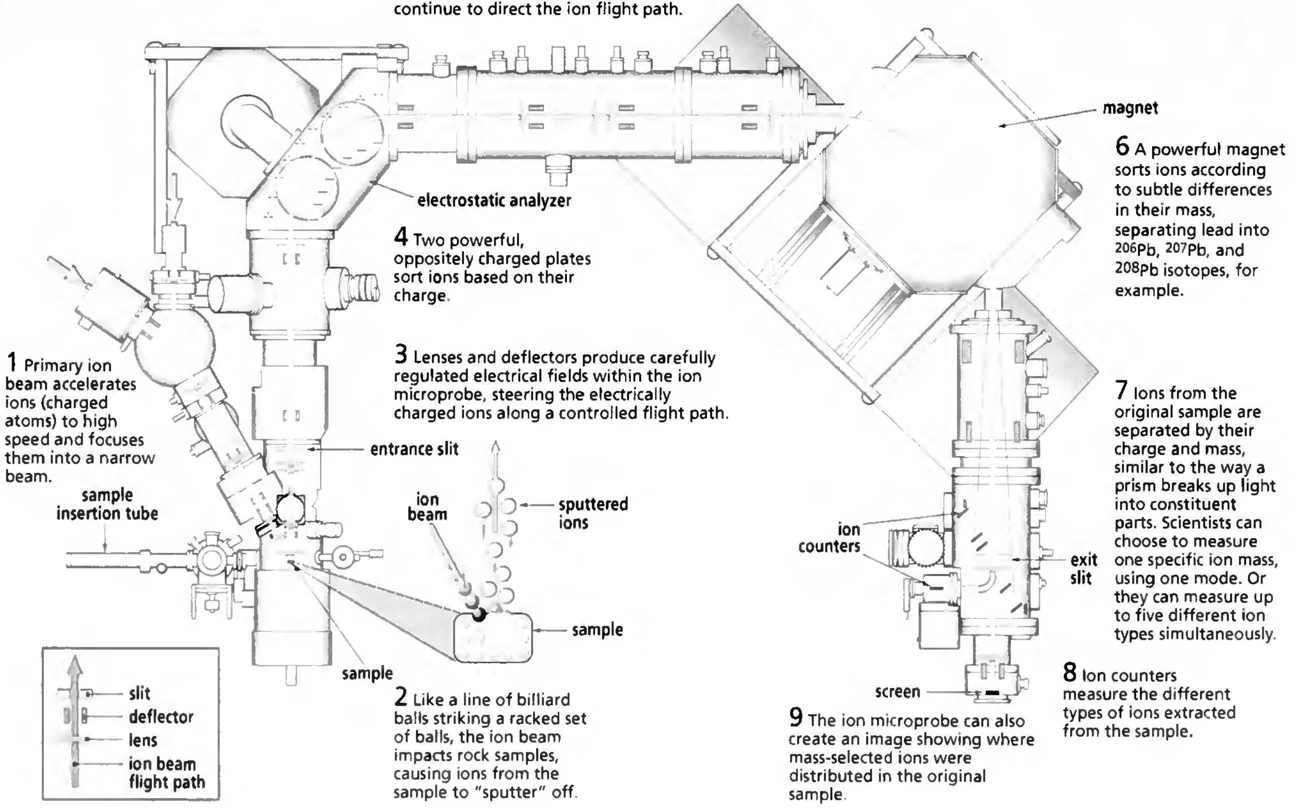
By Nobu Shimizu, Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Every rock on Earth contains a clock, a thermometer, and a barometer. Inside all rocks are elements, or isotopes of elements, called "natural tracers." By examining the presence, proportion, and distribution of natural tracers within rocks, we can reveal the conditions under which the rocks formed. They can tell us when the rocks formed (clocks), how fast they cooled and how they crystallized (thermometers), and the temperatures and pressures they experienced at their creation (barometers).

Just as radioactive tracers are used to understand the dynamics of chemical reactions, natural tracers in rocks can be used to help decipher the whens, wheres, and hows of the complex geological processes that create and maintain our planet. With the right tools, we can extract long-dormant, hidden information about

The tales that rocks can tell

The ion microprobe at WHOI precisely measures very small amounts of isotopes in rocks and other samples, revealing hidden clues about how our planet works. The national facility, supported by the National Science Foundation, is housed in an 800-square-foot laboratory.



1 Primary ion beam accelerates ions (charged atoms) to high speed and focuses them into a narrow beam.

2 Like a line of billiard balls striking a racked set of balls, the ion beam impacts rock samples, causing ions from the sample to "sputter" off.

3 Lenses and deflectors produce carefully regulated electrical fields within the ion microprobe, steering the electrically charged ions along a controlled flight path.

4 Two powerful, oppositely charged plates sort ions based on their charge.

5 Lenses and deflectors located throughout the ion microprobe continue to direct the ion flight path.

6 A powerful magnet sorts ions according to subtle differences in their mass, separating lead into ^{206}Pb, ^{207}Pb, and ^{208}Pb isotopes, for example.

7 Ions from the original sample are separated by their charge and mass, similar to the way a prism breaks up light into constituent parts. Scientists can choose to measure one specific ion mass, using one mode. Or they can measure up to five different ion types simultaneously.

8 Ion counters measure the different types of ions extracted from the sample.

9 The ion microprobe can also create an image showing where mass-selected ions were distributed in the original sample.

Earth's inner workings from rocks.

The Ion Microprobe Facility at Woods Hole Oceanographic Institution is just such a tool. With it, we can peer far back in time and deep into the Earth. To understand processes that form new oceanic crust, for example, we have used the WHOI ion microprobe to study ancient rocks from the crust and underlying mantle, which have been thrust up and exposed on land (in formations known as ophiolite massifs). And we have compared those with rocks from active mid-ocean ridges on the seafloor.

We can also peer into rocks from the surface to incredible depths—almost 450 kilometers down—by probing mineral inclusions in some diamonds formed under pressures at great depth. (Inclusions are minute foreign bodies enclosed within the mass of another mineral.)

Extracting information from rocks

The ion microprobe offers great advantages over previous methods to glean natural tracer information out of rocks. Before, scientists had to break apart sample rocks and extract minerals containing specific tracers. The purified minerals were then chemically processed, and the amounts or types of tracers were determined using various instruments.

It is a painstaking and time-consuming process, and something important is destroyed in the process of mineral extraction and purification: the textural relationships in which mineral crystals occur in the rock. Rock texture is significant because it reflects the dynamic conditions under which minerals crystallized, and it presents a geologic framework within which to interpret the tracer information.

For example, if a rock forms while conditions around it are changing, the minerals in the rock will show different textures or grain sizes depending on the conditions. This information is lost in traditional processing, but retained with ion microprobe analysis because the rock is not broken up. With the ion microprobe, we can look at the composition of very small samples and identify components in situ, even over distances only micrometers apart.

From electron beams to ion beams

The first tools that allowed analysis of a

What the ion microprobe can tell us

How do rocks melt and migrate beneath the seafloor?

The WHOI ion microprobe is helping researchers shed light on a fundamental, but still largely unknown process that shapes our planet—how rock deep beneath mid-ocean ridges melts to form magmas, and how the melted rock then migrates toward Earth's surface at the ridges. The instrument has provided the first unequivocal evidence that a type of melting called "near-fractional melting" is occurring deep beneath ridges.

In near-fractional melting, solid and melted rock do not stay together. The melt finds pathways and immediately escapes the not-yet-melted rock.

We deduced the occurrence of this type of melting by examining compositions of the solid rocks found at mid-ocean ridges. The work is based on our knowledge that when rocks melt, elements are distributed between solid and liquid phases in a particular way. Evidence for near-fractional melting was first found by determining abundance patterns of particular trace elements (the rare earths, or lanthanides) found in a mineral (diopside), which is itself present in very small amounts in rocks (peridotites) dredged from ocean ridge fracture zones. Researchers could not have analyzed such small quantities with conventional geochemical techniques, but the ion microprobe enabled researchers to determine lanthanide abundance patterns in samples and demonstrate this type of melting.

Tiny glass inclusions, about 50 micrometers in diameter, are enclosed in olivine crystals from mid-ocean ridge basalt. The amounts and distribution of isotopes of lead within the inclusions yield information about the mantle source of the basalt.

The same melting has now also been identified in mid-ocean ridge basalt, in tiny glass particles, or glass (melt) inclusions, incorporated into crystals of olivine, a mineral that forms in basalts as they cool and solidify. By determining the isotopic composition of an element, lead, in melt inclusions, we are changing our views about the mantle source for mid-ocean ridge basalt, and about how magma migrates from the mantle to the ocean floor.

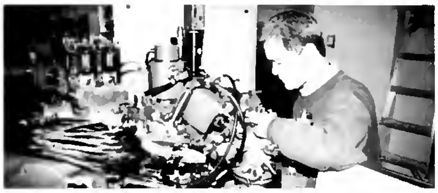
We know that melt inclusions are entrapped in olivine at shallower, less-pressurized levels beneath the seafloor. But the variability of lead isotopes that we are observing in melt inclusions in seafloor rocks samples indicates that melts from different mantle sources are rising separately and are not mixing before they reach the level at which olivine forms.

sample's composition without chemically processing it were earlier electron-beam microprobes. These machines generated electron beams and focused and directed them at a rock sample. The electrons hitting a sample caused the production of X-rays, and measuring the X-ray spectra allowed us to determine the chemical composition of the samples.

In contrast, ion microprobes use focused beams of ions (charged atoms) to bombard a sample. Ions are much heavier than electrons, and the ion beam causes the sample to eject atoms and ions, rather than just emit X-rays. When the ion beam strikes the sample, atoms and ions are "sputtered" (sprayed out) from the sample.

The ion microprobe has two basic parts: the ion-beam source, which focuses and directs microbeams of ions onto the sample; and the mass spectrometer, which measures the signal intensities (abundances) of ions ejected from the sample. Sputtered ions are accelerated into the mass spectrometer, where the ions are detected and distinguished based on their different masses and charges. From the intensities of ions of different elements, we can determine the chemical composition of the sample. From the intensities of isotopes of specific elements, we can identify the isotopic composition of the elements.

The ion microprobe adds new dimensions to our analyses for two reasons. It can detect tracer elements with much greater sensitivity. It also gives us the ability to determine both the chemical composition (the elements present) and the isotopic composition (the proportions of different isotopes of the elements) of minute amounts of tracers, in small samples, without breaking the textural context in the rock.



After a 17-year global migration from his native Tokyo to Washington, D.C., then Paris, France, and Cambridge, Mass., Nobu Shimizu joined the WHOI staff in 1988. He is the "guru of ion probology" in Earth sciences, and a practicing therapist in various relationships (mostly geochemical).

Tom Kleindinst, WHOI

Extracting records of past hurricanes and ocean temperatures from corals

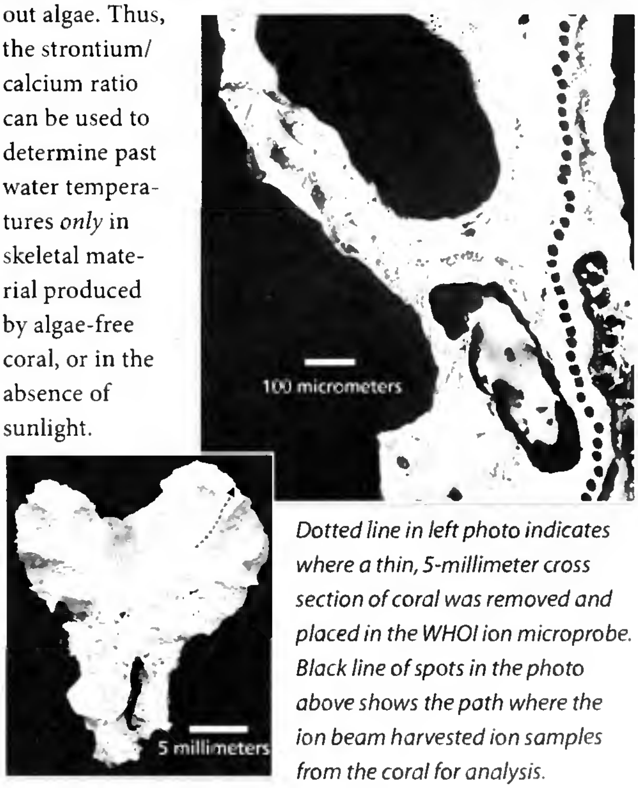
We can study more than rocks with the ion microprobe. WHOI researchers Anne Cohen and Graham Layne have used the facility to examine the hard calcium carbonate skeleton in corals, which can reveal a record of hurricanes and past sea surface temperatures. They sample areas small enough to see layers of skeleton produced by the coral in a day or less.

For the hurricane studies, they use the ion microprobe to determine the ratio of two stable isotopes of oxygen in the carbonate. A higher percentage of the lighter oxygen isotope is incorporated into coral skeletons during periods of very heavy rainfall, which occur during hurricanes. Ancient or fossil corals thereby can reveal a record of hurricane events and patterns stretching into the past.

To estimate past seawater temperatures, researchers often use strontium/calcium ratios in coral skeletons (the higher the strontium, the lower the temperatures). But Cohen used the ion microprobe to reveal a subtle wrinkle in the relationship between the element ratios and water temperatures.

Cohen studied corals living in Woods Hole harbor (*Astrangia poculata*), some of which have algal cells living symbiotically in their tissue, and some of which lack the algae. The photosynthesizing algae directly affects the coral's ability to deposit hard skeleton material and build large coral reefs.

Cohen showed for the first time that strontium/calcium ratios were systematically different in corals with and without algae. Thus, the strontium/calcium ratio can be used to determine past water temperatures *only* in skeletal material produced by algae-free coral, or in the absence of sunlight.



Dotted line in left photo indicates where a thin, 5-millimeter cross section of coral was removed and placed in the WHOI ion microprobe. Black line of spots in the photo above shows the path where the ion beam harvested ion samples from the coral for analysis.

Listening Closely to 'See' into the Earth

A new national facility of cutting-edge seafloor seismographs probes Earth's interior

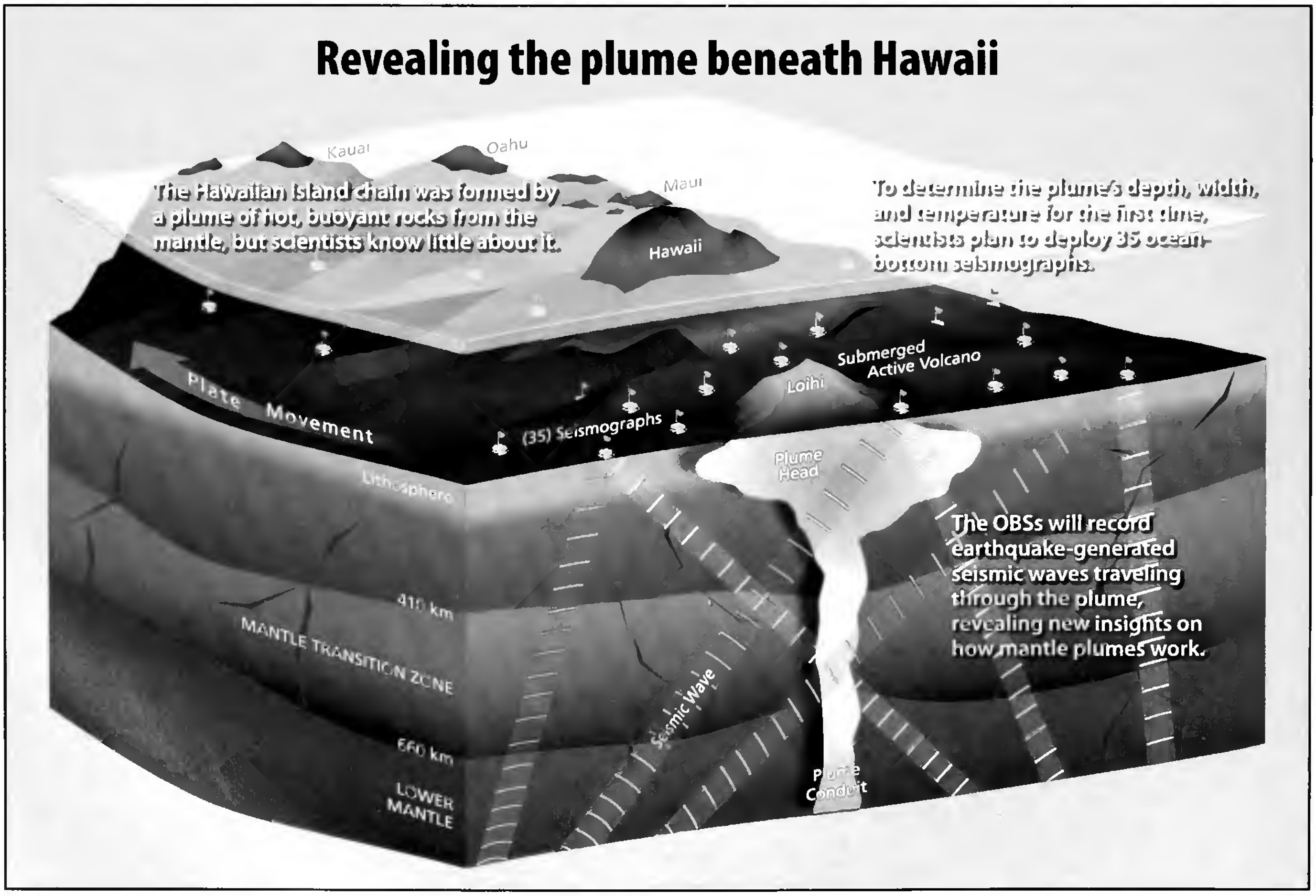
By John Collins, Associate Scientist
Geology & Geophysics Department
Woods Hole Oceanographic Institution

Chemists can monitor reactions in test tubes in their labs. Ecologists can go into the field to make observations. But Earth scientists interested in the structure of Earth's deep interior don't have the luxury of seeing their subject close at hand. Without a way to travel through the Earth, we have had to rely on ways to "see" Earth's structure from a great distance.

To accomplish that, our method employs sound, rather than sight. Whenever an earthquake occurs, scientists can tune in and "listen" to it. We use seismometers and seismographs that measure and record earthquake-generated seismic waves that travel along Earth's surface and through its interior. By analyzing these waves, we can infer a great deal about the characteristics of the materials the waves are traveling through. (See "Earthquakes and Seismic Waves," page 18.)

Within the last decade, two factors have helped make seismology the preeminent tool for determining Earth's hidden interior structure. First, more permanent and temporary seismographs to record seismic waves have been distributed around the globe. Second, international policies have made archives of seismic data freely and widely available on the Internet to any investigator.

Today, excitement and anticipation are growing because of new generations



Revealing the plume beneath Hawaii

The Hawaiian Island chain was formed by a plume of hot, buoyant rocks from the mantle, but scientists know little about it.

To determine the plume's depth, width, and temperature for the first time, scientists plan to deploy 35 ocean-bottom seismographs.

The OBSs will record earthquake-generated seismic waves traveling through the plume, revealing new insights on how mantle plumes work.

Jayne Doucette, WHOI Graphic Services

of seismographs designed for use in the oceans. These new instruments are being built at Woods Hole and two other oceanographic institutions, and they will comprise a new national pool of instruments for use by the scientific community. This new national facility will let us monitor more of the planet with the precision we've long wished for, and thus enhance our ability to answer fundamental questions about our planet.

Mapping Hawaii's plume

Until now, almost all seismic observatories have been located on land, which accounts for only 30 percent of Earth's surface. The lack of evenly distributed seismograph coverage in the oceans has limited our understanding of Earth's structure at both regional and global scales.

On a regional scale, consider the task of understanding the structure of the upper mantle beneath the small geographic region of Hawaii. Hawaii is thought to be the surface expression of a buoyant plume of hot rock in the upper mantle, possibly originating at the core-mantle boundary at a depth of about 2,900 kilometers (1,800 miles). We don't know the width, temperature, or depth of the plume.

To find out, we will need to record seismic waves that travel from a known source, through the plume, to receiving seismographs. But the waves must travel through as little as possible of the rest of the Earth, so that we can attribute any anomalies or alterations in the waves entirely to their passing through the plume.

Hawaii's landmass is so small, however, that land seismic stations cannot be positioned in places to intercept waves that travel through the plume at depth. So we haven't been able to measure how deep the plume is. Nor are the islands close enough together to let us accurately measure the plume's diameter. The only way to determine the plume's structure is by placing seismographs in appropriate locations to intercept waves that have traveled only through the plume—and those locations are on the seafloor.


Victor Bender, WHOI

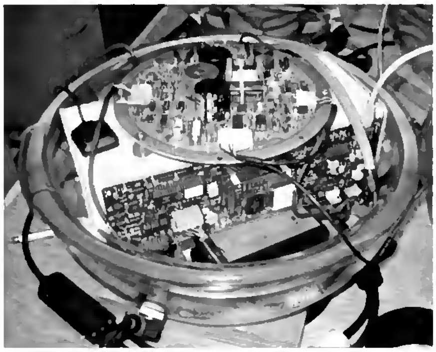
SHORE TO SHIP—A vanload of new WHOI "D2" ocean-bottom seismographs is readied for field testing. The D2s are small and light, for easy deployment and recovery. With a six-month battery capacity, they are designed for relatively short-term experiments. The D2s are available to scientists through the newly created National Ocean-Bottom Seismograph Instrumentation Pool. WHOI Senior Engineer Ken Peal, who helped design the D2, is in the background.

Seismic waves through the Earth

To probe Earth's interior on a more global scale, the most useful earthquakes to study are large and deep. But such earthquakes do not occur uniformly over the planet. They happen only in specific geographic areas called subduction zones, where tectonic plates plunge back into the mantle.

Seismic waves from these earthquakes radiate through Earth's deep interior to the other side of the globe. But because existing land-based seismic stations aren't distributed uniformly on Earth's surface, we don't receive any information from many areas. That leaves us with large gaps in our knowledge about some parts of Earth's deep interior.

Very large earthquakes can actually set the whole planet vibrating in a series of oscillations, commonly likened to the ringing of a bell, which affect the entire surface of the Earth. But we can't measure them over large areas where there are no seismographs, once again leaving us with an incomplete picture of Earth's interior. In fact, the optimum location to observe and measure seismic waves that pass through Earth's core lies in the central Atlantic Ocean—where there are few seismographic stations!


Victor Bender, WHOI

The D2's electronic data logger (above), which records seismic wave measurements, resides in a glass ball in one half of the peanut-shaped D2. Batteries are in the other half.

Seismic data gaps in the ocean

The oceanographic community has long recognized the need for seafloor seismic stations. Since the 1970s, several oceanographic institutions—including Woods Hole, Scripps Institution of Oceanography, and the University of Texas Institute of Geophysics—have designed, built, and operated ocean floor seismic-monitoring instruments, known as ocean-bottom seismographs (OBSs) and ocean-bottom hydrophones (OBHs). The research was funded primarily by the Office of Naval Research.

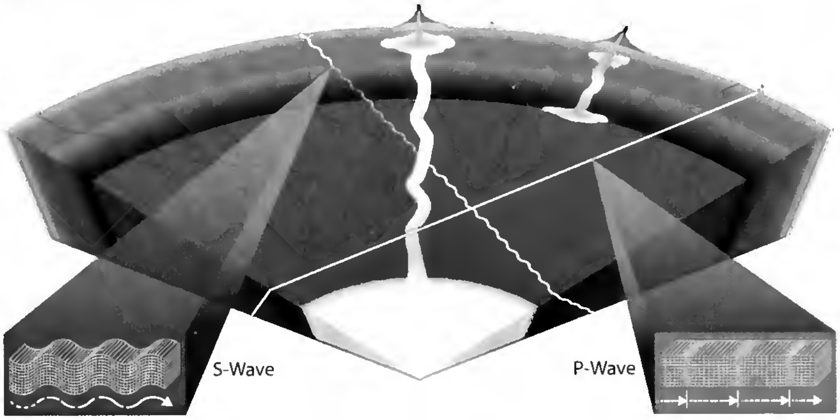
For several reasons, these first-generation OBS and OBH instruments didn't give us a clear picture of Earth's structure.

Earthquakes and seismic waves

When an earthquake occurs, rocks at a fault line slip or rupture, and a portion of Earth's crust physically moves. That releases energy, and two types of seismic waves radiate outward from the earthquake through Earth's interior and along its surface. Compression waves alternately compress and release rocks in the direction the waves are moving (similar to the air compression we hear as sound). Shear waves move rocks perpendicularly to the direction the waves are moving.

Seismographs (seismometers and associated recording systems) detect and measure these waves. Compression and shear waves travel through the Earth at different speeds. By measuring the speed of the waves as they travel through different positions within the Earth, we can draw inferences about the temperature, composition, and degree of deformation of the material that the waves travel through. In turn, better estimates of these characteristics improve our understanding of hidden processes that occur in the Earth's core, mantle, and crust.

With seismic measurements we can also locate an earthquake's source. The characteristics of an earthquake itself, such as its location, magnitude, fault orientation, and fault slip, are important for understanding tectonic processes at global and regional scales, and seismology is essential for understanding the physics of earthquake initiation and rupture.



Jayne Doucette, WHOI Graphic Services

***1**–Shear waves (S-waves) move rocks perpendicularly to the direction the waves are moving (similar to waves at the beach).*

***2**–Compression waves (P-waves) alternately compress and release rocks in the direction the waves are moving (similar to the air compression that we hear as sound).*

Robert Reves-Sohn, WHOI

A D2 is field-tested on the seafloor near the TAG hydrothermal vent site in the North Atlantic. A weight anchors it to the bottom. The seismometer is housed in the silver canister at right.

They required a lot of power, had limited storage capacity, and used inexact clocks that couldn't determine (with enough accuracy) the times when waves from an earthquake arrived.

But today's seafloor seismic instruments are being built with low-power digital electronics, very large storage capacities, and high-precision clocks that drift only a millisecond a day or less. The older instruments measured Earth movements with periods of a second or so, but new seafloor seismometers are sensitive to motions with periods of hundreds to tenths of seconds, which can tell us much more about the Earth's deep structure. And new high-dynamic-range analog-to-digital converters improve upon older converters, which tended to distort both small signals (such as from a distant moderate earthquake) and large signals (such as from a large local earthquake).

A new national seismic facility

Another obstacle in the early days was a limited availability of OBSs. Most early instruments were available only to investigators at institutions that built the instruments, and these investigators didn't necessarily pursue scientific questions of interest to a broader Earth science community. In addition, early seismic data were stored in scattered sites and in a variety of formats, so many of the data remained inaccessible because they were hard to find and use.

Now, with National Science Foundation funding, three institutions—Woods Hole Oceanographic Institution (WHOI), the Institute of Geophysics and Planetary Physics at Scripps Institution of Oceanography (SIO), and the Lamont-Doherty Earth Observatory of Columbia University—will form the National OBS Instrumentation Pool.

Each institution will design, build, and operate instruments, and provide engineering and technical support to deploy the instruments on the seafloor. Investigators can request to use OBSs from the national facility as a part of the standard NSF proposal process, and other private and public organizations can use them as availability permits. All data collected with these new instruments will be centrally archived at the same national data repository used by the U.S. land seismological community. After two years' proprietary access for investigators, the data will be available to all.

Two new kinds of OBSs

WHOI and SIO each will build and operate two distinct types of OBSs. One will be used for short deployments to record predominantly short-period (i.e. high-frequency) Earth motions. The other can be deployed for a year or more to record Earth motions over a much broader range of periods.

Short-period OBSs are usually used in closely spaced arrays for durations of days. They typically record seismic waves from artificial sources, such as those used by the oil-exploration industry, which use compressed air to produce a brief wave pulse. These instruments are used to determine the structure of the outer tens of kilometers of the seafloor.

The WHOI short-period OBSs, called "D2s," have a six-month battery capacity and are equipped with a seismometer and a hydrophone. They can detect Earth motions in both vertical and horizontal directions, and can even record small, short-period earthquakes, such as those associated with hydrothermal vent activity.

In typical experiments using short-period OBSs, large numbers of instruments must be deployed repeatedly during 30-day cruises. So the D2s were designed to be small and light, for easy recovery. They don't need to be opened at sea; instead recorded data can be offloaded easily onto a shipboard data-storage system over an Internet connection.

A long-awaited experiment

The first short-deployment experiments using D2s were completed in the summer of 2002. In April of 2004, we undertook our first really challenging experiment, deploying and recovering some 150 D2s during a 35-day cruise.

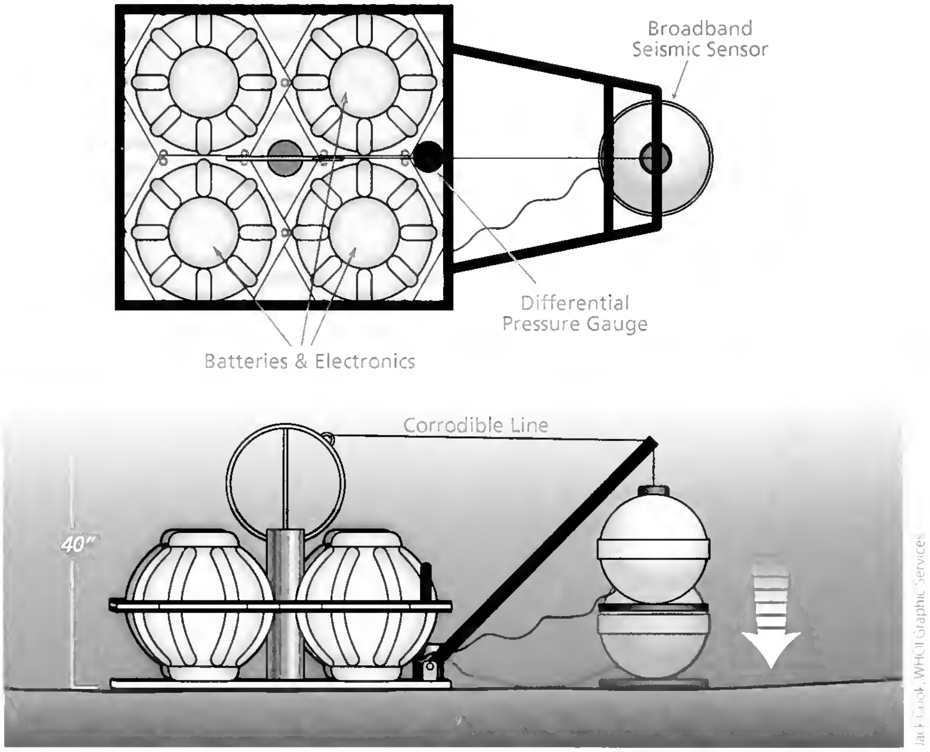
All three institutions are building long-deployment OBSs. These carry long-period pressure sensors and seismometers capable of recording Earth motions with periods ranging from about 40 seconds to 0.1 seconds. The WHOI long-deployment OBS will have the same data logger used in the D2 OBS, but will be equipped with a WHOI-designed acoustic modem that will let investigators on research vessels remotely retrieve data from the OBS sitting on the seafloor. This capability will allow investigators to check that the OBS is performing adequately before the ship leaves the area for a year.

The first long-term deployment is scheduled to take place in December 2004 off Hawaii in the Plume Lithosphere Undersea Melt Experiment (PLUME). The goal of this two-year long experiment—a collaboration between WHOI, SIO, the University of Hawaii, and the Carnegie Institution of Washington—is to image the Hawaiian plume. This one experiment has the potential to revolutionize our understanding of how Earth's mantle convects.

For Earth scientists, the future looks bright, and will sound even better.

Tom Kleindinst, WHOI

Born and raised in Ireland, John Collins came to the United States in 1981 and entered the MIT/WHOI Joint Program. After two years of postdoctoral work in Australia, John returned to WHOI where he has been ever since. Collins' scientific interests focus on investigating the structure of the oceanic crust and lithosphere, and he has played a major role in developing a wide variety of ocean-bottom seismic instrumentation. He has participated in about 20 research cruises that have taken him from the Pacific to the Atlantic. Since 2003, he has served as the manager of WHOI Ocean Bottom Seismometer Instrument Pool.



Jack Cook, WHOI Graphic Services

A NEW GENERATION OF SEISMOGRAPHS—WHOI is designing and building ocean-bottom seismographs (OBSs) for long-term deployments. The four orange fiberglass "hardhats," mounted on a plastic grillwork, contain batteries and electronics. A differential pressure gauge measures earthquake-generated waves in the water. The seismometer is housed in a metal sphere attached to an swivel at right. When the OBS is deployed, a line corrodes, positioning the seismometer on the seafloor.

Realizing the Dreams of da Vinci and Verne

A diverse fleet of innovative deep-submergence vehicles heralds a new era of ocean exploration

By Daniel Fornari, Director
Deep Ocean Exploration Institute
and Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Leonardo da Vinci made the first drawings of a submarine more than 500 years ago, and Jules Verne published *20,000 Leagues Under the Sea* in 1875. But only in the past few decades has the dizzying pace of technological advances allowed us to realize their dreams of exploring the ocean depths and taking humans to the seafloor.

For the past 40 years, submersible human-occupied vehicles (HOVs) such as *Alvin* have given scientists direct access to the seafloor and the ability to explore it from a firsthand and up-close perspective—one they could only fantasize about from the decks of ships. But even more recently, humans have explored the abyss with vehicles that even da Vinci and Verne never conceived: remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs). The latest generation of these innovative deep-submergence vehicles has enhanced human access to extreme abyssal environments and has greatly expanded the capabilities of Earth and ocean scientists to investigate the far reaches and depths of the global ocean.

ROVs, AUVs, and HOVs

ROVs are unoccupied underwater vehicles controlled by a pilot aboard a support ship and tethered to a fiber-optic cable. The cable offers unlimited power to the vehicle, so ROVs can stay on the bottom longer than HOVs. The cable also transmits real-time images and data to scientists aboard ship. The ROV's pilot uses the dexterous, force-feedback manipulator arms to collect samples, perform experiments, and deploy, service, and download sensors in the deep.

AUVs are unoccupied, untethered vehicles that are dispatched on pre-programmed missions in the ocean. Like ROVs, they can operate submerged for longer periods than HOVs. But their free-swimming abilities, combined with more precise control over their movements, also allow them to explore and map much more of the seafloor and the water above it per dive.

AUVs and ROVs, in concert with HOVs, will play indispensable roles in establishing and servicing long-term seafloor observatories. (See "Seeding the Seafloor with Observatories," page 28.) Together, the complementary capacities of all three types of deep-submergence vehicles provide synergies that have revolutionized how scientists conduct research in the ocean.

Revolutionary discoveries

The era of modern oceanography was launched by the HMS *Challenger* expedition (1872-76), and until recently has relied on surface ships that go on expeditions lasting from weeks to months to collect data. Technical advances in instruments, especially after World War II, let scientists collect more and better data, which fueled great leaps in knowledge about the Earth and ocean.

Geophysicists mapped striking seafloor features, ranging from deep trenches to the mid-ocean ridge system—the globe-encircling underwater volcanic mountain chain where the ocean crust is born. (See "Unraveling the Tapestry of Ocean Crust," page 40.) These discoveries led to the plate tectonics revolution in the early 1970s, which created a fundamental new framework for understanding how the Earth works.

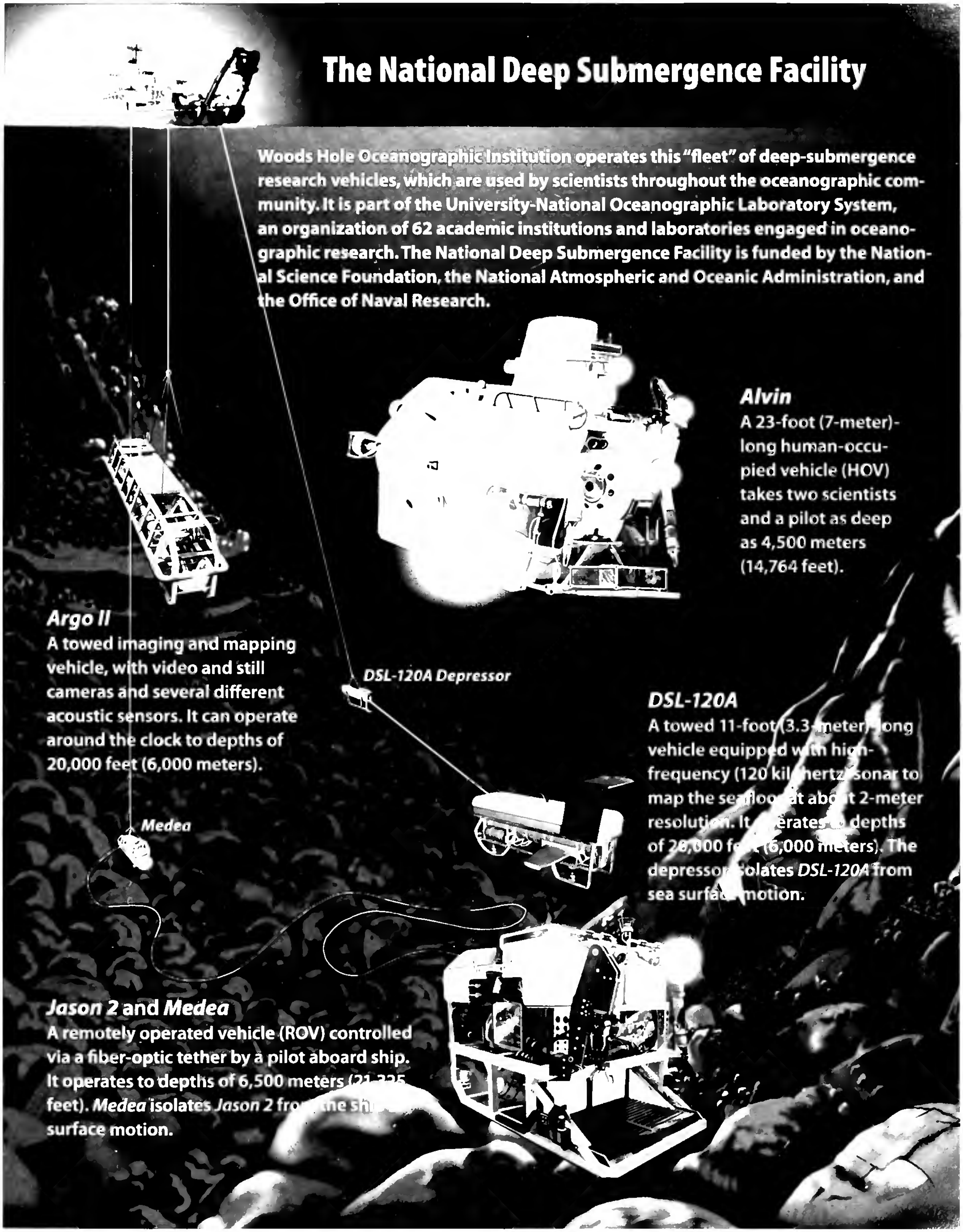
Physical oceanographers pieced together a general understanding of the physics that control the ocean's circulation and water masses. With climatologists, they realized the importance of interactions between the oceans and atmosphere in controlling Earth's climate.

It was only in 1977 that biologists, geologists, and geochemists found lush biological communities living off chemicals issuing from deep-sea hydrothermal vents on the crest of the volcanic mid-ocean ridge. This unexpected discovery transformed conceptual thinking about how and where life could exist on this and other planets and has stimulated new lines of inquiry into the origins of life itself. (See "Is Life Thriving Deep Beneath the Seafloor?" page 72, and "The Evolutionary Puzzle of Seafloor Life," page 78.)

The fourth dimension: time

The discovery of hydrothermal vents also catalyzed a realization that now dominates the thinking of marine scientists—the idea that myriad geological, chemical, biological, and physical processes in the deep ocean and on the seafloor are interconnected. (See "Living Large in Microscopic Nooks," page 86.)

To observe and understand interrelated



The National Deep Submergence Facility

Woods Hole Oceanographic Institution operates this "fleet" of deep-submergence research vehicles, which are used by scientists throughout the oceanographic community. It is part of the University-National Oceanographic Laboratory System, an organization of 62 academic institutions and laboratories engaged in oceanographic research. The National Deep Submergence Facility is funded by the National Science Foundation, the National Atmospheric and Oceanic Administration, and the Office of Naval Research.

Alvin

A 23-foot (7-meter)-long human-occupied vehicle (HOV) takes two scientists and a pilot as deep as 4,500 meters (14,764 feet).

Argo II

A towed imaging and mapping vehicle, with video and still cameras and several different acoustic sensors. It can operate around the clock to depths of 20,000 feet (6,000 meters).

DSL-120A

A towed 11-foot (3.3-meter)-long vehicle equipped with high-frequency (120 kilohertz) sonar to map the seafloor at about 2-meter resolution. It operates to depths of 20,000 feet (6,000 meters). The depressor isolates *DSL-120A* from sea surface motion.

Jason 2 and *Medea*

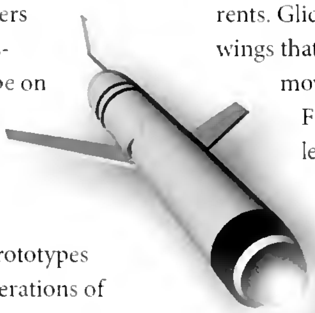
A remotely operated vehicle (ROV) controlled via a fiber-optic tether by a pilot aboard ship. It operates to depths of 6,500 meters (21,325 feet). *Medea* isolates *Jason 2* from the ship's surface motion.

processes that change over time, scientists need to collect a variety of data—over spatial scales ranging from centimeters to kilometers and time spans ranging from seconds to days, years, and decades. They need to establish a continuous, comprehensive, long-term presence in the sea and on the seafloor—instead of trying to piece together processes by taking intermittent snapshots of a relatively few places and events. The difference in approach is like seeking to understand family dynamics by looking at a photo album versus spending a few weeks with a family.

Here is where new ROVs and AUVs will excel. Equipped with new suites of sensors, an expanding fleet of autonomous and remote deep-submergence vehicles will give scientists more time to explore, with expanded capabilities to map, sample, and measure, over more territory—including remote and inhospitable portions of the oceans that have defied comprehensive exploration by surface vessels.

Gliders, drifters, and REMUS

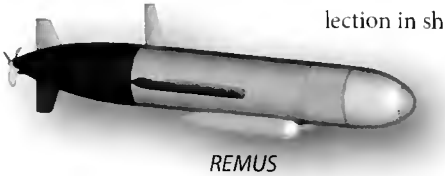
At the Woods Hole Oceanographic Institution (WHOI), the synergy and collaboration among engineers and scientists have consistently pushed the envelope on robotic oceanographic technology. As a result a diverse range of vehicles has evolved from drawing board to prototypes and now into second generations of vehicles working routinely on the ocean frontier. Individual types of vehicles are adapted and equipped to accomplish specific missions.



Glider

In the coming decades, for example, oceanographers will be eager to measure physical and chemical processes that drive the world's ocean circulation and influence Earth's climate. Many of these interactions occur between the atmosphere and ocean over vast regions, between and across oceans. To this day, many oceans—including the South Atlantic, Arctic, Indian, and Southern Oceans—have not been well-studied because of their great size, remote locations, or severe conditions (ranging from sea ice to stormy seas).

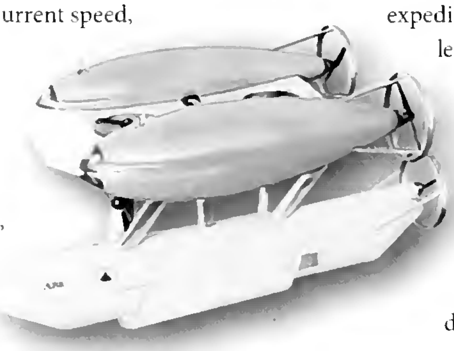
Though satellites provide global coverage, they cannot provide data much beyond the sea surface. AUVs are probably the only way that we will fill in these large gaps in our knowledge and gain a full understanding of the short- and long-term oceanographic processes within nearly half of Earth's ocean basins.



REMUS
(Remote Environmental Sensing UnitS

For this mission, autonomous gliders and drifters are being developed that can travel across open oceans over hundreds of miles and several weeks, taking measurements along the way. Drifters such as Argo, RAFOS, and Spray (now being developed by Brechner Owens at WHOI and Russ Davis at Scripps Institution of Oceanography) are pre-programmed to deflate and inflate a bladder, which causes them to sink as much as 2,000 meters (6,500 feet) in the ocean and then rise again to the surface as they are carried along by currents. Gliders are essentially drifters with wings that provide lift and allow them to move horizontally. At WHOI, Dave Fratantoni and colleagues are leading efforts to use and develop new glider systems.

Equipped with diverse oceanographic sensors, gliders and drifters can make fine-scale measurements of temperature, salinity, current speed, phytoplankton abundances, and chemical changes, and then surface periodically to transmit the data via satellite to scientists on shore. Fleets of these vehicles, numbering in the hundreds and eventually thousands, will be able to make comprehensive studies of vast oceanic regions. The portability of these vehicles also makes them useful to study ephemeral or localized phenomena, such as phytoplankton blooms or upwelling events.



ABE
(Autonomous Benthic Explorer)

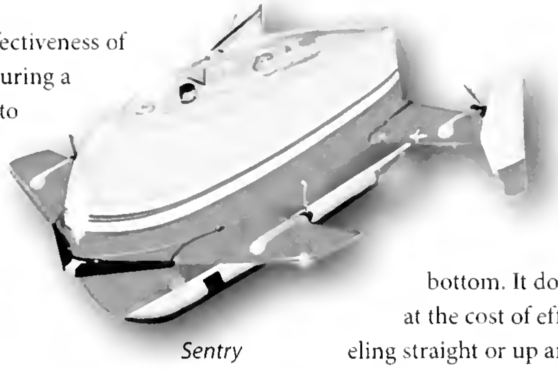
For surveys, mapping, and data collection in shallow depths (330 feet, or 100 meters) and coastal ocean regions, WHOI scientists and engineers led by Christopher von Alt built REMUS (Remote Environmental Sensing Units). This class of AUVs has already logged thousands of research missions. Specially modified REMUS-based vehicles have been used to search for mines in Iraqi harbors and for cracks in tunnels supplying water to New York City from upstate reservoirs.

A pioneer in the ocean frontier

In the deep ocean, the Autonomous Benthic Explorer (*ABE*), developed by WHOI researchers Dana Yoerger, Albert Bradley, and Barrie Walden, has been a pioneer. It has provided a testbed for innovative robotics and electronics that have demonstrated the viability and value of deep-submergence AUV technology for a wide range of oceanographic research. It can dive to depths of 5,000 meters (16,500 feet) for 16 to 34 hours, equipped with an assortment of sensor packages (such as high-resolution sonar, salinity, temperature, and chemical recorders, current meters, and magnetometers) to accomplish a variety of scientific missions, often during the same dive.

AUVs add value to oceanographic expeditions by collecting data autonomously while ships simultaneously acquire data using more traditional means. AUVs can also

Illustrations by E. Paul Oberlander, WHOI Graphic Services


Sentry

maximize the effectiveness of other vehicles. During a 2002 expedition to the Galápagos Rift led by WHOI biologist Tim Shank and his NOAA colleague Steve Hammond, *ABE* demonstrated that it could survey the seafloor by night, surface at dawn, and deliver high-precision maps that scientists in *Alvin* used to guide their explorations that day.

ABE's capability to adapt its navigation to maintain a precise course over rugged seafloor topography gives it the ability to make high-precision seafloor maps. In a typical dive, *ABE*'s sonars can image features less than a meter in length and a few tens of centimeters tall on a square kilometer of terrain. That is the equivalent of being able to see footprints on a football field from the bleachers. The scale and resolution of these maps alone are giving scientists the ability to correlate seafloor features and biological and geological processes in ways that were previously impossible.

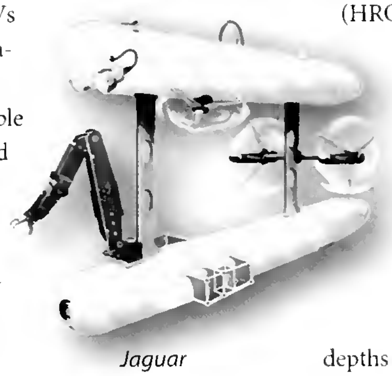
Sentry, Puma, and SeaBED

AUVs' high-resolution mapping abilities will also play a key role in the development of long-term, deep-sea observatories by identifying optimal locales to deploy sensors measuring a wide range of chemical, biological, and geological processes over time. In the future, deep-sea observatories will include docking stations for AUVs. These AUVs will be programmed to be dispatched from their docks to rapidly respond to fast-breaking or ephemeral events in the oceans that ships could never reach in time to observe—an earthquake, for example, or a temperature or chemical change—and conduct timely sampling or deploy experiments.

As good as *ABE* is, WHOI engineers are striving to make it and its progeny better. For instance, *ABE* was designed to be able to move in any direction or turn in place so it could maneuver close to the bottom. It does this well, but at the cost of efficiency in traveling straight or up and down. It is ideal for close-to-the-bottom surveying and photography. The immense value of these maps spurred WHOI engineers to design a second-generation vehicle called *Sentry*, optimized for sonar surveys in rugged terrain. *Sentry* will give up the ability to move directly sideways or to hold position and heading, but it will be much more efficient in forward travel, steep climbs and dives, and vertical motion.


SeaBED

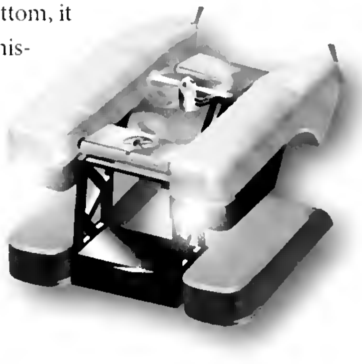
WHOI scientists are also designing other AUVs with specialized capabilities for specific missions. One example is SeaBED, developed by WHOI scientist Hanumant Singh and colleagues. It is an AUV that can fly slowly or hover over the seafloor to depths of 6,000 feet (2,000 meters), making it particularly suited to collect highly detailed sonar and optical images of the seafloor. With Singh and other colleagues, WHOI scientist Rob Reves-Sohn is developing *Puma* and *Jaguar*, two AUVs designed to search for and investigate hydrothermal vents under the ice-covered Arctic Ocean. (See "Unique Vehicles for a Unique Environment," page 25.)


Jaguar

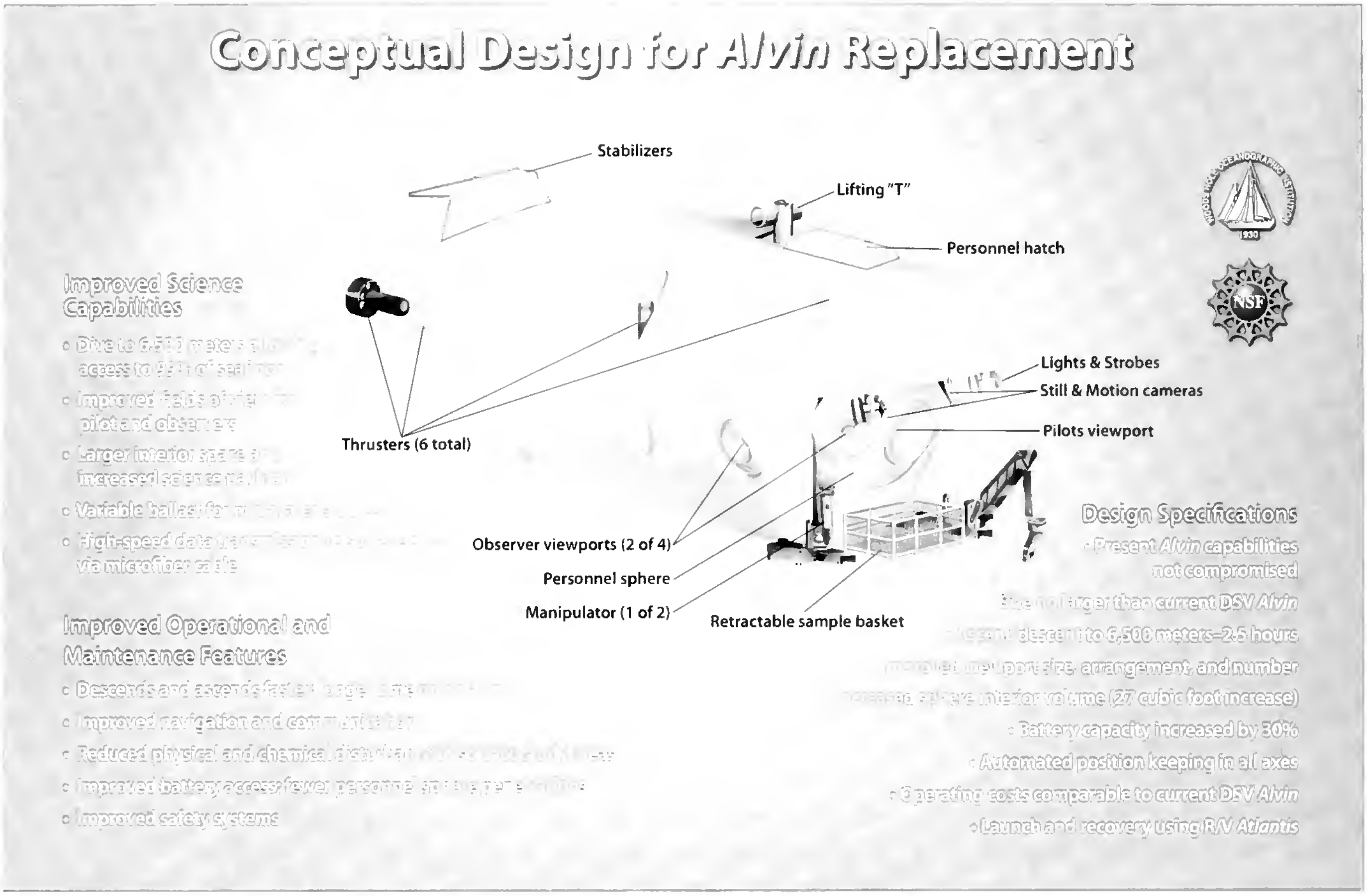
ROVs and HROVs

AUVs' advantages are complemented by ROVs, such as the pioneering *Jason* ROV, first developed in the late 1980s by Andrew Bowen, Dana Yoerger, and colleagues in the WHOI Deep Submergence Laboratory (DSL), under the leadership of Robert Ballard. The lab designed and built an improved second-generation *Jason* ROV, which was launched in 2002 and is now in service as part of the National Deep Submergence Facility at WHOI.

One disadvantage of ROVs, however, is that they can't cover as much ground as AUVs in the same amount of time. The ROV tether, which can be thousands of meters long and an inch thick, produces drag on the vehicle, and makes it less maneuverable and vulnerable to entanglement, especially in difficult terrains. To combine the strengths of both types of vehicles, Bowen and Yoerger of the WHOI Deep Submergence Laboratory, in collaboration with Louis Whitcomb of Johns Hopkins University, have begun to design a Hybrid Remotely Operated Vehicle (HROV), which will be able to switch back and forth to operate as either an AUV or an ROV on the same cruise. It will use a lightweight fiber-optic cable, only 1/32 of an inch in diameter, which will allow the HROV to operate and maneuver at unprecedented depths without the high-drag and expensive cables and winches typically used with ROV systems. Once the HROV reaches the bottom, it will conduct missions while paying out as much as 20 kilometers (about 11 miles) of microcable.


HROV
(Hybrid Remotely Operated Vehicle)

Pilots on surface vessels will remotely control



E. Paul Oberlander, WHOI Graphic Services

the HROV via the microcable, which will be jettisoned upon completion of the mission. Untethered, the HROV will guide itself to the surface for recovery by a ship, and the microcable is then recovered for reuse.

The HROV will bring ROV capabilities to places where it could not be used before, such as the ice-covered Arctic. If the ROV cable is severed during operations, the AUV capabilities will automatically take over to continue the mission autonomously or to return the vehicle to the surface. The HROV will also be capable of diving to 11,000 meters (36,000 feet)—deep enough to explore the deepest parts of the world's oceans in the trenches of the western Pacific.

A new replacement for *Alvin*

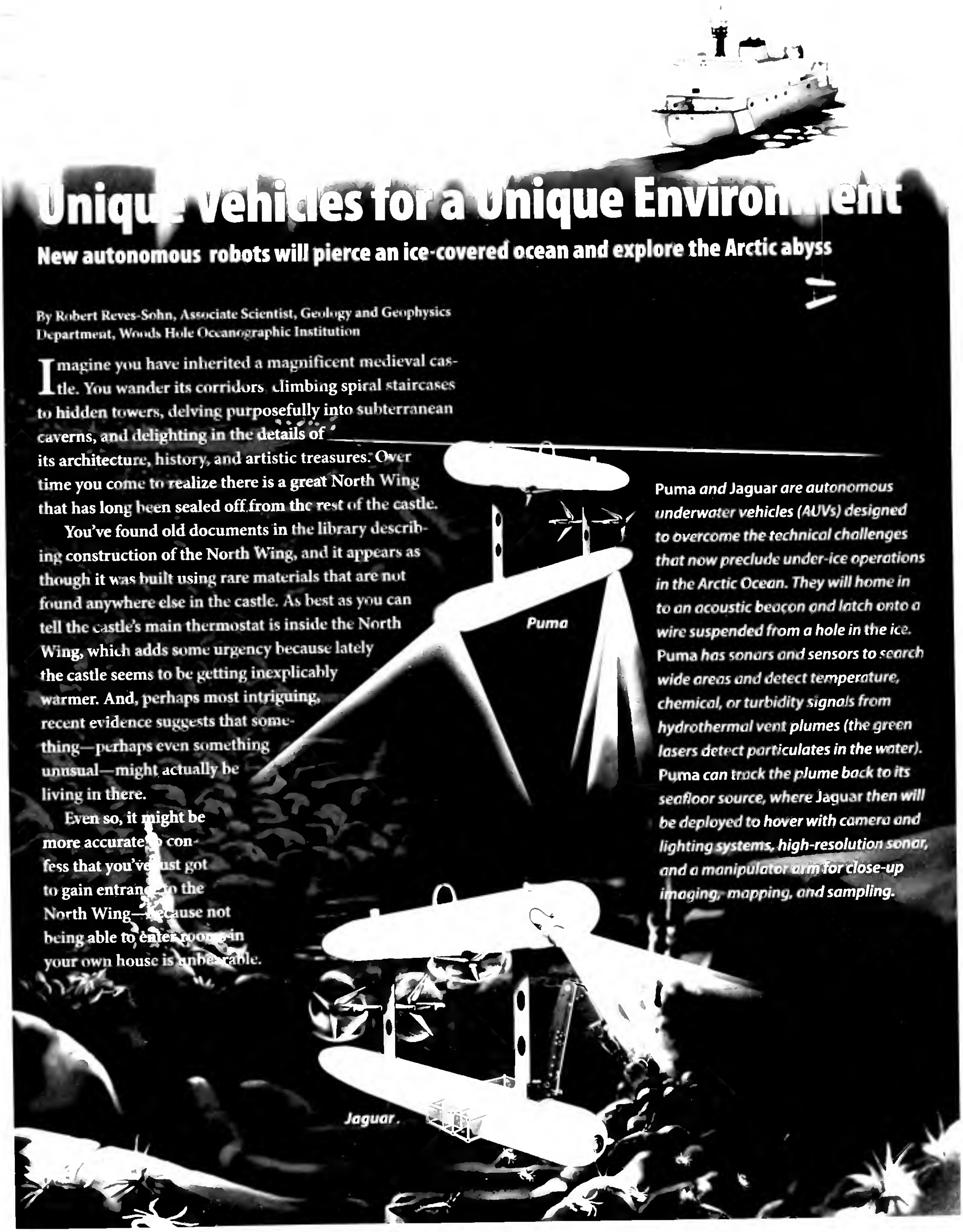
The remote capabilities of AUVs and ROVs have proved enormously valuable, but there is still no substitute for being there. In particular, two-dimensional images from ROVs still cannot provide the direct, three-dimensional, full-contextual vision of the human eye, combined with the ingenuity of the human mind on the scene.

Forty years after *Alvin* was delivered in 1964, WHOI scientists have embarked on designing a new replacement HOV, funded by the National Science Foundation, with many improvements, including an increased diving depth of 6,500 meters (21,325 feet) that will allow it to reach 99 percent of the seafloor. (At its current depth limit of 4,500 meters or 14,765 feet, *Alvin* can reach 63 percent of the seafloor.)

Together, all these new deep-submergence vehicles will be at the vanguard of a new era of ocean exploration, leading us deeper into the ocean frontier and auguring a new era of discovery.

—Oceanus *Editor Laurence Lippsett contributed to this article.*

Dan Fornari (left) became Director of the Deep Ocean Exploration Institute at WHOI in 2004. He is internationally recognized for his research on volcanic and hydrothermal processes and mapping at mid-ocean ridges, and on the structure and magmatic processes at oceanic transforms and oceanic islands, such as Hawaii and the Galápagos. Over 35 years, he has participated in 55 research cruises in the Pacific, Atlantic, and Indian Oceans, and has completed more than 100 dives in Alvin *and other Navy submersibles. In 1993, he became the first Chief Scientist for Deep Submergence at WHOI, and helped usher in a new era in deep-submergence technology using* Alvin *with the ROV* Jason 2 *and high-resolution sidescan sonar systems. Fornari has served on numerous scientific panels, and national and international committees, including the President's Commission on Ocean Exploration in 2003. Together, he and Susan Humphris developed Dive and Discover, an education and outreach Web site (www.divediscover.whoi.edu) that brings the excitement of oceanographic science to thousands of students each day. He is ably assisted most days by his personal assistant, Riley (right).*



Unique Vehicles for a Unique Environment

New autonomous robots will pierce an ice-covered ocean and explore the Arctic abyss

By Robert Reves-Sohn, Associate Scientist, Geology and Geophysics Department, Woods Hole Oceanographic Institution

Imagine you have inherited a magnificent medieval castle. You wander its corridors, climbing spiral staircases to hidden towers, delving purposefully into subterranean caverns, and delighting in the details of its architecture, history, and artistic treasures. Over time you come to realize there is a great North Wing that has long been sealed off from the rest of the castle.

You've found old documents in the library describing construction of the North Wing, and it appears as though it was built using rare materials that are not found anywhere else in the castle. As best as you can tell the castle's main thermostat is inside the North Wing, which adds some urgency because lately the castle seems to be getting inexplicably warmer. And, perhaps most intriguing, recent evidence suggests that something—perhaps even something unusual—might actually be living in there.

Even so, it might be more accurate to confess that you've just got to gain entrance to the North Wing—because not being able to enter rooms in your own house is unbearable.

Puma and Jaguar are autonomous underwater vehicles (AUVs) designed to overcome the technical challenges that now preclude under-ice operations in the Arctic Ocean. They will home in to an acoustic beacon and latch onto a wire suspended from a hole in the ice. Puma has sonars and sensors to search wide areas and detect temperature, chemical, or turbidity signals from hydrothermal vent plumes (the green lasers detect particulates in the water). Puma can track the plume back to its seafloor source, where Jaguar then will be deployed to hover with camera and lighting systems, high-resolution sonar, and a manipulator arm for close-up imaging, mapping, and sampling.

Finding a way in

You come to realize, however, that you're not the first to try. Numerous intrepid individuals have dedicated themselves to the pursuit over the years, their stories comprising a veritable tome of frustration and failure. And why? Because the North Wing is hidden under a moat of water more than two miles deep, which, in turn, is covered by a permanent layer of ice.

Moreover, it is so far north that the compasses and gyroscopes typically used for navigation are essentially useless. The tools required to get through ice and into the abyss to explore the North Wing cannot be bought at any price. You will have to make them yourself.

You have probably guessed by now that the castle in this mental exercise is Earth, and the North Wing is the vast, ice-covered Arctic Ocean Basin. If the old adage is true that we know more about the surface of our neighboring planets than we do about Earth's ocean basins (and it is), then nowhere is it more true than the Arctic Basin.

A blank spot on the map of Earth

Deep-sea research is hard enough as it is. But cover the ocean you're trying to explore with a permanent ice cap, limit your available field season to a few months that are not too cold and dark, and factor in a generally inaccessible location at the very top of the world, and you can begin to appreciate why we know so little about the Arctic Basin.

In fact, were it not for a few Russian and American scientists whiling the months away in camps on drifting ice floes, we would know almost nothing at all about the Earth's great North Wing. (Actually, U.S. and Soviet navies also gathered data about the Arctic during the heyday of Cold War submarine warfare, but this information is generally classified.)

The human spirit cannot abide a puzzle with a missing piece. But this is especially so when the missing piece could fill in crucial details about the origin of Earth's oceans, the evolution of life, and our planet's susceptibility to climate change.

An unexplored frontier

For climatologists and physical oceanographers, it is often said that the Arctic is a canary in the environmental coal mine. In a warming world, the Arctic's delicately balanced ocean circulation and sea ice appears vulnerable to disruptions that could have dramatic impacts on Earth's oceans and climate. Thus, climate change drives a large percentage of Arctic research.

But the Arctic Basin is so unknown and unique, it probably holds more undiscovered scientific treasures than any other ocean basin on Earth. Perhaps the hardest challenge is deciding which fundamental scientific questions to attack first.

For marine biologists, for example, the Arctic represents a potential gold mine. About 65 million years ago, the Arctic Ocean basin became enclosed, with no deepwater connections to any other ocean basin on Earth. Species and biological communities in the Arctic Ocean may have developed and evolved in isolation, possibly making the Arctic a sort of marine equivalent of Australia. (See "The Evolutionary Puzzle of Seafloor Life," page 78).

A 21st-century voyage of discovery

In 2001, Woods Hole Oceanographic Institution (WHOI) scientist Henry Dick was part of a team that conducted the most detailed exploration to date of the Gakkel Ridge, which transects the eastern Arctic Basin and is perhaps the most enigmatic tectonic plate boundary on Earth. Like all mid-ocean ridges, the Gakkel Ridge is an undersea volcanic mountain chain where magma erupts to create new ocean crust that spreads out on both sides of the ridge. It was thought to be spreading so slowly, however, that it would have little volcanic and hydrothermal activity on it.

But Dick and colleagues found tantalizing clues of active volcanism and ubiquitous hydrothermal venting on the Gakkel Ridge. What's more, they gathered evidence that seafloor spreading on the Gakkel Ridge occurs in a fundamentally different way compared to other previously explored ridges. (See "Earth's Complex Complexion," page 36.)

Jayne Doucette, WHOI Graphic Services

An expedition in 2007 is planned to search for, map, and sample hydrothermal vents for the first time beneath the ice-covered Arctic Ocean, along the Gakkel Ridge.

Dick and colleagues recovered rocks from the Gakkel Ridge composed of materials that normally reside in the mantle deep within Earth's interior, and that are rarely found on Earth's surface. These rocks are perhaps the closest modern analogues to the kind of volcanic rocks that erupted billions of years ago in the early stages of Earth's history. They have a distinct chemistry that affects their interaction with seawater circulating through hydrothermal vent systems. (See "The Remarkable Diversity of Seafloor Vents," page 60.) These chemical reactions release exceptionally large amounts of chemical "food" for the kinds of evolutionarily ancient microbes that reside at the roots of the Tree of Life. (See "Is Life Thriving Deep Beneath the Seafloor?" page 72.) The hydrothermal vent fields on the Gakkel Ridge could therefore provide a means to study hydrothermal activity on an early

Earth, and possibly even provide clues to the origin of life on this planet.

Many questions, little data

Scientists only began to get their first detailed look at the Arctic seafloor between 1995 and 1999, when the U.S. Navy and the National Science Foundation (NSF) teamed up to use Navy nuclear submarines for unclassified scientific investigations.

We still have almost no data from most of the mountain chains in the Arctic Basin, so we're still guessing about their composition, age, and origin. Yet, the sparse evidence we do have suggests that the Arctic Basin did not form the same way other ocean basins did, and that it may have the oldest extant ocean crust in the world.

That's why we dream about retrieving data from beneath the Arctic ice cap, and why we have begun to harness 21st-century technology to make those dreams come true. Nuclear subs are far too expensive to build and operate, and besides, they are crushed like tin cans at full Arctic seafloor depths. Instead, in our quaint New England village of Woods Hole, we are developing autonomous underwater vehicles (AUVs) and other advanced deep-submergence technologies that can open up the Arctic Basin to scientific investigation.

Overcoming the ice barrier

Though many scientists dream of getting beneath the ice to study the Arctic Basin, the long-standing commitment to ocean technology and instrumentation at WHOI gives scientists here the opportunity to turn dreams into reality. We formally began a program to develop AUVs specifically for under-ice operations in the Arctic in January 2000 when the NSF Office of Polar Programs awarded WHOI a grant to design, fabricate, and test a prototype vehicle called APOGEE, the Autonomous Polar Geophysical Explorer. The objective was to develop a swimming robot that can carry a variety of scientific sensors to explore the most inaccessible regions of the Arctic Basin, and that can be deployed and recovered through a small hole in the ice.

Life is easier if AUVs can simply pop up on the ocean surface for recovery, but Arctic pack ice adds complications. APOGEE was designed with critical acoustic navigation and control systems that allow it to navigate to a homing beacon, latch itself to a wire suspended from a hole in the ice, and ultimately be recovered by scientists on an icebreaker or an ice camp. Without this essential capability, an AUV in the Arctic would almost certainly be lost.

To the Arctic and beyond?

We conducted our last set of sea trials with APOGEE in 2003. Now, we have begun to build the next generation of Arctic vehicles—under a joint grant (with the University of Maryland's Space Systems Lab) from the Astrobiology Science and Technology for Exploring Planets program of the National Aeronautics and Space Administration.

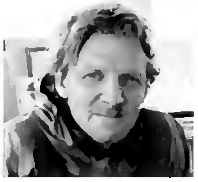
Our mission will be to use AUVs to find, map, and sample hydrothermal vent fields on the Gakkel Ridge. We will develop instrumentation that will guide future efforts to search for life on Europa, a Galilean moon of Jupiter, which may have two necessary ingredients for life: active volcanism and an ocean—albeit an ice-covered one.

The mission will also allow us to study Arctic vent fields for the first time. We will use a small group of purpose-built AUVs, each with different characteristics and equipped with state-of-the-art sensor systems. They will work in concert to study Arctic vent fields. For example, a "bloodhound" AUV (named *Puma*, for Plume Mapper) will be equipped with sensors that can detect tiny telltale temperature, chemical, or turbidity signals in the water. It will survey a wide area to "sniff out" one of the hydrothermal vent plumes that Henry Dick got whiffs of in 2001 and follow it back to its vent field source on the seafloor.

Once a vent is found, "hummingbird" AUVs (named *Jaguar*), will be deployed. These will be able to hover in place, and equipped with camera and lighting systems, high-resolution sonar, and a manipulator arm with storage canisters, they will be used for mapping, imaging, and sampling at vent sites.

Fully autonomous methods have never been used to find and image, not to mention obtain samples from, vent fields in any ocean, not to mention an ice-covered one. The technical challenges are serious and legion, but they are worthy of a cutting-edge oceanographic institution such as WHOI. We are of necessity drawing on the expertise, inspiration, and creativity of dozens of experts hailing from every department within the institution.

There is no denying that we are attempting an ambitious project that faces stiff technical challenges, but this energizes and motivates us. Ultimately, we will succeed or fail based on the talent and dedication of the scientists, engineers, and technicians who are conceiving, designing, and fabricating the new instrumentation we will take to the Arctic. Anyone who knows the people on our team would be reluctant to bet against us.



Sacha Wichers, WHOI

Robert Reves-Sohn is an Associate Scientist in the Geology and Geophysics Department at Woods Hole Oceanographic Institution. He decided to pursue a career in geophysics when, as a grad student at Scripps Institution of Oceanography, he read the instruction sheet on "How to Prepare a Perfectly Putrid Poster" for his first American Geophysical Union meeting back in 1992. The official instructions suggested that the presenter eschew logical arrangement of the material, use illegible fonts, and, most importantly, "consume copious quantities of beer" before presenting the poster. He immediately realized he had found the peer group he had been looking for. His interest in AUVs is a natural outgrowth of his innate tendencies as a technophile, although the notion of using AUVs to get under the Arctic ice pack came to him while playing with a Sesame Street submarine and giving his (then) newborn (now 8-year-old) daughter a bath.

Seeding the Seafloor with Observatories

Scientists extend their reach into the deep with pioneering undersea cable networks

By Alan Chave, Senior Scientist
Applied Ocean Physics & Engineering Dept.
Woods Hole Oceanographic Institution

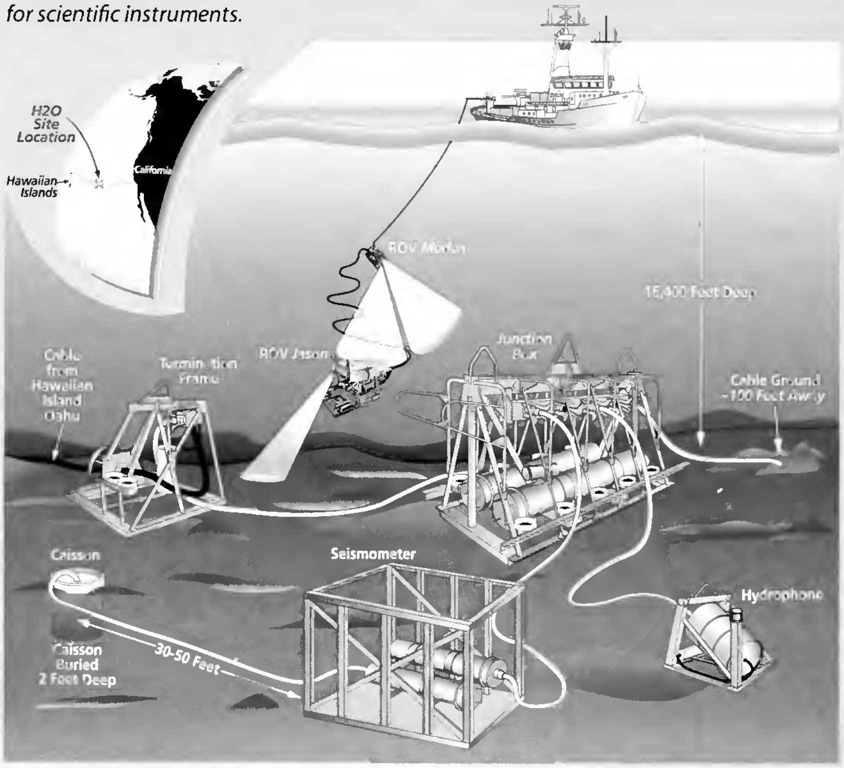
It would be a lot easier to explore the deep ocean, if we only had some electrical outlets and phone jacks on the seafloor. With 21st-century technology, we are starting to install some.

On land, Earth scientists can plug their instruments into electric power lines or rig them with solar panels to make long-term measurements of earthquakes, the planet's magnetic field, and other episodic or ongoing geophysical processes. But many of Earth's most fundamental, planet-shaping processes occur only beneath the ocean, where deploying similar instruments has presented unique challenges.

Expeditions to remote ocean regions are typically more expensive and time-consuming than land-based expeditions. Marine scientists are also limited by the availability of ships and must contend with corrosion problems peculiar to ocean environments. And without sunlight or a continuous electricity supply, scientists have had a limited capacity to supply power to instruments and data recorders in the ocean.

H2O (Hawaii-2 Observatory)

In 1998, scientists used the remotely operated vehicles Jason *and* Medea *to create the pioneering long-term seafloor observatory called H2O (Hawaii-2 Observatory). They spliced an abandoned submarine telephone cable into a termination frame. The frame relays power and communications to a junction box, which serves as an electrical outlet for scientific instruments.*



Jayne Doucette, WHOI Graphic Services

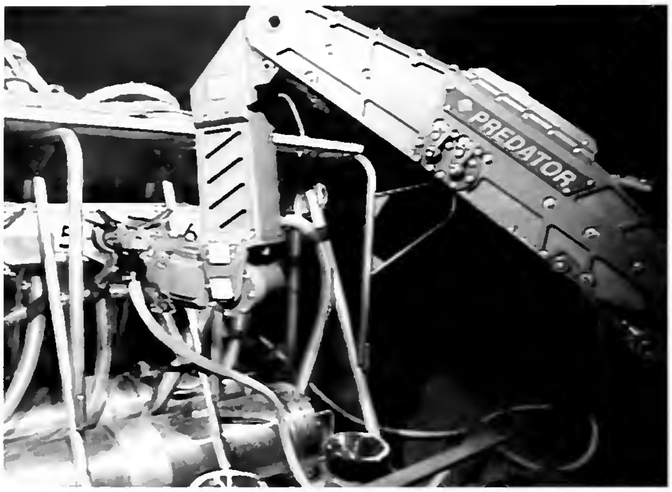
As a result, the record of land-based measurements contrasts starkly with the near-total absence of long-term geophysical data from the seafloor. Instead, ocean scientists tend to have a lot of snapshots of what is happening in the ocean. Since three-quarters of the Earth is covered by ocean, that's like trying to monitor the dynamics of a household by observing events for just a few hours a month in only one bedroom and a closet.

Long-term presence on the seafloor

To comprehend Earth's dynamic behavior, ocean and Earth scientists must do more than observe small regions for short periods. Advances in communications, robotics, computers, and sensor technology now make it possible to get wider and longer views of the oceans.

Remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) can work longer and deeper, and with ever-growing abilities. (See "Realizing the Dreams of da Vinci and Verne," page 20.) Fiber-optic cables and other communications technologies allow more data to be transferred at greater speeds. And with new materials, we can develop hardy instruments that can withstand harsh seafloor conditions.

Establishing a long-term presence in



In 2003, H2O got its first renovation. ROV Jason*'s manipulator arm plugs an instrument into the deep-sea observatory's junction box.*

Jason*'s arm pours glass beads into a container used to bury a seismometer beneath seafloor sediments.*

Photos from *Jason* video

the oceans is no longer a dream. At the H2O "cabled" seafloor observatory (midway between Hawaii and California), the world's second deep-sea science station has been setting a new scientific precedent since 1998 (the first was established off Japan in 1993).

In 2005, the Monterey Accelerated Research System (MARS) project is scheduled to begin full-time observation of phenomena in Monterey Canyon off California. And by the end of the decade, ocean scientists hope to wire and network an entire tectonic plate for observation through the North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE) program.

These initial outposts on the ocean frontier will allow us to examine in detail the interactions that shape the seafloor, generate earthquakes, fuel volcanoes, form ore and oil deposits, transport sediments, circulate currents, and support life in deep-ocean environments.

Bringing the power of the Internet to the seafloor, these cabled observatories will connect scientists in their labs directly to submarine experiments. Scientists will be able to monitor and adjust instruments, or to dispatch AUVs to observe episodic events that previously went undetected. These observatories will also offer students and the public an unprecedented, intimate view of ocean exploration in action.

H20—a pioneering observatory

In 1998, Woods Hole Oceanographic Institution (WHOI) and University of Hawaii researchers seized an opportunity to take a significant first step toward opening the relatively unexplored submerged regions of Earth to more thorough examination.

Beneath 5,000 meters of water (16,400 feet), a submarine telephone cable called Hawaii-2 (HAW-2) stretched across the seafloor from Hawaii to California. AT&T laid the cable in 1964, but when it broke in 1989, the company looked to its fiber-optic future and decided not to fix it. Instead, it donated the cable to the scientific community.

The HAW-2 cable is like a long extension cord delivering electrical power to the seafloor and providing a means for two-way, shore-to-seafloor communications. With funding from the National Science Foundation (NSF), a WHOI/Hawaii science team developed and built a junction box to be spliced into one end of the HAW-2 cable. The junction box is like an eight-socket power strip for the seafloor.

No longer constrained by battery power and limited data recorders, we could install instruments to take continuous measurements of slowly evolving Earth processes and rapidly occurring events. The dream of America's first long-term, deep-ocean observatory became a reality with the establishment of the Hawaii-2 Observatory, or H2O.

The first two instruments plugged into H2O were a seismometer and a deep-water pressure gauge. The seismometer records seismic waves generated by earthquakes, allowing scientists to locate and study the sources. The pressure gauge aids researchers in detecting tsunamis, large waves generated by earthquakes in the open ocean.

In the summer of 2003, H2O got its first renovation. The junction box was raised, upgraded with the latest communications and power interfaces, and lowered again to the seafloor.

In 2005, several new instruments are scheduled to be installed. Magnetometers and other instruments will be set up as part of a seafloor geomagnetic observatory. A new benthic biology experiment, which includes digital cameras and sediment traps, will be able to observe what is living on and falling to the deep ocean floor. A 1.5-kilometer (1-mile) cable will be laid from the junction box to a borehole where another more sensitive seismometer will be deployed.

MARS and VENUS

The next step for deep-ocean observatories is to incorporate fiber-optic communications, allowing high-speed, high-bandwidth transfer of science data and

MARS (Monterey Accelerated Research System)

The next step for deep-sea observatories will be MARS, a test bed using a fiber-optic cable that allows high-speed, high-bandwidth communications and data transfer. MARS will have a 40-mile cable along the north side of Monterey Canyon, connecting a shore station at Monterey Bay Aquarium Research Institute (MBARI) to an undersea node that serves as a power and data-transfer station for instruments.

Courtesy of the NEPTUNE Project (www.neptune.washington.edu) Produced by the Center for Environmental Visualization

computer commands. In the fall of 2002, NSF provided the funding to build a test bed for fiber-optic cabled observatories—a proving ground for the next generation of seafloor observatories.

The Monterey Accelerated Research System (MARS) will consist of 70 kilometers (44 miles) of submarine cable laid out from a shore station along the northern side of the Monterey Canyon to a single science node located 1,200 meters (almost 4,000 feet) below the ocean surface. The science node will serve as a power and data-transfer station for instruments.

Ocean scientists from around the world will be able to design new instruments and then test them by plugging into one of MARS's four standardized ports. Each port will support data transfers of up to 100 megabits per second—comparable with some of the fastest land-based commercial data networks. The cable also will supply up to 10 kilowatts of power—enough to supply a few terrestrial houses, and several orders of magnitude more power than can be supplied with batteries.

Partners in the MARS program include the Monterey Bay Aquarium Research Institute (MBARI), Woods Hole Oceanographic Institution, the University of Washington (UW), and the National Aeronautics and Space Administration's Jet Propulsion Laboratory (JPL).

The University of Victoria (UV) is simultaneously developing a complementary shallow-water test bed—known as the Victoria Experimental Network Under the Sea (VENUS)—in the Strait of Georgia and Saanich Inlet between Vancouver and Victoria, British Columbia.

On to NEPTUNE

Just off the coast of the Pacific Northwest of Canada and the United States lies an ocean scientist's dream. Nearly all of the major Earth-shaping features and processes—seafloor volcanism, hydrothermal vent systems, earthquakes, seafloor spreading, and subduction zones—converge in a reasonably small geographic area. At its coastal edge, sediments from the North American continent pour into the deep sea, while the waters teem with life in the Pacific Northwest's great fisheries.

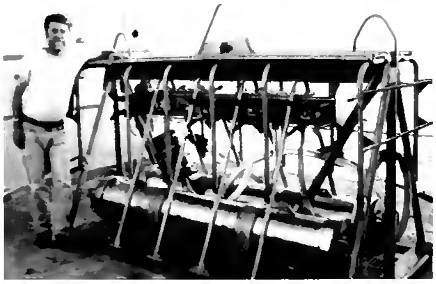
Quite simply, the Juan de Fuca tectonic plate is a comprehensive natural laboratory for ocean science. The plate's proximity to shore and relatively small size make it a cost-effective candidate for incremental but eventually extensive cabling.

The North East Pacific Time-integrated Undersea Networked Experiments (NEPTUNE) project aims to establish an extensive Earth/ocean observatory across and above the Juan de Fuca Plate off the West Coast of the United States and Canada. Researchers are proposing to lay down 3,000 kilometers (1,865 miles) of high-speed fiber-optic submarine cables that will link a series of 30 seafloor nodes, each about 100 kilometers (62 miles) apart. Those nodes would support thousands of assorted measuring instruments, video equipment, and robotic vehicles that could upload power and download data at undersea docks.

Unlike conventional telephone cables, which supply power from shore in a straight line, end to end, NEPTUNE would operate like a power grid, distributing power simultaneously and as needed throughout the network. More than 100 kilowatts of power would flow through the system (roughly the amount of power needed to supply 50 to 100 homes at any given moment).

NEPTUNE would work much like a campus data network, with nodes analogous to buildings and each instrument like a computer workstation. It would provide real-time transmission of data and two-way communications for up to 30 years.

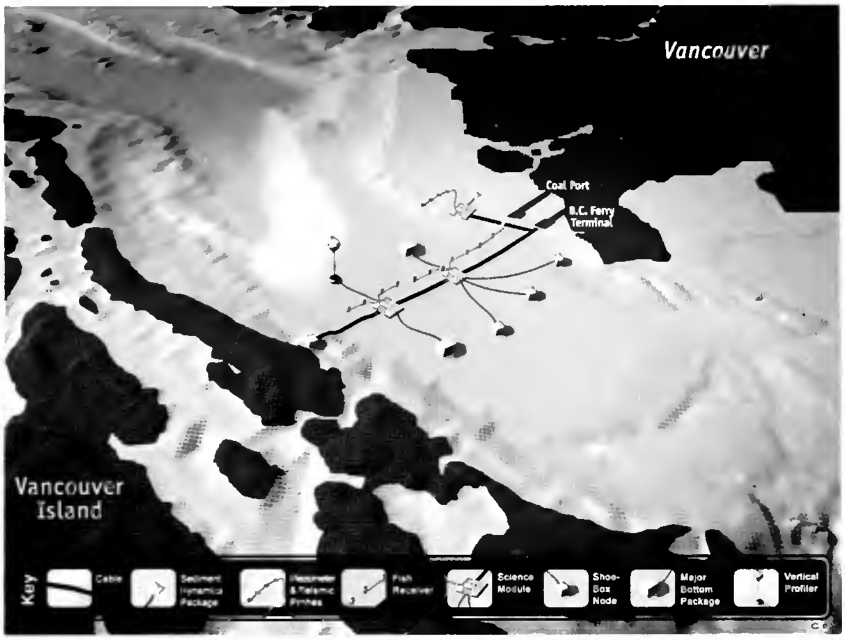
Developers of the NEPTUNE network include many of the same institutions involved in previously mentioned observatory initiatives (WHOI, UW, JPL, MBARI, and UV). We hope NEPTUNE is operational by 2008. It will cost approximately $200 million to develop, install, and operate through the first five years. An entire network of seafloor instruments, distributed over an area of 500 by 1,000 kilometers (310 to 620 miles), would cost less than one satellite or one Coast Guard icebreaker.



Alan Chave is a Senior Scientist in the WHOI Applied Ocean Physics and Engineering Department, where he specializes in going to meetings and writing reports. When time allows, he builds "toys" to throw in the ocean (hoping they will come back) and has been quite successful at this over the years. His major research interest is the design, construction, installation, and servicing of ocean observatories. His group provided the technical lead for the Hawaii-2 Observatory, and he acts as project scientist for the ambitious NEPTUNE project planned for installation in 2008-2009. Chave lives in Falmouth with his wife, daughter, and Portuguese water dog.

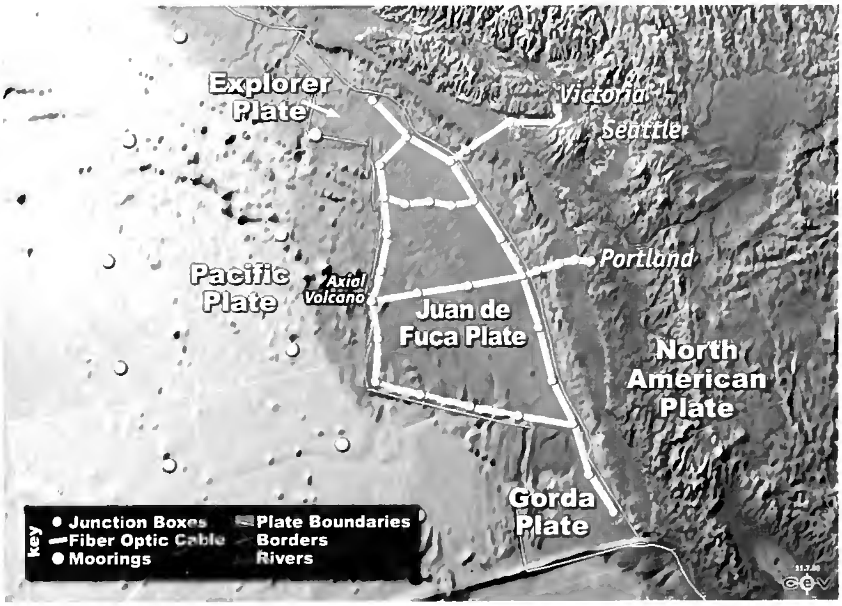
VENUS (Victoria Experimental Network Under the Sea)

The University of Vancouver is developing a shallow-water undersea observatory called VENUS in the Strait of Georgia between Victoria and Vancouver, Canada.



NEPTUNE (North East Pacific Time-integrated Undersea Networked Experiments)

The NEPTUNE project aims to establish an Earth/ocean observatory across the Juan de Fuca Plate off the U.S. West Coast. Researchers propose to lay 1,865 miles of fiber-optic submarine cables linking 30 seafloor nodes that support assorted instruments and robotic vehicles.



A Sea Change in Ocean Drilling

Scientists launch a new drill ship and ambitious research plans

By Dennis Normile and Richard A. Kerr
Science Magazine

In the early 1960s, geologists took their first shot at drilling all the way through Earth's crust and into its mantle with the Mohole Project. It turned out to be a disaster. Named for the Mohorovičić discontinuity, the boundary between the crust and mantle, the ambitious attempt to penetrate 6 kilometers of crustal rock was sunk by cost overruns and management problems and scrapped after a few test holes.

But out of that debacle came a highly successful international scientific endeavor. The decision to drill Mohole from a barge—to take advantage of the fact that the oceanic crust is much thinner than the continental crust—laid the foundation for modern-day scientific ocean drilling. And researchers have exploited the world it opened up to make seminal discoveries about the planet. Now, those efforts are about to enter a new era.

Over the past 40 years, researchers have drilled more than 2,900 holes in the ocean floor, retrieved 319 kilometers of mud and rock core, and studied 35,000 samples. The legacy of ocean drilling includes validating the theory of plate tectonics and tracing Earth's changing climate back 100 million years, as well as inventing the field of paleoceanography.

Since 1984, that work has been carried out under the 22-country Ocean Drilling Program (ODP), a unique effort that ended in September 2003. But it will be replaced by something even more ambitious: In October 2003, Japan and the United States inked an agreement formally creating the Integrated Ocean Drilling Program (IODP). It will eventually include 20 or so other countries, cost twice as much to operate as its forerunner, and use two, and at times three, ships rather than one.

Initially, IODP will rely on an upgraded U.S. drill ship, either a revamped ver-

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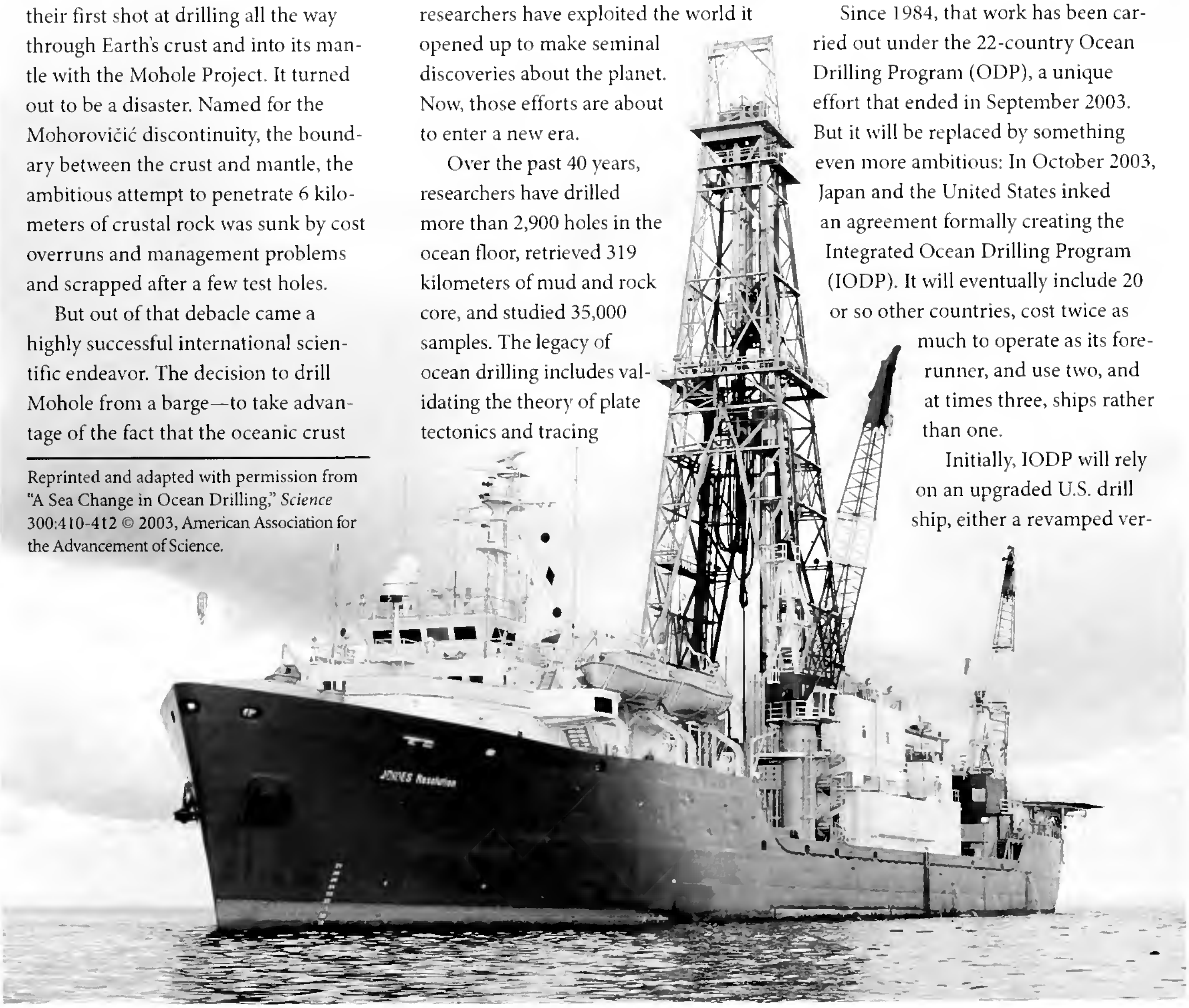


Ocean Drilling Program

Since 1985, the research vessel JOIDES Resolution *has been the workhorse for scientific ocean drilling. Through 2003, the 470-foot-long ship with its 202-foot derrick has drilled more than 1,800 holes in the ocean crust and retrieved samples at some 670 sites.*

A NEW DRILL SHIP—The Integrated Ocean Drilling Program's drill ship Chikyu *("Earth" in Japanese) is launched in Japan, in 2002. The 57,500-ton, 210-meter (689-foot)-long ship will be capable of drilling 7 kilometers (4.35 miles) below the seafloor—sufficient to reach the mantle. Its derrick was installed in September 2003 and after sea trials,* Chikyu *should be ready by late 2006.*

Japan Marine Science and Technology Center and the Integrated Ocean Drilling Program

sion of ODP's workhorse, the *JOIDES Resolution*, or a new vessel with similar capabilities. By late 2006, it will be joined by a brand-new ocean drilling vessel, Japan's *Chikyu*, equipped with technology that will allow it to literally break new ground.

Together, the two ships will enable Earth scientists to bore more and much deeper holes than is currently possible and in locations that are now inaccessible. There are even going to be "mission-specific platforms" that will drill niche locations such as the icy Arctic Ocean and shallow coastal waters.

A new drill ship for a new era

The biggest change in operational capabilities will come when the 210-meter, 57,500-ton, $475 million *Chikyu* starts drilling. For all its achievements, the *Resolution* has serious limitations. It can't drill in shallow water or farther down than 2 kilometers. Nor can it tolerate the icy conditions of the Arctic Ocean. What's more, sedimentary basins have been largely off-limits because oil and gas deposits have posed safety and environmental hazards.

The *Chikyu* will overcome some of these constraints. It will have a second pipe, called a riser, that will enclose the drill pipe and allow circulation of a heavy but fluid drilling mud that will flush debris from deep holes and shore up unstable sediments. The arrangement will also protect against blowouts when the bit penetrates pressurized oil or gas deposits. Attempts at drilling very deep holes using the *Resolution* were frustrated by the friction and by debris piled up in the hole.

"Because of the capabilities of the riser vessel, [all sorts of drilling] projects will be more viable," said Hisatake Okada, a paleoceanographer at Hokkaido University in Sapporo.

But all of this comes at a steep price. The annual budget of ODP ran about $80 million, with 60 percent of that sum put up by the U.S. National Science Foundation (NSF) and the rest split among the other member countries. Countries spent additional funds to support scientists analyzing drilling samples and data.

In comparison, IODP's annual operating budget is expected to start at $160 million and rise depending on the amount and nature of drilling carried out. Japan and the United States will split at least two-thirds of the operating costs equally, with other countries providing the rest—and also funding mission-specific platforms.

Researchers are arguing that the scientific advances will be worth the price, from a better understanding of earthquake mechanisms and the history of global climate change to the discovery of new energy sources and unusual microbes for use in biotechnology. And governments so far seem convinced.

Exploring large igneous provinces

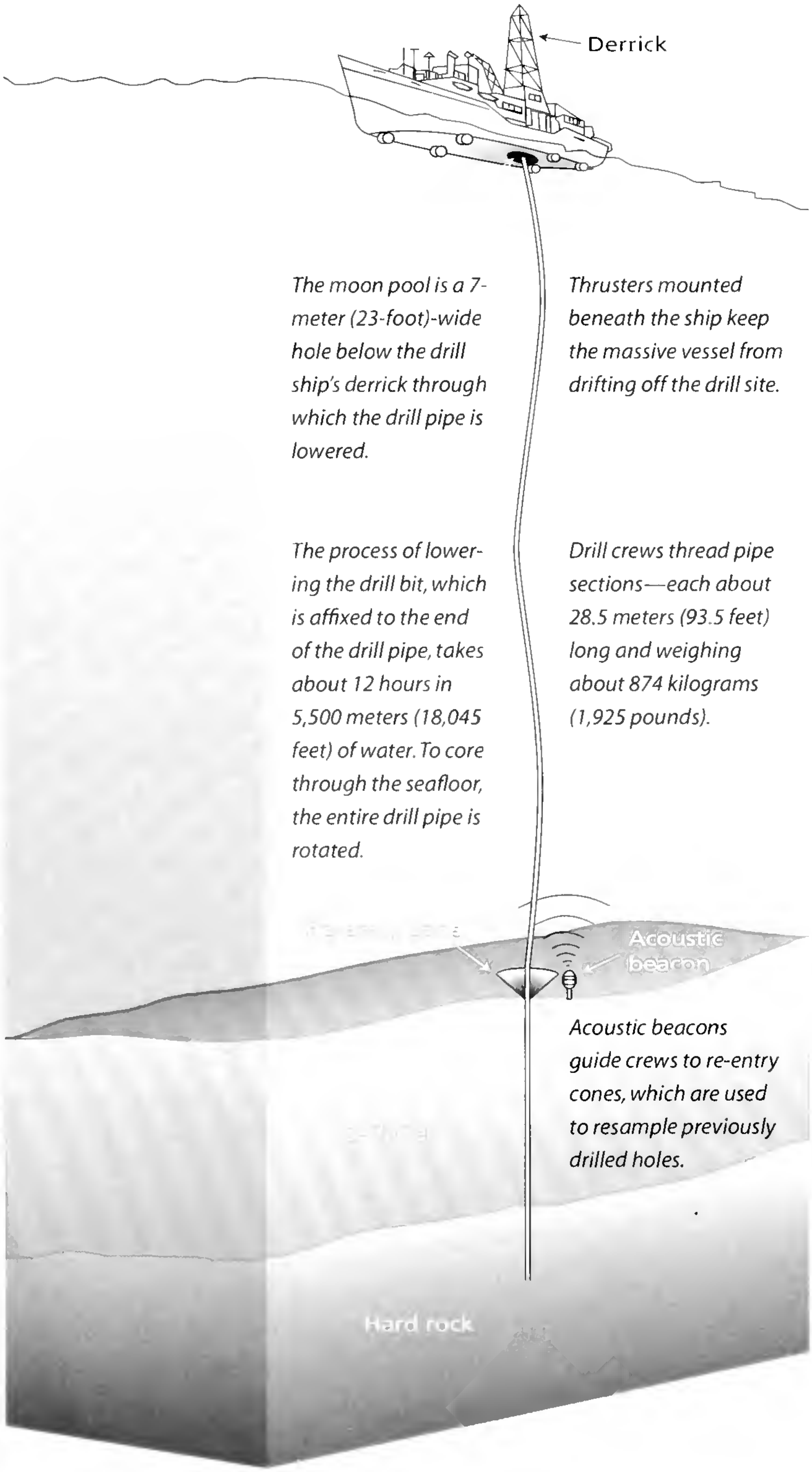
Ocean drilling's first significant achievement came in geophysics. "Past successes have changed our understanding of how Earth works," said oceanographer Larry A. Mayer of the University of New Hampshire, Durham. By dating rock recovered from numerous seafloor locations, researchers in the early 1970s confirmed the basic cycle of plate tectonics: New ocean crust forms at mid-ocean ridges and spreads outward toward deep-sea trench subduction zones. Crustal drilling also showed how great upwellings of hot rock, called plumes, could create chains of islands and seamounts such as Hawaii. (See "Motion in the Mantle," page 6.)

These discoveries have raised new questions about solid Earth cycles and geodynamics, one of three broad themes in IODP's initial science plan. Earlier drilling showed that large parts of the crust were formed by anomalous volcanic events separate from plate tectonics.

Oceanic plateaus, so-called large igneous provinces, formed mostly during the mid-Cretaceous period 100 million to 140 million years ago when massive amounts of material burst through tectonic plates, venting heat and magmatic gases from Earth's interior. These features have as yet been barely sampled by drilling. Researchers hope that data from a combination of numerous shallow holes drilled by a riserless ship and deep holes drilled later by *Chikyu* may relate these events to Earth's evolution and reveal whether or not they triggered climatic changes that led to mass extinctions.

Another major geophysical target will be subduction zones, where the clash of

Drilling the seafloor



The moon pool is a 7-meter (23-foot)-wide hole below the drill ship's derrick through which the drill pipe is lowered.

Thrusters mounted beneath the ship keep the massive vessel from drifting off the drill site.

The process of lowering the drill bit, which is affixed to the end of the drill pipe, takes about 12 hours in 5,500 meters (18,045 feet) of water. To core through the seafloor, the entire drill pipe is rotated.

Drill crews thread pipe sections—each about 28.5 meters (93.5 feet) long and weighing about 874 kilograms (1,925 pounds).

Acoustic beacons guide crews to re-entry cones, which are used to resample previously drilled holes.

sinking and overriding plates generates 90 percent of the world's earthquakes. *Chikyu's* first target, reached by consensus, will be the Nankai Trough subduction zone offshore of Honshu, Japan's main island.

Chikyu's riser will allow boring through the deep sedimentary deposits atop overriding plates. Those deposits were off-limits to the *Resolution* because of the danger of a blowout caused by inadvertently tapping into oil and gas deposits and by the depth of the fault target.

Gaku Kimura, a geologist at University of Tokyo, says *Chikyu* will also be able to install a new generation of instruments in the bore hole to monitor fault zone temperatures, stresses, deformation, and fluid pressures.

"This is a completely different scientific approach" to studying rock samples, said Kimura. "It's like the difference between studying a live human being and dissecting a corpse." An improved understanding of earthquake mechanisms could help Japan and other onshore communities assess the risk of future earthquakes.

IODP may even take another shot at penetrating the Mohorovičić discontinuity. With the lubricating drilling mud circulating through its riser, *Chikyu* should be able to reach 6 kilometers and into the upper mantle. Such a hole would help refine knowledge of the structure, composition, and physical properties of the oceanic crust.

Probing climate changes on Earth

Although geophysics was the prime motivation for the first ocean drilling cruises, scientists in other disciplines soon capitalized on the data obtained from the cores. "Paleoceanography is one of the strong successes of ocean drilling," said Jerry McManus, a paleoceanographer at the Woods Hole Oceanographic Institution in Massachusetts.

Paleoceanographers recognized that cores recovered from layered sediments provided clues to a variety of climatic phenomena, sometimes going back 120 million years. McManus credits ocean drilling


Ocean Drilling Program

CORE CURRICULUM—A team of scientists on the drill ship Resolution *examines seafloor core samples to reconstruct events and phenomena occuring over millions of years of Earth history.*

with clinching the orbital theory of climate change over millions of years, when Earth's wobbling drove climate oscillations. It also documented extreme climates such as the thermal maximum of the late Eocene (55 million years ago) and rapid climate change.

But the use of drilling for paleoceanographic studies has been held back by the limitations of the *Resolution.* It cannot drill in water much shallower than 100 meters, ruling out the inner continental shelves and coral reefs that hold long records of climate and sea-level change. And it can't handle more than the passing bit of sea ice, which has kept it entirely out of the Arctic Ocean.

"You could lay out all the existing Arctic cores in my office," said oceanographer Theodore Moore of the University of Michigan, Ann Arbor. A successful mission to the deep Arctic, he said, would provide "an entire history from 50 million years ago to the present."

Under IODP's initial science vision, mission-specific platforms capable of drilling in niche locations would play a major role in studying environmental change, processes, and effects. European scientists, for example, obtained sufficient funding to send a drill ship to retrieve long sediment cores from the Arctic Ocean in the summer of 2004.

Seafloor fuel, sub-seafloor life

The third leg of the IODP scientific tripod, studying the deep biosphere and the sub-seafloor ocean, is also the newest. The original ocean drillers never imagined there could be life within the extreme temperatures, pressures, and chemical environments of the ocean floor. But reports of microbial colonies at seafloor vents and volcanic rifts demonstrated otherwise. Now some experts in extremophiles, as these microbes are called, believe that as much as two-thirds of Earth's microbial population may be buried in oceanic sediment and crust. (See "Is Life Thriving Deep Beneath the Seafloor?" page 70.)

One major challenge will be to define the range of temperatures, pressures, chemistry, and other conditions under which these seafloor communities thrive and to map their geographical distribution. Researchers would also like to clarify whether these microbes get their nutrients from material that filters down from the surface or from updrafts of fluids flowing through the interface between sediments and hard rock.

The findings "could revolutionize ideas about the origins of life," said Asahiko Taira, director-general of the Center for Deep Earth Exploration at the Japan Marine Science and Technology Center. Researchers also hope to add to the handful of industrially useful microbes already isolated from deep-sea regions.

Another underresearched area of inquiry is gas hydrates, deposits of ice-encapsulated methane. Although a potential new source of clean energy, they also could release a significant amount of greenhouse gases into the atmosphere if thawed as a result of global warming. Scientists want to learn how microbes generate the methane, how hydrates form, and whether methane can be produced at prices competitive with those of other fuels. (See "When Seafloor Meets Ocean, the Chemistry Is Amazing," page 66.)

These intriguing questions weren't even on the radar screen of those working on the ill-fated Mohole Project. But if IODP comes up with some answers, its scientists will owe a debt of gratitude to those who conceived and carried out the first scientific attempt to probe what lies beneath Earth's oceanic crust.

Dennis Normile of Science *magazine studied civil engineering at Villanova University and briefly considered going on for graduate work in geology. Instead he ended up doing his best to counter the effects of earthquakes on buildings as a structural engineer working in Anchorage, Alaska. He has been the Japan correspondent for* Science *since 1995 and has followed the evolution of the IODP ever since it was first proposed at a meeting in Hayama, Japan, in 1996.*

Richard A. Kerr of Science *magazine has covered the Earth and planetary sciences (and a bit of paleontology) since 1977 at* Science. *He went there from the University of Rhode Island a week after successfully defending his dissertation on the humics in seawater. The frustrations of trying to understand such gunk were enough to drive him into journalism, where the breadth of an education in oceanography has served him well.*

Earth's Complex Complexion

Expeditions to remote oceans expose new variations in ocean crust

By Henry J.B. Dick, Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Even as you read this, Earth's crust is continually being reborn and recycled in a dynamic process that fundamentally shapes our planet. We're not generally aware of all this action because most of it occurs at the seafloor, under a formidable watery shroud, and often in remote regions of the oceans.

The creation and cooling of oceanic crust is the primary means by which heat escapes from Earth's interior. This dynamic planet-scale crucible transports heat, chemicals, and minerals from Earth's interior to its surface.

Over the long haul, the process ultimately determines Earth's chemical makeup. It affects the amount of carbon dioxide and water in the crust, oceans, and atmosphere, and it produces zinc, copper, and other mineral deposits, including some gold and silver. So how Earth's crust forms is more than just an academic question.

The seafloor layer cake

Several generations of scientists have dredged rock samples from the seafloor, employed submarines and robots to study it, and even drilled into it to learn a considerable amount about the shallow oceanic crust. (See "A Sea Change in Ocean Drilling," page 32.) We've analyzed seismic waves that penetrate and reflect off rock

Henry Dick, WHOI

MAIDEN VOYAGE—Scientists and crew on the first cruise of the U.S. icebreaker Healy *in 2001 successfully performed 200 dredge operations in the ice-covered Arctic Ocean, collecting some 4,000 seafloor rock samples.*

layers deep in the crust in an effort to decipher its characteristics—similar to the way physicians use an MRI to peer below the skin. (See "Listening Closely to 'See' into the Earth," page 16.) We've also studied ophiolites—isolated portions of the seafloor that tectonic forces have thrust up and exposed on continental margins. (See "Unraveling the Tapestry of Ocean Crust," page 40.)

From early studies, a simple picture emerged: It seemed the ocean crust was relatively homogenous in composition, structure, and thickness—sort of a geological three-layer cake about 6 to 7 kilometers (3.7 to 4.3 miles) thick. On top was lava that spilled out and cooled rapidly into a glassy substance called basalt, which carpeted the ocean bottom. Below were great, vertical sheets of molten rock called dikes—the pathways by which magma was injected to the surface from deeper layers. Finally, lying atop the mantle itself, was a lower layer composed of magma that rose directly from the mantle, cooled more slowly, and crystallized into a rock known as gabbro.

This was a neat picture and a great first step, but nature, like life, usually turns out not to be so simple. And so it is with seafloor crust.

Forays to remote mid-ocean ridges

The layer cake model began to crumble in the 1980s when scientists began dredging, drilling, and diving around the great transform faults that offset volcanic mid-ocean ridge segments in the Atlantic and Indian Oceans. They gathered new evidence suggesting that the gabbro layer of ocean crust may be missing entirely in some locations and thicker than expected in others. It turned out that ocean crust, forged under different circumstances in different places, could be very different.

Surprising discoveries further reshaped our concept of ocean crust after several recent research voyages to the world's slowest-spreading ocean ridges, which are located in remote, largely unexplored regions. In particular, our work on the Southwest Indian Ridge in December 2000 and January 2001 revealed an area several thousands of miles square where there appeared to be almost no crust at all; rather, the Earth's mantle rises up between the diverging Antarctic and African plates to spread directly onto the seafloor. There is no layer cake here—just the mantle plate beneath the seafloor.

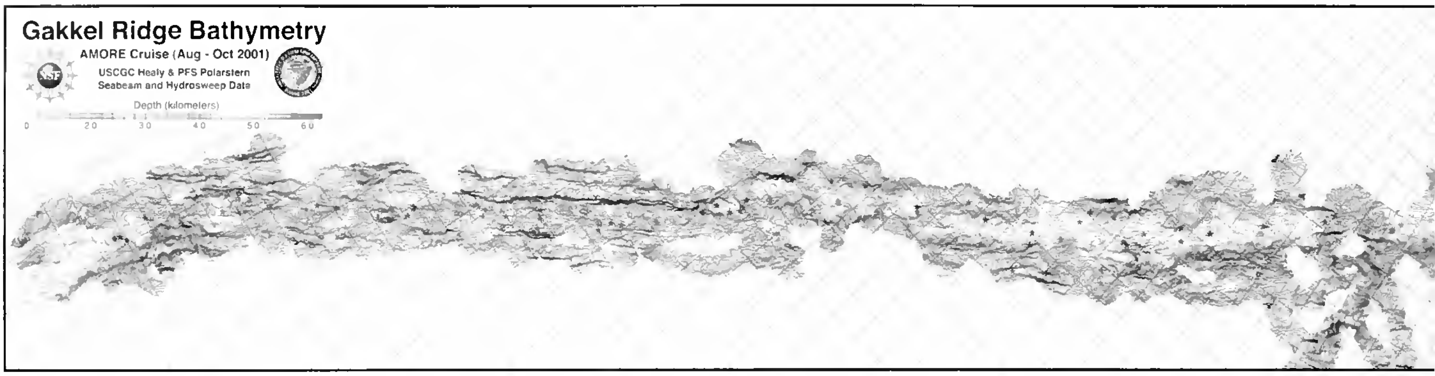

Henry Dick, WHOI

BREAKING THE ICE—The U.S. icebreaker Healy *performed well on its 2001 Arctic Ocean expedition to explore the Gakkel Ridge—the deepest and slowest-spreading ridge on Earth.*

Despite the ultraslow spreading and apparent lack of volcanism, these same cruises discovered areas with massive sulfide deposits of potential economic importance. These deposits are formed by minerals precipitating out of hydrothermal fluids rising out of the crust. (See "The Remarkable Diversity of Seafloor Vents," page 60.) This was a complete surprise to those who believed such deposits would be found only at faster-spreading ridges, where magma rose more actively from the mantle.

In July 2001, we ventured to the Arctic aboard the new U.S. Coast Guard icebreaker/research vessel *Healy*. We made the first detailed maps of large portions of the Gakkel Ridge, which extends from north of Greenland almost to Siberia. It is both the deepest ocean ridge, ranging from 3 to 5 kilometers (1.8 to 3 miles) deep, and the slowest-spreading, ranging from one inch per year near Greenland to half an inch per year at its eastern end off Siberia.

Theory predicted that as seafloor spreading slowed along the ridge, volcanism would wither and the ridge would become essentially a crack in the planet where solid mantle rock would be pulled up by the spreading plates to form new seafloor. We did, indeed, find mantle rock rising in great solid slabs to form new seafloor; but we also found that isolated volcanoes persisted as far as we could survey to the east. The generation of magmas in the Earth proved far more complicated than anyone imagined!

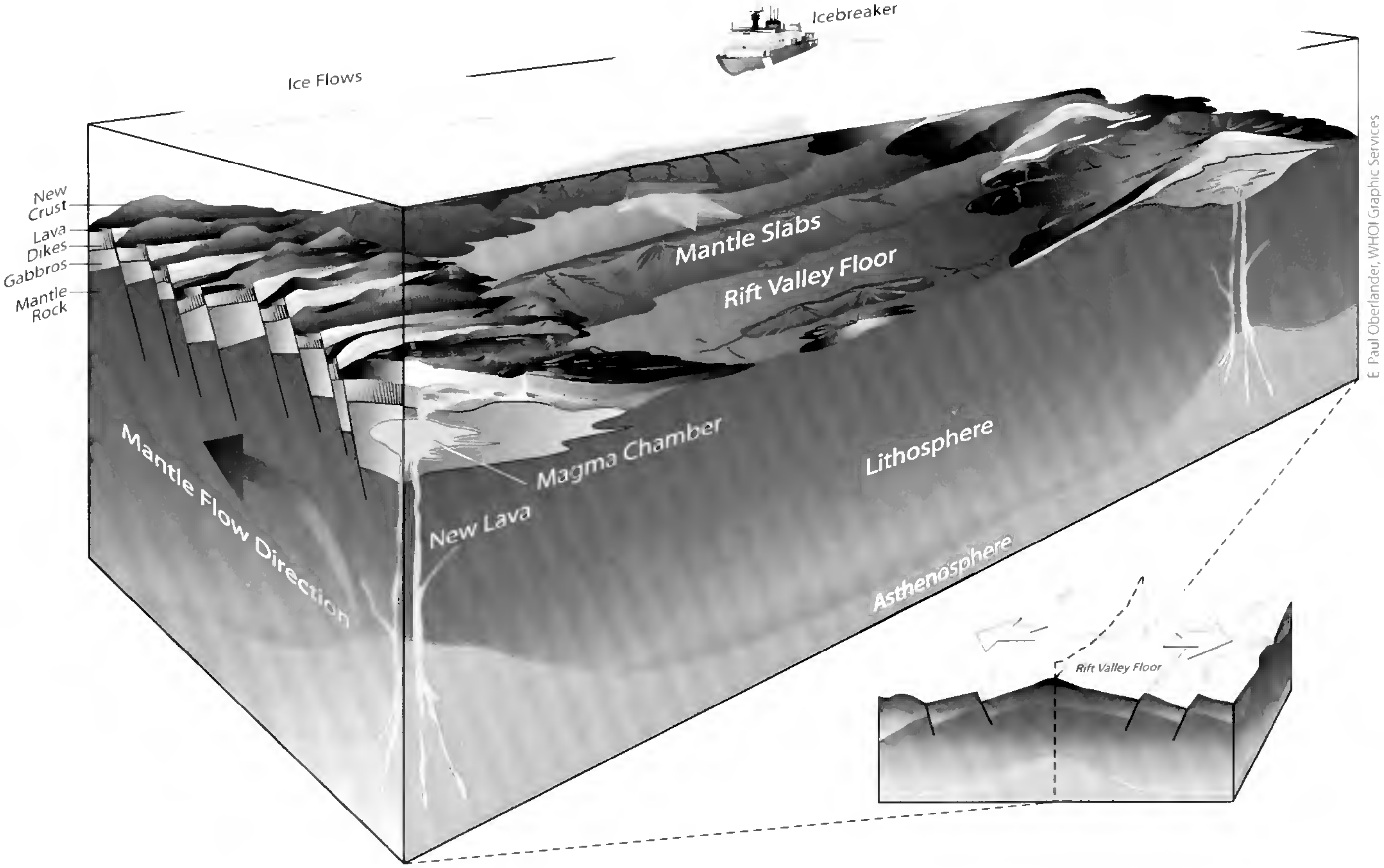


Along the Gakkel Ridge, we not only sampled more hydrothermal deposits, we also detected abundant active hydrothermal venting in a region where current theory predicted their absence. The discovery offers the potential to find vent sites with unique fauna that have evolved in isolation from those in other oceans.

These discoveries have now led to the realization that instead of two great classes of ocean ridges—slow and fast—there is a third category, ultraslow, which may make up as much as one-third of the global ocean ridge system. These ultraslow ridges—so unlike the more explored and better-known Atlantic and Pacific Ocean ridges—represent a new frontier.

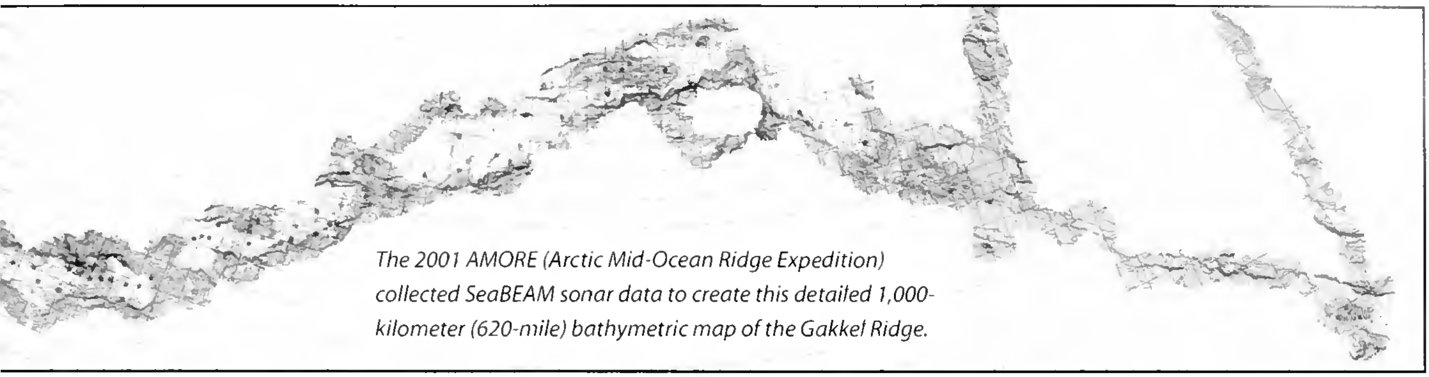
New territories and technologies

From all of this, it is clear that, despite many decades of seafloor study, we have



E. Paul Oberlander, WHOI Graphic Services

A NEWLY DISCOVERED TYPE OF MID-OCEAN RIDGE—Volcanic activity at mid-ocean ridges creates new seafloor crust that spreads outward to cover 70 percent of Earth's surface. Recent expeditions have shown that instead of just two classes of ridges—fast-spreading and slow-spreading—there is now a third, ultraslow. Ultraslow-spreading ridges, which may make up one-third of the global ocean ridge system, have distinctive characteristics. Like other mid-ocean ridges, ultraslow ridges have areas where magma rises from the mantle and erupts at the seafloor to create new ocean crust. But in between, there are also amagmatic zones, where solid slabs of mantle rock rise directly to the seafloor.



The 2001 AMORE (Arctic Mid-Ocean Ridge Expedition) collected SeaBEAM sonar data to create this detailed 1,000-kilometer (620-mile) bathymetric map of the Gakkel Ridge.

just begun to delineate the varied character of ocean crust. Our recent discoveries resulted from pushing current technologies to their limits, creating new ones, and exploring uncharted territories.

The Ocean Drilling Program, for example, recently drilled the first deep hole into the lower ocean crust, in an area where faulting has exposed a deep section of the lower ocean crust and mantle. Cores from this hole, nearly a mile deep, confirm that the composition of the lower ocean crust differs as one goes farther down. But how significant is a single hole? The answer lies in detailed mapping of large areas of the seafloor around this drill site, and at other tectonic windows into the lower ocean crust.

Development of new tools and techniques will bring further progress in understanding the modified (or crumbled or perhaps crazy) seafloor layer cake. We are envisioning new, broader approaches to map large areas of seafloor without an expensive ship in constant attendance—easily deployable seafloor rock drills for collecting samples, for example, and the marriage of new instruments with autonomous vehicles. (See "Realizing the Dreams of da Vinci and Verne," page 20.)

With these approaches, marine geologists will create a series of touchstones at specific sites across the ocean basins. By extrapolating sections in between these touchstone sites with remote geophysical sensing, we will be able to paint a fully detailed picture of the skin that gives Earth its unique complexion.

[illegible] WHOI Graphic Services

ULTRASLOW BUT VOLCANICALLY ACTIVE—Scientists had predicted that the Gakkel Ridge was spreading far too slowly to promote volcanism, but an expedition in 2001 found surprising evidence for active volcanoes and hydrothermal vents.

Henry Dick has been a Senior Scientist at Woods Hole since 1990. He first became interested in geology as a boy when he found a rock collection in an outbuilding at his grandparents' home in Vancouver, Wash. His great-grandfather was a geologist sent out west in the 1890s by his uncle, Spencer Fullerton Baird, who also founded the U.S. Department of Fisheries. For his Ph.D. at Yale, Dick backpacked more than 60 square miles of the rugged Kalmiopsis Wilderness in southwestern Oregon, mapping ancient ocean crust and mantle formed at a former island arc. He came to Woods Hole to find out if rocks at mid-ocean ridges were really different from those he'd seen in the Oregon coast ranges and worked with Wilfred Bryan in the Geology and Geophysics Department. The answer proved to be yes, and he had so much fun finding out, that he's stayed around. Dick works almost exclusively on regions of the Earth with an average population density of less than one person per thousand square miles. He is currently involved in the discovery of a new class of ocean ridges found in the Arctic Ocean and around Antarctica with colleagues at WHOI, the University of Tulsa, and the Max Planck Institute in Germany. A lot of his time is spent fishing for broken bits of the Earth's mantle found in great faults along the ocean ridges. He has a remarkably dedicated wife named Winifred and three children, Helene, Spencer, and Lydia, who think their dad goes to sea too much. He's promised them he won't even look at the ocean for at least a year, much less get his feet wet—after his next cruise this fall!

Unraveling the Tapestry of Ocean Crust

Scientists follow a trail of clues to reveal the magmatic trickles and bursts that create the seafloor

**By Peter Kelemen, Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution**

Most people know that oceans cover about 70 percent of Earth's surface. Fewer people realize that the crust beneath oceans and continents is fundamentally different. Why this is so remains a mystery that scientists are still trying to solve.

Oceanic crust is generally composed of dark-colored rocks called basalt and gabbro. It is thinner and denser than continental crust, which is made of light-colored rocks called andesite and granite. The low density of continental crust causes it to "float" high atop the viscous mantle, forming dry land. Conversely, dense oceanic crust does not "float" as high—forming lower-lying ocean basins. As oceanic crust cools, it becomes denser and ultimately sinks back into the mantle under its own weight after about 200 million years.

Earth's continental crust, on the other hand, is up to 4 billion years old, and it is thought to be the product of geologic recycling processes far more complicated than those that create ocean crust. If we can decode and read the relatively simple story of how oceanic crust is formed, we may someday be able to decipher the more complex record of how the continents developed.

Sounding out seafloor structure

Because most oceanic crust is hidden from view beneath many kilometers of water, our research must be conducted "remotely," often using acoustic techniques. Sound—emanating from an earthquake, an explosion, or a relatively benign source known as an airgun—travels through different rocks at different speeds. Geophysicists infer the basic geologic structure of underlying rocks by measuring the time it takes for sound to travel from one source to many different receivers, or from many sources to a single receiver. (See "Listening Closely to 'See' into the Earth," page 16.)

In the oceans, this technique has yielded a simple picture of a basaltic, layered crust about 7 kilometers (4.3 miles) thick, underlain by the mantle. Rock samples obtained via dredging, submersible operations, and drilling confirm that the top of the oceanic crust, where it is not obscured by sediments, is composed of basaltic lava that originates in the mantle.

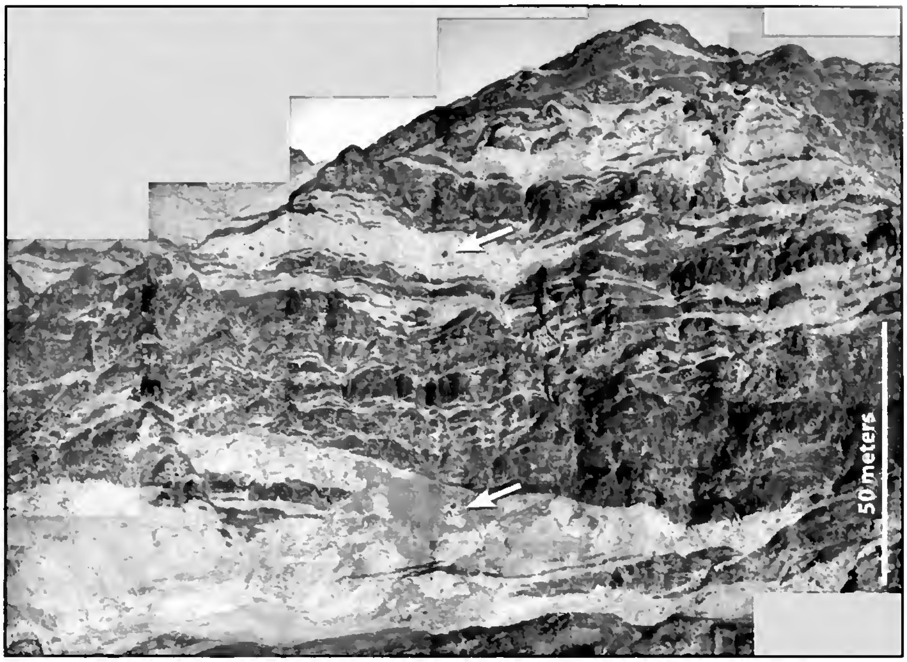
At the dawn of the modern theory of plate tectonics in the 1960s, geologists and geophysicists realized that the entire oceanic crust was created from basaltic lava along linear chains of seafloor volcanoes known as mid-ocean ridges, or spreading ridges. Seafloor spreading carries older oceanic crust away from the ridges over tens of millions of years, until it cools, becomes denser, and "falls" back into the mantle in areas known as subduction zones.

Peter Kelemen, WHOI

THE SEAFLOOR, ON LAND—In a few places on Earth, blocks of oceanic crust (called ophiolites) have been thrust onto the continents, giving scientists the unusual chance to get a firsthand look at rock formations that were once beneath the seafloor. The largest ophiolite is in Oman.

Seafloor clues in the desert

In a few places on Earth, blocks of oceanic crust, called "ophiolites," have been thrust, relatively intact, onto the continents during collisions between tectonic



Mike Braun, WHOI

WALKING ON THE OCEAN FLOOR—WHOI scientists Peter Kelemen (top arrow) and Greg Hirth (50 meters directly below) walk on rocks that once were in the upper mantle below the seafloor. In this photomosaic of a mountainside in Oman (and in photo on preceding page), light-colored rocks (dunite) are ancient channels through which melt once flowed through the mantle.

plates. Tilting and subsequent erosion allow scientists to walk through a section that once extended 25 kilometers (15 miles) into Earth's interior. The largest and best exposed of these, the Oman ophiolite near the Persian Gulf, comprises about ten blocks that together cover roughly the same area as Massachusetts.

The great extent of these ophiolites, once deep beneath the seafloor but now exposed, provides a comprehensive view of the internal geometry of oceanic plates that is unmatched by any sampling or imaging technique at sea. Like pot shards covered with hieroglyphics, ophiolites open a window onto an ancient, largely vanished world, and provide a rare avenue for systematic investigation.

In the late 1960s and early 1970s, geologists and geophysicists observed similarities between the layered structure of oceanic crust, as interpreted from sound velocities, and the layering in ophiolites. A thin, upper layer in oceanic crust (with low sound velocities) corresponds to a layer of sediments and lava flows in ophiolites. A deeper layer (with faster sound velocities) corresponds to an ophiolite layer of "gabbro," which formed when molten basalt solidified beneath Earth's surface. In both oceanic crust and ophiolites, the gabbro layer is underlain by the mantle, which extends thousands of kilometers down to Earth's core.

A striking feature of well-exposed ophiolites is a continuous layer of "sheeted dikes" that lies between the lava and the gabbro. These dikes are tabular rock formations, about a meter wide, created by periodic bursts of molten rock. They stand side by side, like soldiers in formation, each dike adjacent to neighboring dikes, or sometimes leaning or intruding into them.

This recurring structural pattern occurs because all oceanic crust is newly created at spreading mid-ocean ridges on a kind of continuous conveyor belt: Each dike, in a simple view, forms directly at the center of a ridge. It then spreads out from the ridge center, as another dike forms behind it, in an ongoing process that creates the continuous layer observed in ophiolites. Nothing like that happens in continental crust, where new dikes more randomly intrude older rock.

Going with the flow

During the 1970s and 1980s, geophysicists and geologists strove to understand how basaltic lava forms beneath spreading ridges. They theorized that because the oceanic plates pull apart at the surface, new material must rise to fill the gap. As the material rises, the pressure that helps keep it solid decreases. This allows hot mantle rocks to partially melt and produce basaltic liquid. This so-called "melt" is less dense than surrounding solids, and so it buoyantly rises to the surface to form the crust.

However, this theory raises as many questions as it answers. From lava compositions, we know that from an enormous volume of mantle rock, only small amounts of rock partially melt to create oceanic crust. Melt forms in micron-size pores along the boundaries of innumerable crystal grains across a mantle region that is 100 to 200 kilometers wide and 100 kilometers (61 miles) deep. From this vast region, however, the melt somehow is focused into only a 5-kilometer (3 mile)-wide zone at a spreading ridge. How is lava channeled from tiny pores in a broad area of melting into a narrow area where it forms new oceanic crust topped by massive lava flows?

My colleagues in exploring this mystery, working in various combinations, have included Greg Hirth, Nobu Shimizu, and Jack Whitehead at Woods Hole Oceanographic Institution (WHOI), Marc Spiegelman of Lamont-Doherty Earth Observatory, French geologists Adolphe Nicolas and Françoise Boudier, Massachusetts Institute of Technology graduate student Vincent Salters, and MIT/WHOI Joint Program students Einat Aharonov, Mike Braun, Ken Koga, and Jun Kornaga. Our research has been funded by the U.S. National Science Foundation, the WHOI Interdisciplinary and Independent Study Award program, and the Adams Chair at WHOI.

We have shown that melt travels through the mantle in porous channels, similar to channels filled with gravel that provide permeable pathways through clay-rich soil. Melt rising through the hot mantle can partially dissolve minerals around them and gradually enlarge the pores along the boundaries between individual crystal grains. This, in turn, creates a favorable pathway through which more melt can flow—in a positive feedback loop that spontaneously creates channels that focus the flow.

Small channels formed in this fashion coalesce to form larger channels, in a network analogous to a river drainage system. The number and size of melt flow channels we observe in the mantle section of ophiolites support these theories.

Melt lenses and periodic bursts

New questions arose. If melt flows through the mantle in micron-scale pores along the boundaries of crystal grains, where does it accumulate to form massive lava flows at spreading ridges? And, if porous flow is a continuous, gradual process, what causes the periodic bursts of molten rock that create new dikes?

Once again, the Oman ophiolite provided clues. Nicolas and Boudier found small formations of gabbro, called sills, embedded in the shallowest mantle rocks. Chemical analyses of these sills indicated that they crystallized from the same melt that formed gabbro, sheeted dikes, and lava flows in the crust. In addition, the gabbro, dikes, and lava flows all had an identical, distinctive pattern of alternating bands of dark and light minerals.

It seemed to us that the entire gabbro layer in the Oman ophiolite crust, from uppermost mantle to the surface, could have formed when melt material periodically collected in relatively small pools that subsequently crystallized into solid "melt lenses." Over time, a myriad of these melt lenses accumulates—embedded within each other and stacked atop each other or side by side—to produce gabbro's rocky, banded fabric.

Clogged pores build up pressure

Why would melt lenses first appear in the uppermost mantle, immediately beneath the base of the crust? We propose that such lenses form where melt, approaching the seafloor, begins to cool. Melt rising through the hot mantle can dissolve minerals surrounding it to create pore spaces, but cooling melt will begin to crystallize and clog pores.

Two scenarios are possible: When the supply of melt from below is low, conduits become narrower. The melt is forced outward around impermeable barriers, migrating via diffuse porous flow along crystal grain boundaries throughout surrounding rock.

But when melt supply is large, as it is immediately beneath a spreading ridge, buoyant melt accumulates beneath impermeable barriers and creates excess pressure. Eventually, the melt bursts through the barriers and creates a melt-filled fracture that intrudes the overlying crust. If the fracture propagated high enough in the crust, it would form a sheeted dike, and if it reached even higher, it would spill out onto the seafloor and feed a lava flow.

In this cycle of buildup and release, minerals alternately crystallize and melt under conditions of higher and lower pressure. At relatively high pressure, much less of the light-colored mineral (plagioclase) is formed, compared with darker-colored minerals. At lower pressure, the proportion of plagioclase is larger. Thus, periodic pressure changes result in the light-and-dark banding observed in ophiolite gabbros.

Paths of most resistance

Working from geological evidence in ophiolites, together with physical and chemical theory, we hypothesize that there are two distinct ways to transport melt that forms oceanic crust. Within the melting region in the mantle, melt can dissolve minerals and create additional pore space. As a result, continuous, high-porosity conduits form a coalescing drainage network that focuses melt transport to the spreading ridge.

At shallow levels beneath the ridge, cooling melt begins to crystallize, clogging pore space along crystal grain boundaries. As a result, flow becomes diffuse, and melt accumulates beneath impermeable barriers. Pressure builds up until the melt periodically bursts through overlying barriers, and melt-filled fractures are injected into overlying rocks to feed dikes and lava flows. Together, these processes form a highly organized system that consistently produces new oceanic crust with a regular structure along spreading ridges.

In our ongoing research, we are more rigorously testing theories about how porous conduits form in the mantle. We seek to understand in more detail how melt lenses form beneath spreading ridges. And we want to figure out the factors that determine why and when diking and eruption events occur.

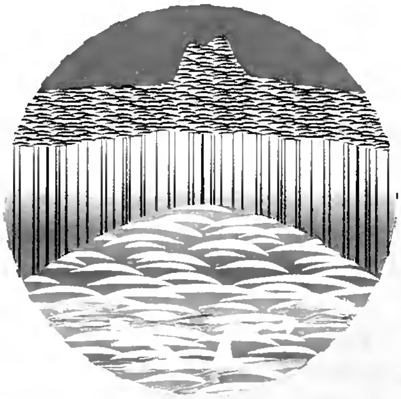
Matt Jackson, WHOI

Peter Kelemen was at WHOI, as a postdoc and scientist, for 15 years. During this time he and his wife, Rachel Cox, acquired a house, two kids, and Rachel's Ph.D. in physiology from Boston University Medical School. During the first four of his six years as an undergraduate, Kelemen was an English and philosophy major at Dartmouth College. He then realized he would need to get a job when he graduated. In the meantime, he learned technical climbing techniques. He reasoned that it would be best to work outside in the mountains, and so switched to a major in Earth sciences. In 1980, Peter and friends founded Dihedral Exploration, a consulting company specializing in "extreme terrain mineral exploration." Until 1991, he split his time between geological research and mineral exploration, in the process obtaining a Ph.D. from the University of Washington. As a mineral exploration consultant and research scientist, Kelemen has been fortunate to work in the mountains of California, Oregon, Washington, British Columbia, Peru, the Yukon, Alaska, the Indian Himalaya, and Karakorum Ranges, East Greenland, along the Mid-Atlantic Ridge, and in the Oman ophiolite, where oceanic crust has been thrust on land. In 2004, he became the Arthur D. Storke Professor at Columbia University.

How is ocean crust made?

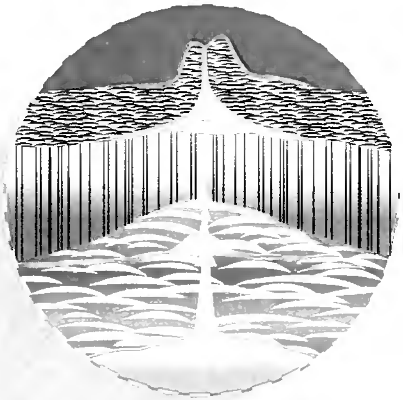
The crust beneath oceans and continents is fundamentally different. Continental crust is made of light-colored rocks called andesite and granite. Ocean crust is composed of dark-colored rocks called basalt and gabbro. Ocean crust originates as a "melt" that forms in submicroscopic pores in rocks in Earth's hot mantle and rises to the surface.

Scientists have pieced together clues to discover: 1) how melt that forms over hundreds of kilometers in the mantle is focused into a five-kilometer volcanic zone beneath mid-ocean ridges, and 2) how oceanic crust is formed with a relatively uniform, three-tiered structure consisting of gabbro, sheeted dikes, and lava flows.



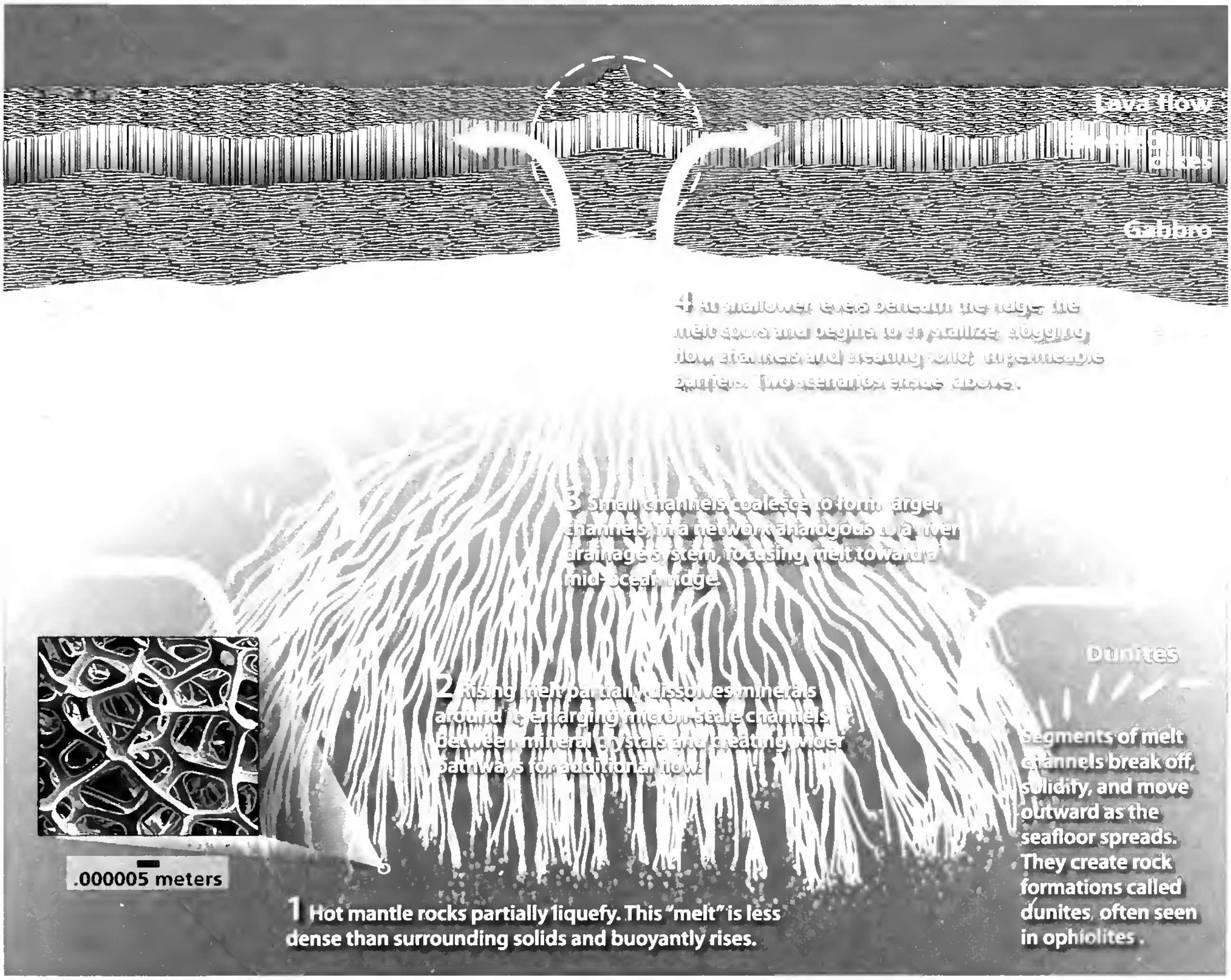
◄ Scenario 1

When the supply of rising melt is low, it is forced outward and around impermeable barriers and trickles along tiny pore spaces throughout surrounding rock.



Scenario 2 ►

When the supply of rising melt is large, it accumulates beneath impermeable barriers. Pressure builds until the melt bursts through the barriers and creates a melt-filled fracture that intrudes the overlying crust. If the fracture propagates high enough in the crust, it forms a sheeted dike. If it reaches even higher, the melt spills over on the seafloor and feeds a lava flow that solidifies into basalt.



4 At shallower levels beneath the ridge, the melt cools and begins to crystallize, clogging flow channels and creating solid, impermeable barriers. Two scenarios arise above.

3 Small channels coalesce to form larger channels, in a network analogous to a river drainage system, focusing melt toward a mid-ocean ridge.

2 Rising melt partially dissolves minerals around it, enlarging micron-scale channels between mineral crystals and creating wider pathways for additional flow.

1 Hot mantle rocks partially liquefy. This "melt" is less dense than surrounding solids and buoyantly rises.

Segments of melt channels break off, solidify, and move outward as the seafloor spreads. They create rock formations called dunites, often seen in ophiolites.

Paving the Seafloor—Brick by Brick

New vehicles and magnetic techniques reveal details of seafloor lava flows

By Maurice A. Tivey, Associate Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Most of Earth's crust is manufactured at the bottom of the sea. Deep beneath the waves and beyond our view, magma erupts along a 40,000-mile volcanic mountain chain that bisects the ocean floors and encircles the globe. The lava flowing from these mid-ocean ridges solidifies into new ocean crust that spreads out and paves the surface of our planet.

That's the "big picture." But our ability to understand all the subtle and complex details of this fundamental, planet-shaping process is blocked by the oceans themselves. Miles of water prevent us from seeing the seafloor directly, and we can't survive the darkness and high pressures at the seafloor to explore it firsthand.

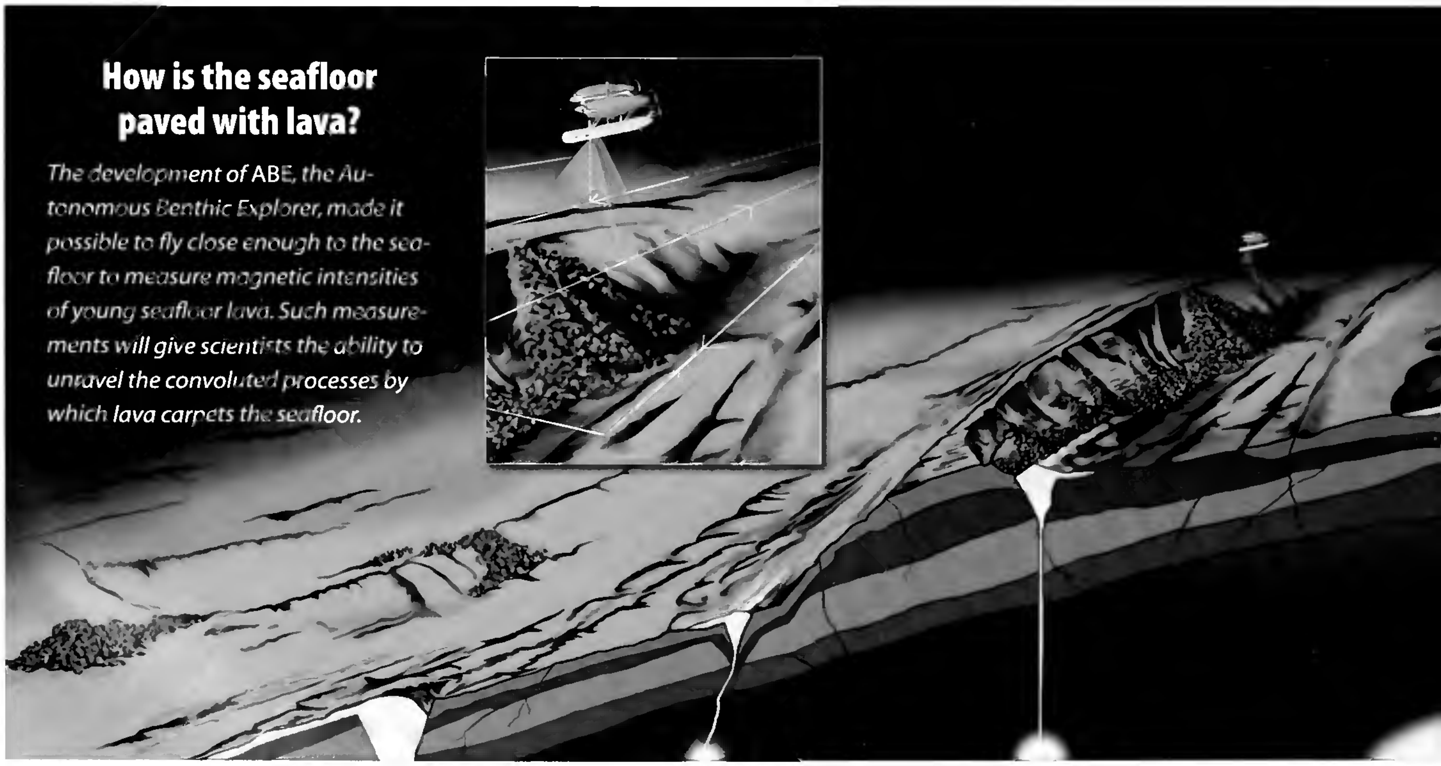
Exploring from afar

Imagine explorers from another planet hovering in a spaceship high above a large American city. From this lofty perspective, the explorers would deduce that the urban landscape was not natural, but constructed somehow in particular ways.

To understand this landscape, they would want to know: When were individual structures made? Of what materials? In what sequence? How are the roads, buildings, and sidewalks erected? Why are they located where they are? Which came first? The extraterrestrials would have to zoom down to get a closer look and perhaps take some close-up photos and samples to untangle the myriad factors that cumulatively result in cities.

For ocean scientists to zoom down and take a closer look at the seafloor requires specialized equipment. In the past decade, we have taken big technological leaps. New undersea vehicles have given us unprecedented access to the seafloor and new abilities to collect previously unattainable data.

Our goal is to understand the seafloor processes that turn molten lava into fresh crust. In particular, we are developing an



How is the seafloor paved with lava?

The development of ABE, the Autonomous Benthic Explorer, made it possible to fly close enough to the seafloor to measure magnetic intensities of young seafloor lava. Such measurements will give scientists the ability to unravel the convoluted processes by which lava carpets the seafloor.

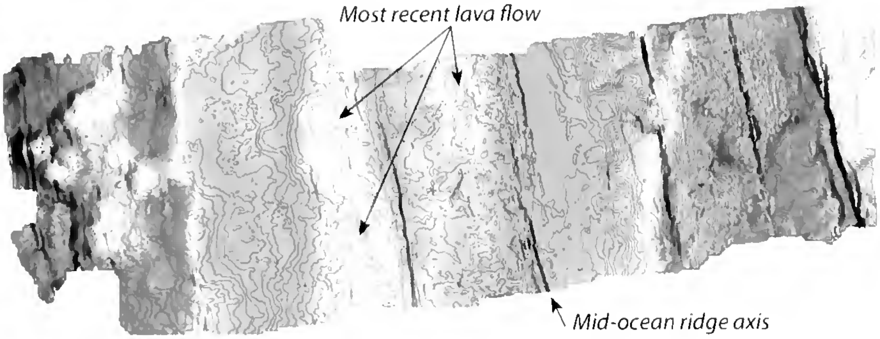
innovative technique: measuring the magnetic properties of very young seafloor rocks. It is revealing new details of how, where, and when lava erupts, and how it flows and accumulates on the ocean floor.

Telltale magnetic clues

As hot lava erupts, magnetic iron oxide crystals (magnetite) within it orient themselves to align with Earth's magnetic field. When the lava cools and solidifies, its magnetic crystals are "flash frozen"—pointing north. The rocks' magnetic direction, or "polarity," is preserved.

But the magnetic north pole has not always been where it is now. Throughout Earth's 4.6 billion-year history, its magnetic field has flip-flopped several times—with the magnetic north sometimes facing south, or vice versa, as it is today.

The time periods when many of these magnetic reversals occurred are well-documented. So seafloor lavas provide a built-in chronometer or calendar that we can use to determine when they were created. Thus, the continually forming ocean crust is kind of a tape recorder of Earth's magnetic field history.



TRACKING SEAFLOOR LAVA FLOWS—By superimposing magnetic measurements on detailed seafloor topography maps like this one, scientists can distinguish how, when, and where individual lava flows occurred on mid-ocean ridges. Younger lava has the highest magnetic intensities (red and yellows). Above, the most recent lava flow erupted from the ridge axis, overlaid older lava flows, and pooled to the left of the axis.

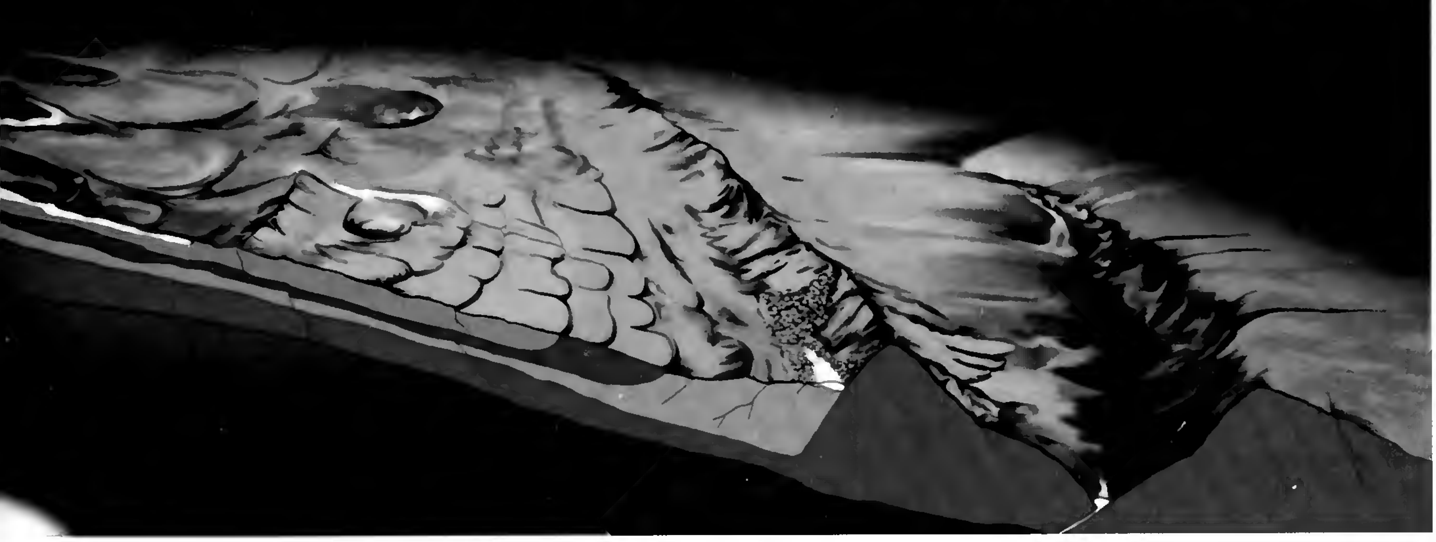
A magnetic mirror image

In the late 1960s, this phenomenon provided crucial evidence confirming that the seafloor was indeed spreading apart. This concept is at the core of the revolutionary theory of "plate tectonics."

In the early 1960s, scientists analyzed the magnetic properties of rocks in terrestrial outcrops and developed a timescale that chronicled the reversals of Earth's magnetic field. At sea, scientists collected magnetic data from sensors towed from ships and found remarkable magnetic patterns in seafloor rocks that were subsequently correlated with the magnetic reversal "clock" established in terrestrial rocks.

On both sides of mid-ocean ridges, scientists found a pattern of alternating magnetic "zebra stripes." "Black" stripes represented rocks imprinted when Earth's magnetic field was in a normal direction, as it is today, and "white" represented rocks imprinted when the field was in a

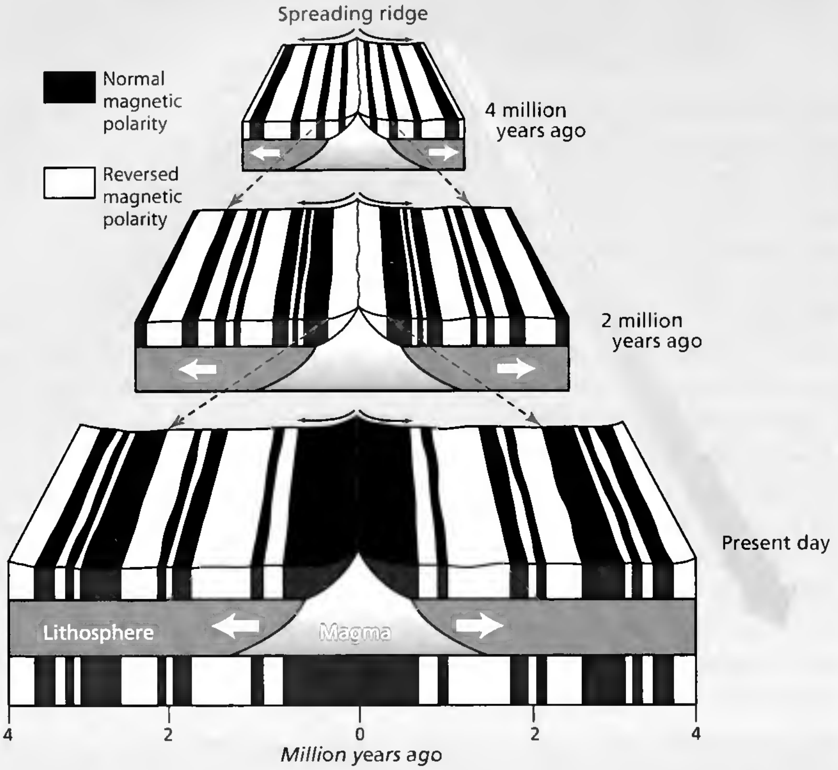
Scientists are investigating whether fresh lava (red) erupts from a central point in the mid-ocean ridge (as depicted below) and cascades downhill to overlay older lava flows (gray), or whether lava erupts from several isolated, outlying magma chambers to create discrete patches of seafloor (as depicted on the left side of illustration). Or perhaps both processes occur.



E. Paul Oberlander, WHOI Graphic Services

Magnetic 'zebra stripes'

Seafloor lavas have built-in magnetic "clocks" that reveal their age. When seafloor lava solidifies at the seafloor, its magnetic crystals are quenched in alignment with Earth's magnetic field, and the rocks' magnetic "polarity" is preserved. But Earth's magnetic field has reversed many times over the planet's history—with the magnetic north sometimes facing south, or vice versa, as it is today.



New seafloor is created at mid-ocean ridges (with the prevailing magnetic signature) and spreads out in both directions, creating a symmetrical "zebra-stripe" pattern of alternating rocks with either "reversed" or "normal" polarity.

Jack Cook, WHOI Graphic Services

reversed direction.

The stripes ran parallel to the ridges, and the pattern was astonishingly symmetrical on either side of the ridges. This mirror image could form only if new seafloor was created at the crests of ridges (with the prevailing magnetic signature) and then spread outward in both directions.

A new way to measure 'young' rock

Historically, magnetic data were collected with magnetometers towed at the ocean surface by research ships. They provided a large-scale picture (like the view of a city from a high-flying spaceship) of how ocean crust forms over many millions of years and hundreds of miles.

To get a more detailed view, we began to look at rocks less than 100,000 years old and within just a few miles of the ridge crest. This was problematic, because the most recent magnetic reversal occurred 780,000 years ago. We had no way of finding the age of lava younger than this.

To solve this dilemma, we began to examine not only the polarity of Earth's magnetic field, but also the strength of the field, or intensity. The intensity of Earth's magnetic field has also varied dramatically through time, and ocean floor sediments have preserved a record of Earth's magnetic field intensity over the past few hundred thousand years.

So while magnetic polarity measurements give us ages within millions to hundreds of thousands of years, intensity measurements give us ages within thousands to tens of thousands of years—a minute hand on the magnetic clock. Thus, within a patch of young lava with the same magnetic orientation, we can distinguish older and younger rocks, and we can begin to unravel the sequences in which they were deposited on the seafloor.

Unprecedented seafloor access

To detect magnetic intensities, we must take measurements within meters of the rocks—something we just could not do until recently. In 1993, we received an opportunity to use a magnetometer aboard the submersible *Alvin*, and we confirmed for the first time that we could detect strong magnetic intensity signals in freshly erupted lava. The invention and development at WHOI of the Autonomous Benthic Explorer (*ABE*) in the mid-1990s made it possible to measure magnetic intensities over wide swaths of seafloor lava.

ABE can maintain a stable ride and a constant altitude over changing seafloor contours—features that make it well-suited for collecting high-resolution magnetic measurements. Over several hours, it can survey 20 to 25 kilometers (12 to 15 miles) of seafloor. At the same time, its sonar can take measurements to create fine-scaled topographical maps.

The maps give us detailed, three-dimensional pictures of contorted amalgamations of lava flows. By superimposing magnetic measurements on these maps, we can distinguish the extent and volume of individual lava flows in the upper crust and tell when they erupted. We can begin to unravel how flows are buried by subsequent flows like a deck of cards. *Alvin* plays a crucial complementary role, giving us an essential visual picture of the seascape and the ability to sample fresh lava for precision dating.

Dan Fornari, WHOI

THE AUTONOMOUS BENTHIC EXPLORER (ABE)*— Developed by Al Bradley, Dana Yoerger, and colleagues at WHOI,* ABE *can maintain a stable ride and constant altitude over changing seafloor topography. It can make detailed seafloor maps and collect high-resolution magnetic data.*

Many bursts or a 'crack of doom'?

My colleagues in this National Science Foundation-sponsored research—Hans Schouten, Dan Fornari, and Ken Sims at WHOI, and Jeffrey Gee at Scripps Institution of Oceanography—focus on the ocean bottom because seafloor lava flows are young and not yet buried by thick muds. They also have not lost their magnetic intensity due to chemical alteration with seawater, so they accurately record Earth's recent magnetic field history.

The lavas found at mid-ocean ridges erupt more often, are better-preserved, and are less disturbed than those found on continents. These attributes give us an opportunity to get a more "brick-by-brick" understanding of how the surface of Earth is paved.

For example, does lava erupt at a central "crack of doom" atop a ridge, and then spill over and cascade downhill to bury older lava flows (as portrayed in the right side of the illustration on pages 44-45)? Does it burst from several outlying magma chambers through narrow channels to create discrete patches of seafloor (as in the left side of the illustration)? Or are both processes at work?

Answers to these questions will delineate the width of the zone along mid-ocean ridges in which new seafloor crust is formed. It will also reveal how frequently and periodically ridge eruptions take place—which, in turn, will tell us about the heartbeat of magma movements deeper in the Earth.

Tom Kleindinst, WHOI

Maurice Tivey followed his grandfather and father to sea, as they both served in the British Royal Navy. His marine science career began with geological studies at Dalhousie University in Nova Scotia and rock magnetism work at the University of Washington. He came to WHOI in 1988 as a Postdoctoral Scholar. Maurice has been involved in 32 research voyages and made 27 dives in deep-sea submersibles including Alvin, *the French sub* Nautile, *and Japan's* Shinkai 6500. *His research interests encompass all of magnetism but especially focus on high-resolution magnetic measurements of the seafloor, and what they can tell us about how the ocean crust is formed and how the field has changed through time. When at home, he plays soccer with friends and coaches in the local youth league. He recently bought a telescope to peer into the heavens, as an excuse to get more gadgets and as an alternative to continually looking under water.*

Earthshaking Events

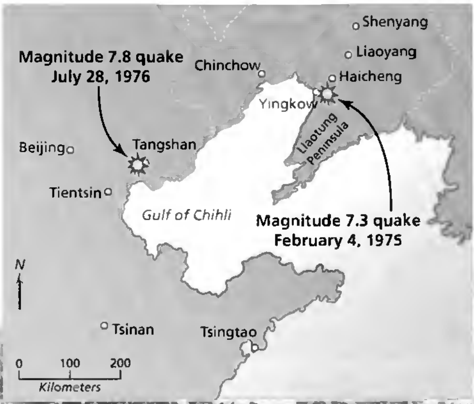
New research on land and sea reinvigorates hopes of forecasting where earthquakes are likely to occur

By Jian Lin, Associate Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

When I was still a schoolboy in China, two major earthquakes occurred, about a year apart. They had a profound impact on my life and on the Chinese people.

The first quake, with a magnitude of 7.3, struck the northern city of Haicheng on Feb. 4, 1975. For six months before the quake, a series of much smaller quakes had rumbled in the region. They accelerated on Feb. 3, and in the early morning of Feb. 4, the government began to issue warnings, shutting down factories and urging people to remain outdoors. Despite the frosty weather, people moved into open fields, where children watched movies instead of going to school. The shock arrived at 7:36 p.m. While more than one million dwellings were badly damaged, the quake's death toll was relatively low at 1,328. The foreshocks had offered a warning signal, and this amazingly successful earthquake prediction probably saved tens of thousands of lives.

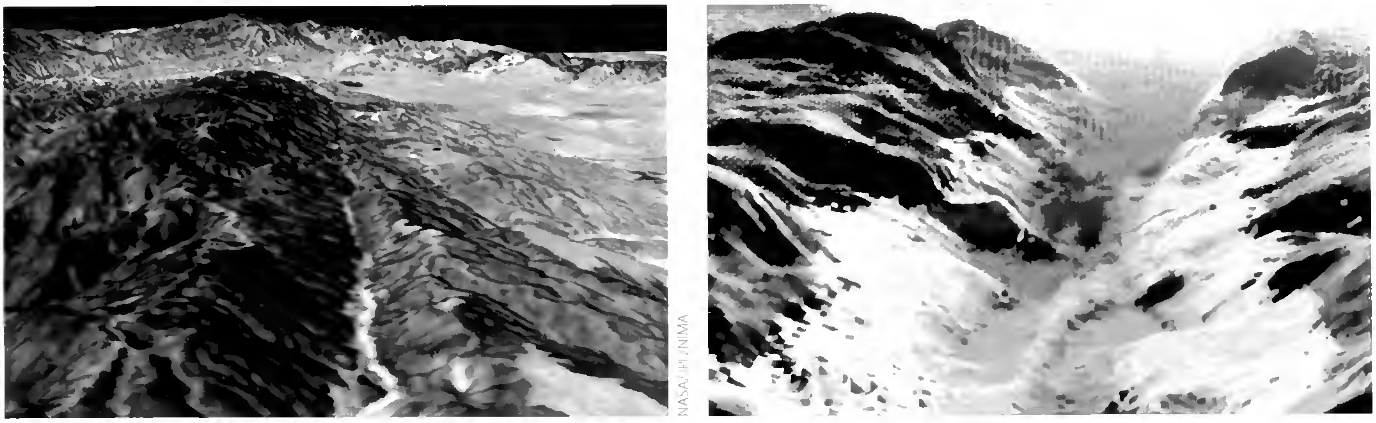
Seventeen months later, the people of Tangshan, a city 280 miles southwest of Haicheng, were not so lucky. On July 28, 1976, a magnitude 7.8 earthquake released the energy equivalent of



Jack Cook, WHOI

China Stock Photo Agency Map: Jack Cook, WHOI Graphic Services

A CITY FLATTENED—Without warning, a magnitude 7.8 earthquake struck the city of Tangshan in China, killing 242,769 people and destroying 90 percent of the city's buildings. A similar earthquake struck 17 months earlier about 280 miles northeast near Haicheng. But a series of smaller foreshocks provoked Chinese officials to issue warnings urging people to remain outdoors, and only 1,328 people died.



NASA/JPL/NIMA

Tom Reed, University of Hawaii

ABOVE AND BELOW THE OCEAN—Faults on land, like the San Andreas Fault near Palmdale, Calif. (left), are similar to those in the ocean, like the Atlantis Transform Fault in the Atlantic Ocean (right, three times vertical exaggeration). But in many ways, oceanic faults are easier to study and offer the potential to discover fundamental aspects about earthquakes that are applicable to land.

400 Hiroshima atomic bombs combined. There were no foreshocks, and therefore no warning.

The quake struck at the worst time, 3:42 a.m., when most people were sleeping in their beds. It lasted only about 90 seconds, but about 90 percent of the houses and buildings in Tangshan collapsed. A total of 242,769 people died, and 169,851 were severely injured, according to an official tally.

Bamboo and body bags

The Tangshan earthquake occurred during a political era when China shrouded itself from outside eyes. So the devastation it wrought did not make headlines in the West. But it left an imprint on me and other Chinese that is perhaps as profound and indelible as September 11th on the current generation.

My home province in southern China harbors bamboo forests, and much of our harvest was sent to Tangshan to construct emergency shelters. I also recall vividly that factories in my home city made a huge quantity of large plastic bags to be sent to Tangshan. So many people died, those plastic bags were needed to bury the dead.

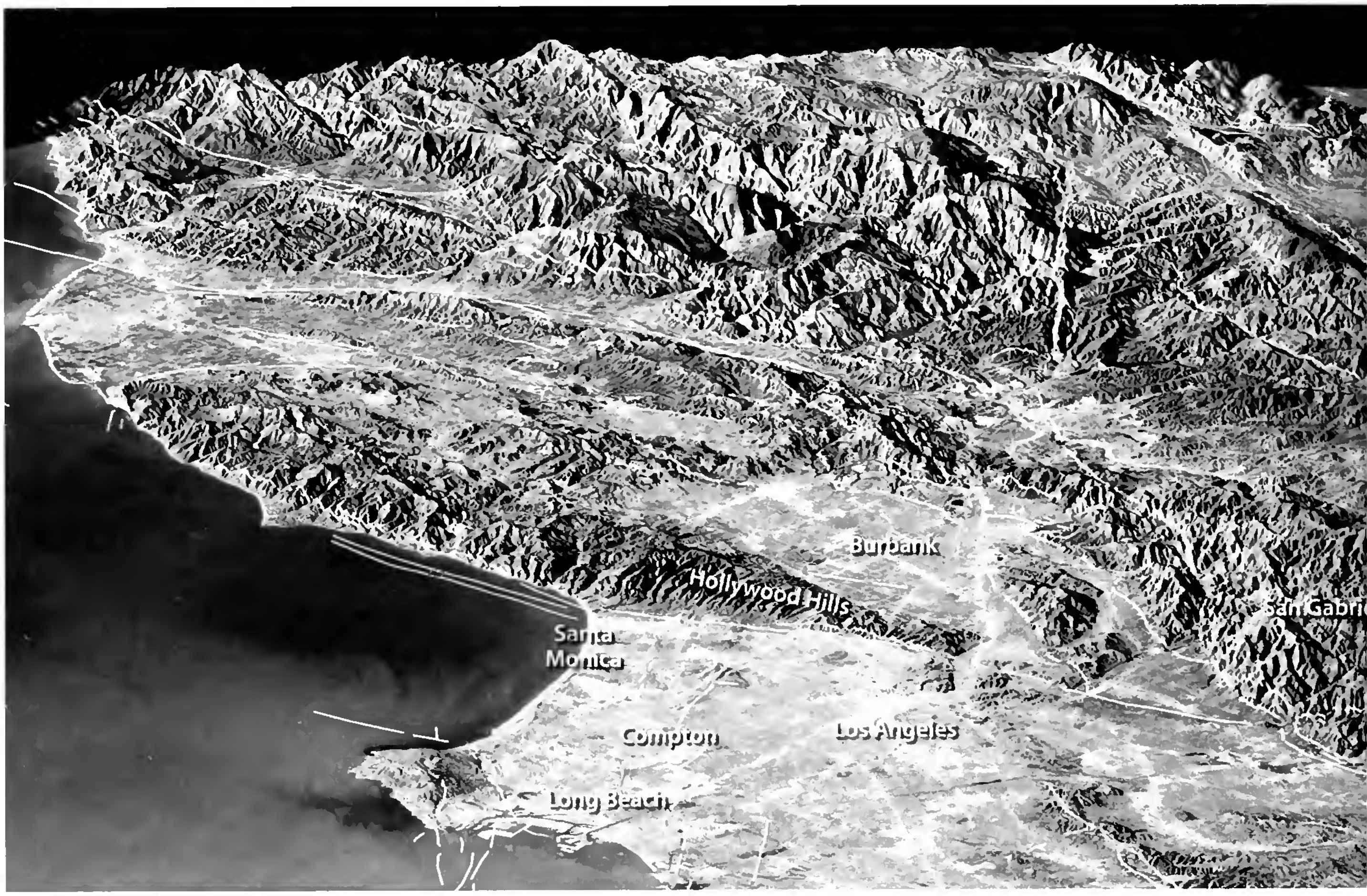
Undoubtedly, these events encouraged me to become a geophysicist and earthquake researcher—to seek to understand the fundamental physics of earthquakes and learn, for example, why foreshocks preceded the quake in Haicheng, but not in Tangshan. Underlying all the scientific efforts of earthquake researchers are the goals of forecasting earthquakes and saving lives.

In many ways, earthquake research is like cancer research: They are scientific challenges that offer huge potential benefits to society, yet both have turned out to be far more complex and intractable than we thought and hoped they would be. But scientists have made important advances in cancer research, and I believe that new seismological research on land and in the oceans has us on the path to make similar advances in seismology.

Location, location, location

We know, in general, where earthquakes typically occur. They happen near faults, or fractures in the Earth's crust where rock formations—driven by the inexorable movements of Earth's tectonic plates—grind slowly against each other and build

RUPTURED LANDSCAPE—WHOI geophysicist Jian Lin stands near the plainly visible surface of the Pleasant Valley Fault in Nevada, which caused a magnitude 7.1 earthquake in 1954.



WHERE THE FAULTS LIE—A satellite image shows a portion of the San Andreas Fault and neighboring faults (white lines) in Southern California.

up stress. At some point, stress surmounts friction, and the rocks slip suddenly, releasing earthshaking seismic energy.

We have a general idea where major faults are near Earth's tectonic plate boundaries. Many faults in California are named, including the famous and highly visible San Andreas Fault, which stretches from north of San Francisco to northern Mexico. But there are many much smaller and less well-known faults that might prove even more dangerous because they are closer to, and even directly underneath, urban centers such as Los Angeles. In many places, including right beneath Los Angeles, faults don't break the surface. We have only vague ideas about the locations of these so-called "blind faults," until surprising earthquakes illuminate their existence.

Forecasting the timing of earthquakes is more difficult. Our best estimates are currently based on the general theory that faults accumulate strain and slip on a somewhat regular schedule. This isn't very useful for very large faults and great earthquakes, which require centuries of strain buildup before they rupture.

From Joshua Tree to Hector Mine

In our quest to forecast earthquakes, scientists have searched for any signs of precursors that might provide warning. Even a few minutes warning would be useful, providing enough time to stop trains, shut down nuclear power plants, or turn off the gas in your house, for example.

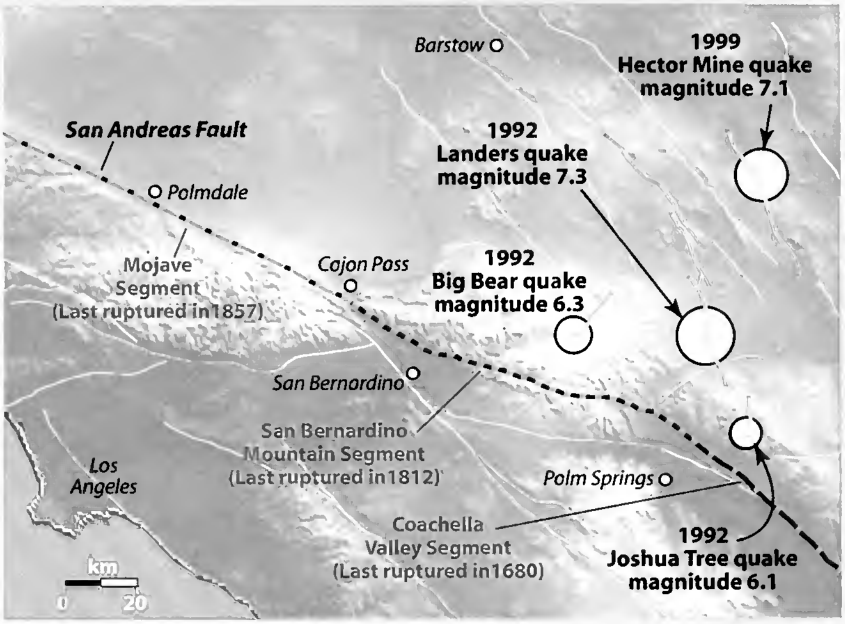
Scientists have investigated changes in groundwater levels and electromagnetic fields and unusual animal behavior before major quakes, but the evidence so far, though intriguing, is often complex and not conclusive. Seismologists are also examining changes in seismic patterns that may foretell large quakes—an increase in smaller earthquakes, as happened before Haicheng, or perhaps a dying out of smaller earthquakes immediately before the Big One.

With colleagues Ross Stein of the U.S. Geological Survey (USGS), Geoffrey King of Institut de Physique du Globe in France, and Andrew Freed of Purdue University, I have explored an intriguing seismic pattern in Southern California that we believe can improve our capability to identify areas that are more susceptible to future earthquakes. Our research has been supported by the National Science Foundation (NSF), the USGS, and the Southern California Earthquake Center.

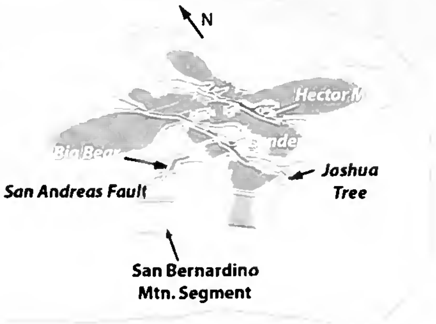
Since 1992, a sequence of four moderate to major earthquakes has occurred in the Mojave Desert—near Los Angeles, but fortunately in sparsely populated, outlying regions. In April 1992, a magnitude 6.1 quake struck near the town of Joshua

NASA/JPL/NIMA

Does strain 'creep' through the crust?



Since 1992, a sequence of four moderate to major earthquakes has occurred in sparsely populated places in the Mojave Desert, near the towns of Joshua Tree, Landers, Big Bear, and Hector Mine.



Computer models (right) simulated how the Joshua Tree, Landers, Big Bear, and Hector Mine quakes alleviated stress in some places (blue areas) and transferred and increased stress (red areas) to adjacent regions. In a domino-like effect, strain can "creep" through the crust, interact with neighboring faults, and trigger another earthquake elsewhere. Scientists believe that the Landers and Hector Mine quake sequence has shifted stress toward the San Bernadino Mountain segment of the San Andreas Fault and increased the likelihood of a quake there.

Tree, on a small fault about 20 kilometers east of the San Andreas Fault. Two months later, on another fault about 30 kilometers north, a magnitude 7.3 quake occurred in Landers—followed just three hours later by a magnitude 6.3 quake near the town of Big Bear.

Do quakes "talk" to each other?

In the wake of these earthquakes, we calculated how rocks shifted and deformed. We constructed a three-dimensional computer model that simulated how stress was transferred throughout the rocks in the regions, from the brittle upper crust to the more fluid-like lower crust. The model pointed to an increase in pressure of 1 to 2 bars in the direction of the town of Hector Mine, about 20 kilometers northeast of Landers.

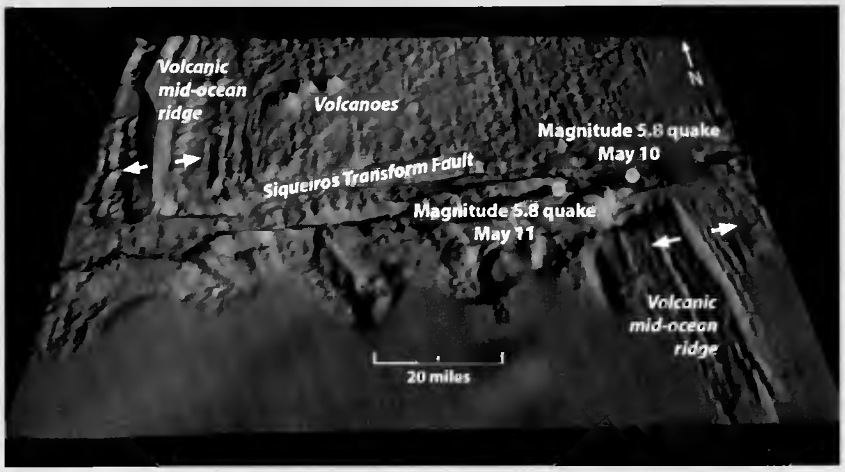
One bar is equivalent to the pressure exerted by pushing your hands together. That's not much, but applied over a wide area that is on the verge of a quake, it adds up. In 1999, a magnitude 7.1 quake hit Hector Mine. We believe the Landers and Big Bear quakes transferred stress, through the crust and the slowly creeping upper mantle, toward the Hector Mine fault and hastened its eventual failure seven years later.

Our research indicates that as an earthquake alleviates stress on one fault, it can shift that stress to adjacent areas. In a domino-like effect, strain can "creep" through the crust, interact with neighboring faults, and trigger another earthquake elsewhere.

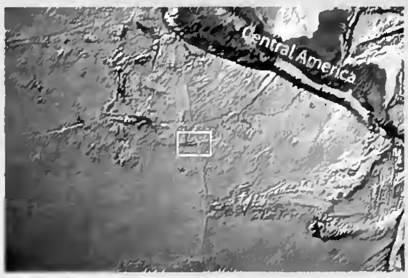
In this way, earthquakes carry on a conversation with each other. If we listen in, we can begin to understand and monitor how one quake can influence the timing and location of earthquakes on faults "down the line."

Subsequent research on fault systems in Turkey and Japan has shown that these concepts of "creeping" and "stress triggering" may give us a valuable new tool

Eavesdropping on oceanic quakes



In early May of 1998, hydrophones began to record a flurry of small earthquakes near the Siqueiros Transform Fault, an 80-mile fault sandwiched between two volcanic mid-ocean ridges in the Pacific Ocean. The flurry culminated in a magnitude 5.8 quake on May 10. This was followed by another flurry of smaller quakes in an outlying area about 20 kilometers away and another magnitude 5.8 quake only 18 hours after the first one. New findings like this reinvigorate hope that further understanding of foreshocks can provide warning of larger quakes, at least in some places on Earth.



Jack Cook, Jian Lin, and Trish Gregg, WHOI

to assess where earthquakes are more likely to happen next. We believe, for example, that the Landers and Hector Mine quake sequence has combined to shift stress toward the San Bernardino Mountain segment of the San Andreas Fault and increases the likelihood of a quake there.

Faults under the oceans

Simple explanations for earthquakes on land have been difficult to unravel because continental crust is old and usually has a long, complex, and tortured history. It is a conglomeration of many types of rocks that have been distorted by erosion and chemical "weathering" over tens of millions to hundreds of millions of years; overwritten by many periodic bursts of volcanism; and repeatedly fractured and refractured by earthquakes.

These confounding complications have encouraged seismologists to study a simpler system that naturally creates earthquakes—on the bottom of the ocean, where the majority of Earth's tectonic plates collide and where about 80 percent of seismic activity on Earth takes place. Many of the plate borders are marked by volcanic mountain chains called mid-ocean ridges, where new ocean crust is created. The mid-ocean ridges are offset, in a zigzag pattern, by great transform faults, which resemble faults on land.

The seafloor offers many advantages: ocean crust that is pristine and composed of only a few types of rocks; fault systems that are uncomplicated and undistorted; and far more seismic activity to observe. By studying seafloor systems, we have the potential to discover fundamental aspects about earthquakes that are applicable to land.

Searching for warning signals

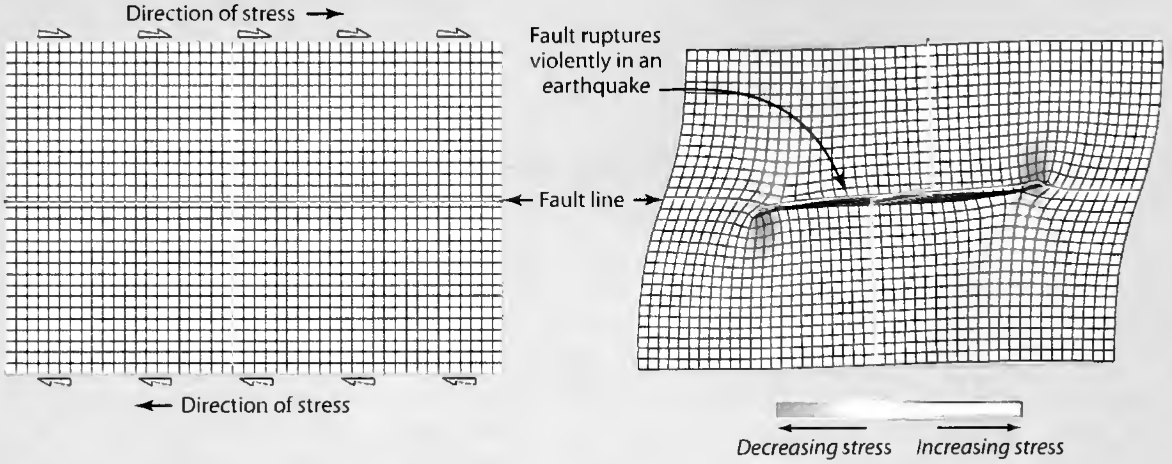
Studying earthquakes in the oceans presented its own difficulties in the past. Beyond the expenses and logistics of seagoing research, seismometers previously could not stay down long enough to capture seismic events and could not record a broad range of seismic waves. But the growing potential of long-term ocean observatories, new generations of seismic instruments, and exponentially increased computer power are dramatically increasing our chances of making seismological breakthroughs. (See "Seeding the Seafloor with Observatories," page 28, and "Listening Closely to 'See' into the Earth," page 16.)

Previous experiments by researchers have shown tantalizing evidence of precursory "slow" quakes before a major quake on oceanic faults. Instruments installed on land recorded a very slow creeping event 100 seconds before a magnitude 7.0 quake in 1994 on the Romanche Transform Fault in the equatorial Atlantic Ocean, a fault very similar to San Andreas. A similar experiment in the Prince Edward Transform Fault in the Indian Ocean showed a slow creeping event 15 seconds before a magnitude 6.8 earthquake.

In 2004, funded by NSF and the WHOI Deep Ocean Exploration Institute, we analyzed seismic data collected by the National Oceanic and Atmospheric Administration (NOAA) since 1995 along the Siqueiros Transform Fault, an 80-mile fault sandwiched between two volcanic mid-ocean ridges in the Pacific Ocean. NOAA's seismic instruments are suspended in the SOFAR (sound fixing and range) channel, an exceptionally good zone of sound transmission that is 700 to 1,500 meters beneath the sea surface. Shaking from even a small quake in the ocean crust can vibrate into the SOFAR channel and be recorded by NOAA instruments hundreds of kilometers away. (See "Ears in the Ocean," page 54.)

The NOAA instruments recorded many small quakes on the Siqueiros Transform Fault. Trish Gregg, a graduate

Quakes shift stress from place to place



A computer model simulated how stress on rocks is transferred in a region. At left, rocks on either side of a fault push against each other, building up stress. At right, the stress overcomes friction, and the fault ruptures violently in an earthquake. In the aftermath, stress is alleviated in some areas (blue) and transferred and increased to other neighboring areas (red).

Ross Stein, USGS

student in the MIT/WHOI Joint Program, Deborah Smith, a geophysicist at WHOI, and I read the records carefully, and we were surprised! Beginning in early May of 1998, several small earthquakes began, culminating in a magnitude 5.8 quake on May 10.

As we did in California, we calculated how this main shock changed the stress field in the region. In the areas where we calculated that the stress was transferred, smaller quakes continued to occur. Then, another flurry of smaller quakes began to occur in an outlying area about 20 kilometers away, followed by another magnitude 5.8 quake in that area only 18 hours after the first one.

Flurries of foreshocks also appear to have occurred prior to a number of other moderate-size earthquakes in our study region in the Pacific. These new findings give us confidence that we can figure out how foreshocks are created and that we can calculate how and where one earthquake can transfer stress and trigger another earthquake nearby. The research reinvigorates hopes that at least some earthquakes on Earth have relatively high predictability.

A rising phoenix

Almost three decades after its devastating earthquake, Tangshan is a flourishing new city. Its population has increased by more than 50 percent since 1976. Tangshan was one of the first Chinese cities honored by the United Nations for its hospitable residential environments. A new city landmark—the Phoenix Hotel—rises 112 meters into the sky and is specially designed for resisting shakes from major earthquakes.

However, the people of Tangshan are fully aware of the constant danger posed by a very complex network of faults in northern China. Recently, I began to collaborate with colleagues to evaluate how the Haicheng, Tangshan, and other moderate-size quakes in the region may have "talked" to each other. We hope to assess more accurately seismic risks for the Beijing-Tianjing-Tangshan triangle, the true cultural and political heartland of China—so that the future will bring us fewer earthquakes without any warning like Tanshan.

Jian Lin was born and raised in China's southern coastal city of Fuzhou, not far from the quake-prone island of Taiwan. When he was small, his father explained to him that the dangling light in their house went into a wild swing because of a major quake in Taiwan. The mid-1970s was an unusually apprehensive era when the whole nation of China felt as if quakes could occur anywhere at any time. Lin became a voluntary "earthquake watcher" in school. He kept a diary of water level changes in an abandoned well and the gentle tilting of the ground, phoning in readings to a local seismological center. He studied physics and seismology at the University of Science and Technology of China, conducted Ph.D. research at Brown University in Providence, R.I., and pursued earthquake geophysics at the U.S. Geological Survey in Menlo Park, Calif. At WHOI, he has investigated mid-ocean ridges, hotspots, and underwater volcanoes, while continuing his work on quakes. The Institute for Scientific Information recently recognized Lin as among the most cited authors on earthquake research in the past decade. His paper with Geoffrey King (Institut de Physique du Globe) and Ross Stein (USGS) was the most cited earthquake research article in the past decade.

Ears in the Ocean

Hydrophones reveal a whole lot of previously undetected seafloor shaking going on

By Deborah Smith, Senior Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

If you sought to delve into the forces that drive and shape the face of the Earth and that distinguish it from all other planets in our solar system, you would shine a spotlight on the mid-ocean ridges.

This 75,000-kilometer (45,000-mile)-long volcanic mountain chain bisects the seafloor and wraps around the entire globe. It is the site where magma continuously erupts to create new crust. As the crust spreads out on both sides of the ridges, it paves the surface of the planet and sets in motion the tectonic forces that cause continents to rip apart and collide, and oceans to open and close.

This planetary extravaganza, full of fury and sound, is accompanied by a constant drumbeat of earthquakes and volcanic eruptions. But the oceans act like a great blue curtain, completely shrouding our view and muting the sound.

About 80 percent of volcanic and earthquake activity on Earth occurs on the seafloor, but it is like those proverbial trees that fall in forests when nobody's there. If we could eavesdrop on all that seismic activity, we could glean a great deal of information about the workings of our planet.

To do that, Earth scientists have employed instruments that record seismic waves generated by earthquakes and volcanoes. (See "Listening Closely to 'See' into the Earth," page 16.) But these studies have suffered from two primary limitations. The instruments have been installed in land-based networks, which cover broad areas over long time periods but can detect only large-magnitude earthquakes in the oceans. Experiments using ocean-bottom seismometers can detect seafloor earthquakes with precision, but they are best-suited to monitor small areas.

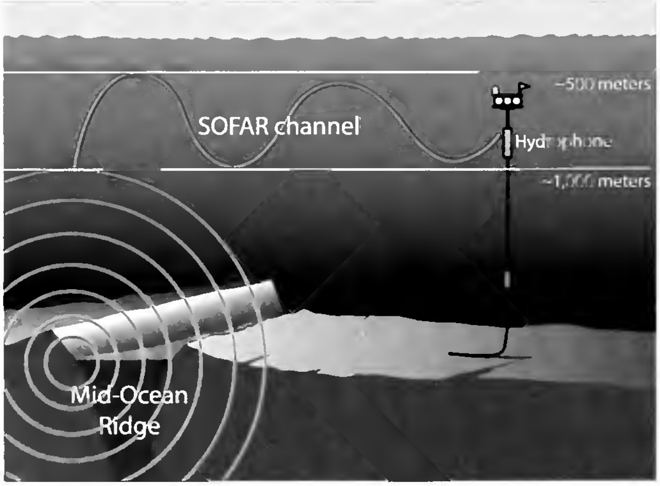
But now, the ending of the Cold War has given Earth scientists an unprecedented opportunity to take advantage of a tool created to wage that war—a project launched by the U.S. Navy in the 1950s that went by the code name Jezebel.

SOFAR, so good

The roots of Jezebel actually began at Woods Hole Oceanographic Institution during World War II when two scientists, Maurice Ewing and J. Lamar Worzel, began to conduct basic research on acoustics in the ocean—seeking any advantages that would help the Navy detect enemy submarines or mines, or help U.S. subs avoid detection. In a critical experiment, they detonated 1 pound of TNT under water near the Bahamas and detected the sound 2,000 miles away near West Africa.

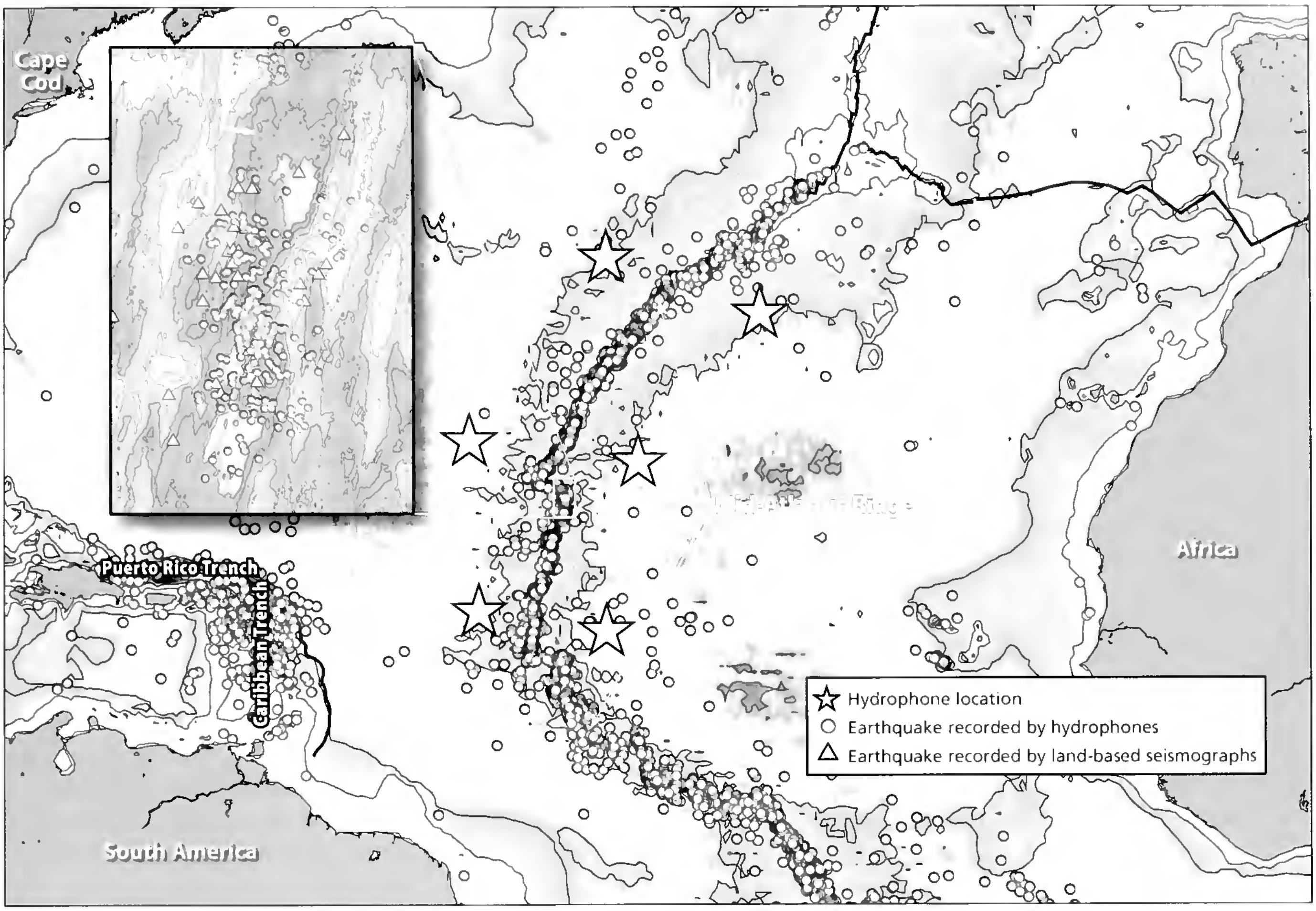
The test confirmed Ewing's theory that low-frequency sound waves were less easily scattered or absorbed by water and could travel far without losing energy. The key, however, was the discovery of a layer of water in the ocean that acted like a pipeline to channel low-frequency sound and transmit it over vast distances. This sound pipeline, called the SOFAR (Sound Fixing and Ranging) channel, was independently discovered by Russian scientist Leonid Brekhovshkikh, working simultaneously with underwater explosions in the Sea of Japan.

The key to the SOFAR channel is that sound energy, traveling in waves, speeds up in waters where temperatures are warmer (near the surface) or where pressure is higher (at depths). But in between lies the SOFAR channel, which is bounded by water layers where sound velocities increase. The boundaries act like a ceiling and floor: When sound energy enters the channel from below, it slows down. When it hits the ceiling, it does not keep going, but rather, it is refracted back downward.



Jack Cook, WHOI Graphic Services

New hydrophone arrays have been developed to detect and monitor previously "unheard" volcanic and earthquake activity in the oceans. They are deployed in the SOFAR channel, a layer of water in the ocean that channels sound waves generated by seismic events and allows them to be transmitted and detected thousands of miles away.



Courtesy of Deborah Smith, WHOI

SOUND AND FURY ON THE SEAFLOOR—An array of six hydrophones (yellow stars) recorded 7,785 seismic events (red dots) between 1999 and 2002, mostly along the Mid-Atlantic Ridge and the Puerto Rico and Caribbean Trenches. A close-up of one portion of the ridge reveals that land-based seismographs recorded far fewer seafloor seismic events (white triangles) over a much longer period (26 years).

Then it hits the floor, and it is refracted back upward. In this way, sound is efficiently channeled horizontally with minimal loss of signal over thousands of kilometers.

The Navy immediately saw the value of the SOFAR channel, launching Jezebel, which later became the Sound Surveillance System, or SOSUS. It deployed a network of underwater microphones, called hydrophones, connected by undersea cables to onshore facilities. The hydrophones were installed in locations to optimally exploit the SOFAR channel. The Navy could detect radiated acoustic energy of less than a watt at ranges of several hundred kilometers—a sensitivity that often could distinguish the number of propellers a submarine had.

The fall of the Berlin Wall in 1989 marked the end of the Cold War, and in 1991, the Navy declassified SOSUS and entertained the idea of allowing scientists to use it for basic research. Scientists at the National Oceanic and Atmospheric Administration's Pacific Marine Environmental Laboratory (PMEL) in Seattle had the clever idea of using the Northeast Pacific Ocean SOSUS array to detect low-level seismic waves on the Juan de Fuca Ridge off the Pacific Northwest. The waves were generated by magmatic eruptions or rocks slipping along faults to cause earthquakes.

But since SOSUS covered only a portion of the world ocean, PMEL launched a strategy to develop moored, autonomous hydrophones that could be deployed for long durations in the SOFAR channel to monitor seismicity in more remote ocean regions. In 1996, PMEL deployed long-term hydrophones in the eastern equatorial Pacific between 20°N and 20°S and began monitoring them successfully. That led me to ask if NOAA could deploy similar hydrophones in my neck of the woods—the North Atlantic Ocean.

With support from the National Science Foundation, our research team—myself, Christopher Fox and Haru Matsumoto of NOAA PMEL, and Maya Tolstoy of Lamont-Doherty Earth Observatory, and later Robert Dziak of NOAA PMEL and Oregon State University—deployed six autonomous hydrophones, designed and built by NOAA's PMEL, in the North Atlantic in 1999. In a sweet coincidence, we used Lamont's ship, R/V *Maurice Ewing*, named after the SOFAR channel's co-discoverer. We placed the six hydrophones on the flanks of the Mid-Atlantic Ridge between 15° and 35°N—

three on each side, each spaced about 550 nautical miles apart.

Eavesdropping on the Earth

We selected this section of the Mid-Atlantic Ridge because it has been studied intensively over many years, beginning with the famous FAMOUS (French-American Mid-Ocean Undersea Study) Project in 1974—the first expedition using human-occupied vehicles to explore a mid-ocean ridge—and more recently by the French-American Atlantic Ridge project, which extended from 15°N to 40°N.

The entire length of the ridge in this region, as well as a few areas extending onto the ridge flanks, has been surveyed using multibeam sonar. This provides detailed bathymetric maps that give scientists the seafloor equivalent of the lay of the land. In addition, the area includes several sites, such as the TAG hydrothermal vent field, where detailed multidisciplinary investigations are taking place.

All of these studies provide a framework—a wide view and select close-up images of the region—on which we now can superimpose a soundtrack of seismic events. By combining these data, we can correlate the occurrences, locations, and timing of various seismic events with the seascape on which they are occurring.

We can begin to unravel, for example, a whole series of questions and cause-and-effect relationships: How frequently does magma erupt on mid-ocean ridges, and in which locations? And how do these temporal and spatial patterns influence the geological landscape, and vice versa? Where and when do different magnitudes of earthquakes occur? Can they give us clues to help us predict where and when earthquakes will likely occur on land?

An unheard seismic symphony

The ability to attack all these questions hinges on getting good hydrophone data. In short, the array worked beautifully. Between 1999 and 2002 the Mid-Atlantic hydrophones recorded 7,785 seismic events in the study area—more than five times as many as were recorded by seismometers on land.

The hydrophones also detected seismic events that release energy at levels 1,000 times less than events detected by land-based seismometers (down to magnitude 2.5). These events, mostly small faults moving, previously fell on the deaf ears of land-based networks, which do not detect seafloor seismic events smaller than about magnitude 4.5.

This data set provides us with an unparalleled view of the seismicity of the ridge over a broad region and over a broad range of event magnitudes. Joined by new collaborators—DelWayne Bohnenstiehl of Lamont-Doherty and Javier Escartin, Mathilde Cannat, and Sara Bazin of the Institut de Physique du Globe—we have begun to piece together temporal and spatial patterns of seismic events, which, in turn, can shed light on fundamental planet-shaping processes that occur at the ridges.

Stripes and gaps

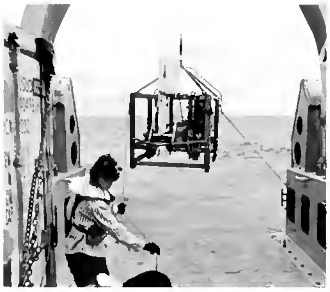
Initial results show areas on the ridge with intense and persistent seismic activity, which we call "stripes," that stand in sharp contrast with areas that lack seismicity, which we call "gaps." Our hypothesis is that the "stripes" correspond to areas where the crust is thicker, colder, and more brittle. In these places, stress builds in rocks until a threshold is reached and the rocks slip suddenly, causing earthquakes. The gaps represent areas where the crust is hotter and thinner, and stress is more easily accommodated by gradual deformation in the rocks, perhaps producing earthquakes too small to be detected by hydrophones. (See "Peering into the Crystal Fabric of Rocks," page 57.)

The gaps might also turn out to correlate with the presence in the crust of a type of rock called serpentinite, which is more slippery than other crustal rocks. It slides rather than breaks, and therefore reduces the probability of earthquakes. Clues like these, discovered on the seafloor, could apply to land and aid in the quest to forecast where earthquakes are more likely to occur. (See "Earthshaking Events," page 48.)

On a small scale, the distribution of seismicity on mid-ocean ridges has important implications for hydrothermal vents and their biological communities because magmatic eruptions initiate, maintain, and destroy them. (See "The Evolutionary Puzzle of Seafloor Life," page 78, and "Is Life Thriving Deep Beneath the Seafloor?" page 72.)

On a larger scale, we are analyzing seismic patterns for clues that will more precisely reveal the directions in which three of Earth's tectonic plates are moving. A cruise in 2005 will investigate a telltale area of high seismicity that we discovered 70 kilometers west of the Mid-Atlantic Ridge between 12.5°N and 13.5°N, which we hope will reveal the location of the triple junction where the South American, North American, and African Plates all meet.

Long-term hydrophone arrays have given us our first glimpse of the robust seismic activity rumbling on the seafloor. As seismic monitoring continues and expands into other oceans, we will accumulate a treasure trove of new information to explore the Earth.



Deborah Smith grew up in the cornfields of Illinois. She now travels to the far reaches of land and sea to investigate how volcanoes are built. She has hiked through tropical forests in Hawaii and Tahiti and over the cold, barren terrain of Iceland. She has mapped underwater volcanoes along a mid-ocean ridge at the location where one can't be farther away from land and still be on the planet: halfway between New Zealand and South America. In an effort to share the experiences of scientists with the general public, she has developed a Web site that profiles the careers of women oceanographers (http://www.womenoceanographers.org).

Peering into the Crystal Fabric of Rocks

When you get right down to it, earthquakes and volcanoes have atomic-scale causes

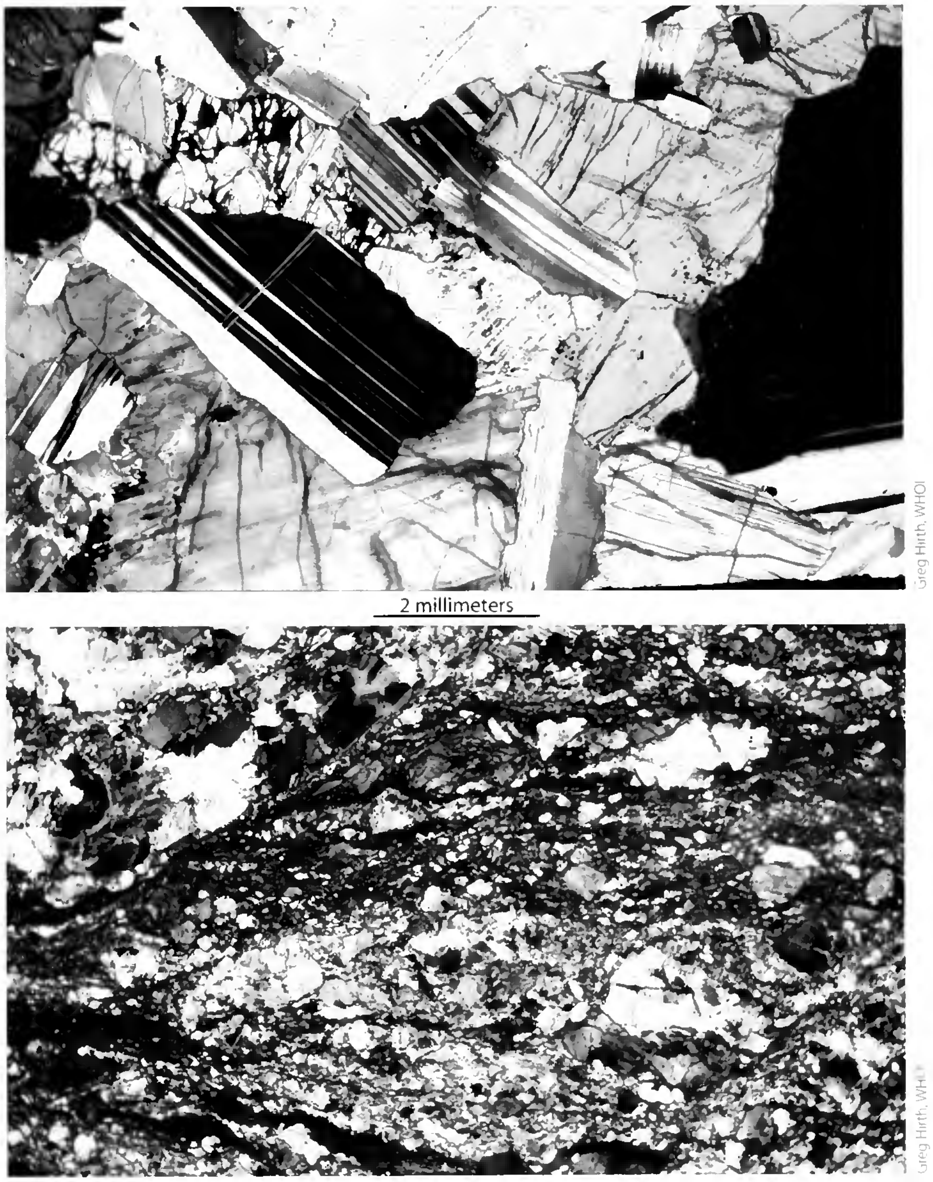
By Greg Hirth, Associate Scientist
Geology & Geophysics Department
Woods Hole Oceanographic Institution

"Rock solid" is an oxymoron, to my way of thinking. Oh, the expression does have some truth in that minuscule, superficial portion of our planet where humans dwell. But the majority of rocks nearly everywhere else in the Earth are continually changing their physical characteristics. Just below Earth's surface, rocks are constantly subjected to heat that causes them to flow like syrup, and to intense stress that causes them to crack like glass.

On a planetary scale, the flowing and breaking of rocks causes volcanism and earthquakes, which pose hazards to people. But on an even more fundamental scale, the face of the Earth is continually shaped and reshaped because rocks *aren't* rock solid. They slide, crack, flow, and melt. These abilities underlie larger processes by which mountains and volcanoes are made, continents are rifted, new seafloor is created, and the great tectonic plates comprising Earth's surface are set in motion to collide or slide against each other.

It turns out that the same forces that affect rock formations across continents and ocean basins—heat and pressure—also affect the deformation of rocks on the microscopic scale. Rocks are composed of a fabric of crystals. Just the way a solid metal paper clip—when heat or force is applied—can bend, break, or stretch, so, too, can the crystal fabric within rocks.

The core of my research is to investigate the microstructures and micromechanics of crystals within rocks. My field of science, called rheology (from the



MAJOR CHANGES BEGIN MICROSCOPICALLY—Using optical and electron microscopes, scientists can detect how crystals within rocks change their sizes, shapes, and orientations when the rocks are subjected to heat and stress. These atomic-scale changes can ultimately lead to earthquakes and volcanoes. Large crystals are evident in a photo of "undeformed" rock from the Indian Ocean seafloor (top). But (bottom), the crystals are broken and ground up in similar rock subjected to stress.

In this rock sample, heat has caused crystals to change shape and "flow" within the rock, which accommodates strain without causing the crystals to break.

Greg Hirth, WHOI

Greek word *rheos*, meaning current), is the study of the flow of matter. Amazingly, understanding what happens on an atomic scale provides insights into what happens on a planetary scale.

From crystals to earthquakes

My work is similar to that of material scientists, who might examine the microscopic textures of bricks or steel to determine loads in house walls or fatigue thresholds in airplane wings. My friends jokingly call me a "rock psychologist," because I study the properties of rocks under stress and strain.

Heat and stress cause chemical and physical alterations and defects in the crystal structure of rocks. Under stress, atoms are pushed against other atoms, sending further ripples of changes down the line, like people crowding in subway cars. Chemical bonds break. The rocks' well-ordered lattice of atoms breaks down and rearranges itself.

In short, crystals change their size, shape, and orientation within rocks. Using optical and electron microscopes, we can detect these changes in rocks' crystalline structure. The changes we identify provide telltale information on threshold temperatures or stress levels at which the rocks' interior structure began to crack, flow, or melt. Thus, rheology holds the key to answering a fundamental question like "How deep into the crust will earthquakes occur?"

Flowing rocks

Near the surface, rocks are unconsolidated and porous. There's sufficient room to accommodate any force applied. It's like pushing a pile of sand. As a consequence, large earthquakes are infrequent.

But deeper down in the Earth, there's less excess room to accommodate strain. The stress in rocks builds up. At a threshold point, the stress surmounts the strength of the rocks' crystal structure. Bonds between atoms break suddenly. The rocks crack and slide, releasing pent-up energy. The result is an earthquake.

Deeper in the Earth, however, temperatures rise. The heat encourages some—but not all—of the atomic bonds within the rocks' crystal lattice to break, freeing atoms from their rigid atomic scaffolding to move momentarily. The atoms reorient themselves in relation to neighboring atoms, bonding with them in new alignments that actually change the shape of the crystal.

This movement of atoms within rock crystals (and the crystal shape-changing it causes) accommodates the strain on the rock, so that the stress never builds high enough to cause the rock to break. At lower temperatures, the same stress would shatter all the atomic bonds at once. At higher temperatures, the rocks "flow." At still higher temperatures the rocks liquefy, or melt.

This phenomenon of flowing rocks explains why earthquakes diminish deeper in the Earth. Along plate boundaries, such as the San Andreas Fault in California, earthquakes are restricted to depths between 3 and 15 kilometers (2 to 9 miles).

In the lab and in the ocean

To test these theories, we conduct experiments that subject various rock samples to temperatures and pressures they encounter within the Earth. By studying the microstructure of the rock samples—before and after—we can map the changes in crystal structure that accommodate different experimental strains, and we can reveal much about the processes that determine the rocks' strength and vulnerabilities.

But these experiments use samples on the scale of one's pinkie finger and take place over the course of a day. Do similar microstructural changes occur in the "real" Earth, over distances of tens of kilometers and time spans of millions of years?

To confirm our laboratory experiments, we investigated rocks collected by the Ocean Drilling Program from the Indian Ocean. With support from the National Science Foundation (NSF), we examined both undeformed rocks and the same type of rock from deeper beneath the surface, where it had been deformed by heat and pressure.

These oceanic rocks are good models for validating experimental analyses of rocks because they are freshly made, with no previous history of deformation, and then they have been rapidly exposed to cold seawater, which effectively quenches them with their microstructure preserved.

Continental rocks, in contrast, are old and have been subjected to repeated shifts and traumas and exposed to high temperatures over their long histories. All these factors modify their microstructure, often blurring and overprinting records of their deformation.

We see similar microstructural changes in oceanic rocks and in our experimental samples. That gives us confidence that the microscopic rock behavior and mechanics observed in laboratory samples can sharpen our understanding of rock dynamics on a planetary scale.

Going against the crystal grain

With this confidence (and NSF support), we have applied a rheological approach to elucidate details of many other intriguing questions about the Earth. For example, how is new ocean crust created at mid-ocean ridges? This process, which continually paves and repaves Earth's surface and creates new oceans and continents, starts on an atomic level when crystals within rocks in the mantle begin to melt.

How and when do rocks with different types of crystals melt? How does this melt dissolve the edges of other rock crystals to create pore space in which it flows? How do these microscopic rivers of molten rock coalesce, grow larger, and rise to the surface to form new oceanic crust? All these processes are ultimately controlled by basic, atomic-scale physical and chemical properties of rocks, which I have been investigating in collaboration with WHOI colleagues Wenlu Zhu, Peter Kelemen, and others. (See "Unraveling the Tapestry of Ocean Crust," page 40.)

I have also been examining another intriguing and important microscopic phenomenon of flowing rock. When rocks' symmetrical crystal lattice breaks down, crystals begin to deform and flow in a particular direction. The rocks' crystal lattice eventually realigns—not symmetrically, but oriented in the particular direction that the crystals flowed in.

The phenomenon has important implications for scientists trying to learn more about Earth's interior using a primary tool: seismic waves. Earth scientists deduce a great deal about the characteristics of rocks within the Earth by analyzing the speed of seismic waves traveling through them. But seismic waves will travel more slowly when they go against the crystal alignment, and faster when they travel in alignment with the crystal structure.

A new generation of ocean-bottom seismometers promises to lead to new discoveries about the shrouded inner workings of the inaccessible mantle. (See "Listening Closely to 'See' into the Earth," page 16.) But a more detailed understanding of mantle rheology will be critical to interpret the new seismic data most precisely.

Life thrives between the cracks

More recently, we have also been applying rheological techniques to illuminate how hydrothermal vent systems evolve. These systems occur on mid-ocean ridges, where magma from Earth's mantle rises toward the surface and heats rocks below the seafloor. (See "The Remarkable Diversity of Seafloor Vents," page 60.)

Cold seawater percolates downward through cracks in the ocean crust and is heated up. The seawater reacts chemically with the rocks to create hot, mineral-rich hydrothermal fluids that rise and are vented at the seafloor, where they provide nutrients that sustain thriving communities of deep-sea life.

Once again, this entire biogeochemical cascade of events has a rheological foundation—the cracks and conduits within ocean crust that set the stage for the process. We have been investigating the micromechanics of cracking of peridotite in the face of the hot and cold temperature contrasts it experiences.

When peridotite cracks, it creates permeable pathways for seawater to percolate downward. The water chemically reacts with peridotite to create another type of rock, called serpentinite.

Serpentinite is a more slippery substance than peridotite, which may be an important factor in causing fewer earthquakes along faults in the ocean. With my WHOI colleagues Jian Lin and Jeff McGuire, we are exploring how we can use our knowledge of earthquakes in the oceans to increase our understanding of earthquakes on land, too. (See "Earthshaking Events," page 48.)

In addition, the chemical reactions that form the serpentinite from seawater may provide critical conditions for the development of some hydrothermal vents. Thus, the micromechanics of fractures in rocks and the evolution of permeability in oceanic crust will also play a key role in exploring a new frontier: the potential for a deep biosphere of microbial life beneath the seafloor. Microcracking continually creates new mineral surfaces that are exposed to fluids and microbes—creating the sites and conditions for the biogeochemical reactions that may sustain large communities of microbes. (See "Is Life Thriving Deep Beneath the Seafloor?" page 72.)

In the Earth sciences, microscopic cracks can open entirely new vistas, and how matter flows turns out to matter quite a lot.

Tom Kleindinst, WHOI

Greg Hirth spent much of his youth enthusiastically running around the woods of Ohio and the mountains of Colorado. He went to Indiana University to study political science with an idealistic goal of changing the role of politics in environmental affairs. But he quickly changed his major to geology, motivated partly by opportunities to work in the field. In his geology textbooks, Hirth read about the research of his father, John, a material scientist. That spurred his pursuit of a Ph.D. in rock deformation at Brown University, where he met his wife, Ann Mulligan (now an Assistant Scientist in the Marine Policy Center at WHOI). Hirth came to WHOI in 1993, where he has pursued a myriad of research opportunities in the ocean, field, and lab (particularly with colleagues at MIT). He is particularly grateful for his colleagues' encouragement to go back to his roots and study geology in the field. Ann and Greg now enjoy gardening, following the fortunes of the Patriots and Red Sox, and the wilds of Cape Cod, through which Hirth also leads trips for the Cape Cod Bird Club.

The Remarkable Diversity of Seafloor Vents

Continuing explorations reveal an increasing variety of hydrothermal systems

By Margaret Kingston Tivey, Associate Scientist
Marine Chemistry & Geochemistry Department
Woods Hole Oceanographic Institution

In late summer of 1984, I anxiously awaited my first trip to the seafloor in the submersible *Alvin*. There was a delay in launching the sub, but I resisted the urge to have a drink, anticipating one final trip to the bathroom before crawling into *Alvin's* three-person, 6-foot sphere for eight hours. I was excited not only about my first chance to dive, but about visiting the home of the seafloor rocks I had long been studying for my master's thesis.

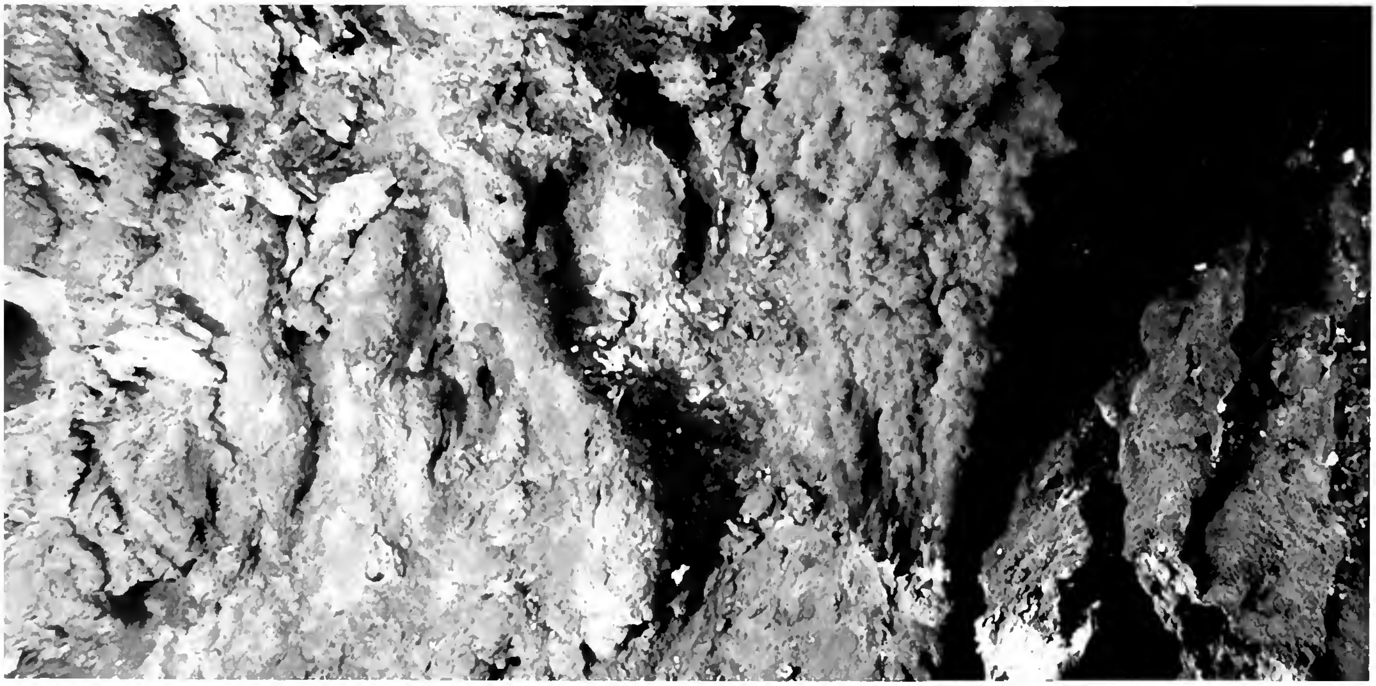
Since 1982, I had spent most of my waking hours examining pieces of seafloor vent deposits that had been recovered during a routine dredging operation along the Juan de Fuca Ridge off the Pacific Northwest coast. Expecting to find common seafloor rocks called basalts, scientists were surprised to pull up fragments and boulders of massive sulfide covered with small tubeworms. They had discovered the fifth and, at the time, newest site of hydrothermal venting on the seafloor, a place now known as the Main Endeavour Field. These rocks helped launch my scientific career.

In the years leading up to my 1984 dive, I had learned that hydrothermal vent systems played a significant role in transferring heat and mass from the solid Earth to the ocean, and that the vent sites host unusual biological communities, including tubeworms, bivalves, crabs, and fish that thrive in the absence of sunlight. It was also becoming clear that the relatively constant chemistry of the ocean was in part sustained by hydrothermal activity.

What my colleagues and I were only beginning to realize then was that hydrothermal vent systems are like snowflakes—no two are ever exactly alike.

Long-standing mysteries

When scientists in *Alvin* discovered the first active hydrothermal system in 1977 at the Galápagos Rift, they found warm fluids, later determined to be a blend of cold seawater and hot vent fluids, seeping from sea-

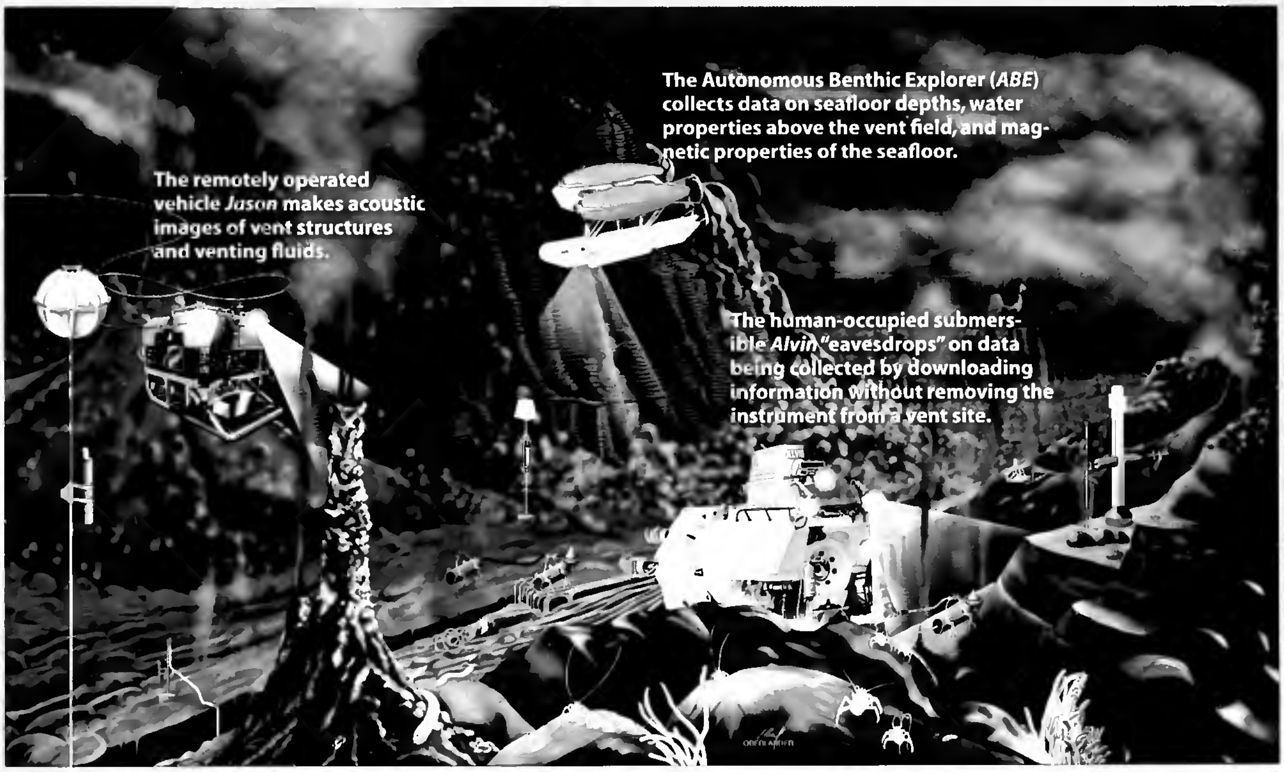


HEAT AND 'SMOKE'—*When hot hydrothermal fluid jets from the seafloor and mixes with cold seawater, fine particles of dark metal sulfides precipitate out of solution, creating the appearance of black "smoke."*

IMAX film by William Reeve and Stephen Low, Stephen Low Productions

A seafloor observatory

In 2000-2001, scientists collaborated on the most comprehensive study of a hydrothermal vent system to date, making complementary and continuous observations at the Main Endeavour Field off the Pacific Northwest coast. This schematic depiction shows the various instruments deployed and vehicles used (though the vehicles were not used simultaneously). They measured currents, pressure, vent fluid temperatures and flow rates, chemical properties, and seafloor magnetic properties. The project, funded by the National Science Foundation, is a model for future long-term seafloor observatories.



[illegible] WHOI Graphic Service

floor crust. Never-before-seen organisms were present at the vents, including large clams and tall, red-tipped tubeworms.

In 1979, a second active hydrothermal system was discovered along the East Pacific Rise. At that site, much hotter fluids (350°C) jetted from tall rock formations composed of calcium sulfate (anhydrite) and metal sulfides. When the clear hot fluid jetting from these chimney-like structures mixed with cold seawater, fine particles of dark metal sulfides precipitated out of solution, creating the appearance of black "smoke" (hence the name "black smoker chimneys.")

The discovery of these vent systems immediately answered a question long posed by geophysicists: How is heat transferred from Earth's interior to the oceans? Earlier studies had shown that, contrary to model predictions, not as much heat was being transferred by conduction (particle-to-particle transfer) near the ridge crests.

Scientists hypothesized that heat was also transferred by convection, as fluid circulated within the crust near mid-ocean ridges. Sure enough, cold seawater is entering cracks and conduits within seafloor crust. It is being heated by underlying rocks and rising and venting at the seafloor, carrying significant amounts of heat from Earth to ocean.

The chemistry of the ocean

The discovery of vents allowed scientists to begin to answer another major question: How does the ocean maintain its relatively constant chemical composition? Over time, rivers drain materials into the oceans, and winds blow in particles, some of which dissolve to add chemical elements to the oceans. Some of these elements, in turn, exit ocean waters, settling in ocean sediments, for example.

Many components of seawater—including lithium, potassium, rubidium, cesium, manganese, iron, zinc, and copper—enter the oceans via vents. They are leached from seafloor crust by subterranean chemical reactions with hot hydrothermal fluids. Other hydrothermal vent reactions draw elements out of seawater and place them back into the Earth.

For example, magnesium eroded from

land is carried to the ocean by rivers. Yet magnesium concentrations have not increased in the oceans. Scientists puzzled for decades over where all the magnesium could be going.

Scrutinizing hydrothermal vents, researchers found that seawater entering seafloor crust is rich in magnesium, but fluids exiting the vent are free of it. Oceanographers surmised that magnesium is left behind in the crust, deposited in clay minerals as seawater reacts chemically with hot rock.

Dive to Main Endeavour Field

In those early years when observations were few and samples fewer, my thesis rocks provoked considerable interest. In some ways, the rocks were similar to those recovered from the East Pacific Rise, but in other ways they were quite different.

The Main Endeavour Field samples were rich with amorphous silica, which should precipitate only if the hydrothermal fluid had cooled without mixing with seawater. And they did not contain anhydrite, a common vent chimney mineral that dissolves in seawater at temperatures less than about 150°C (302°F).

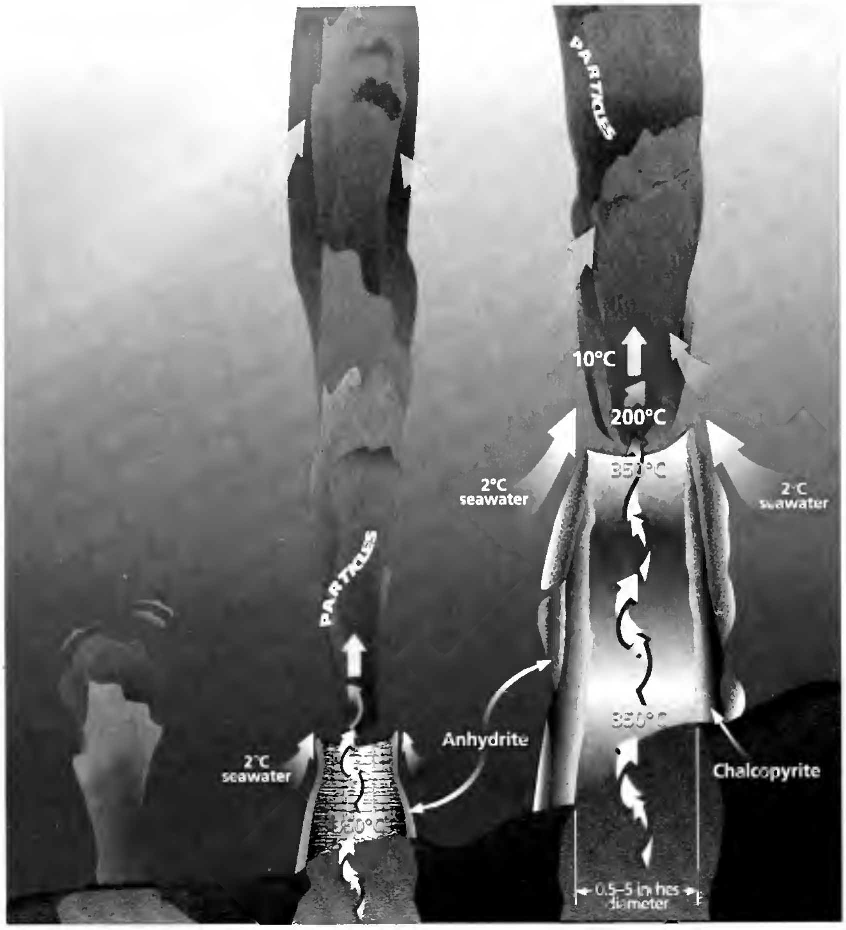
We theorized that the dredged pieces must have come from the low-lying mounds that lay beneath and around black smoker chimneys. Our dives to the Endeavour Field in 1984 would tell us if we were correct.

The trip to the seafloor took 90 minutes. As we approached the seafloor, the pilot asked me to look out my viewport and let him know when I saw bottom. *Alvin*'s lights were turned on. It was like the curtain going up in a dark theater and the stage lights going on. We were hovering over the same basaltic rocks that I had spent countless hours studying in photographs.

Then to my right, I could see a rock wall rising from the seafloor. It was obvious from the hedges of pencil-diameter tubeworms sticking out of the tops and sides of the cliffs that I was looking at large hydrothermal vent structures. The view was nothing like what had been described at the East Pacific Rise. Instead of low-

The birth of a black smoker

The key to the creation of black smoker chimneys is an unusual chemical property of the mineral anhydrite, or calcium sulfate ($CaSO_4$). Unlike most minerals, anhydrite dissolves at low temperatures and precipitates at high temperatures greater than ~150°C (302°F).



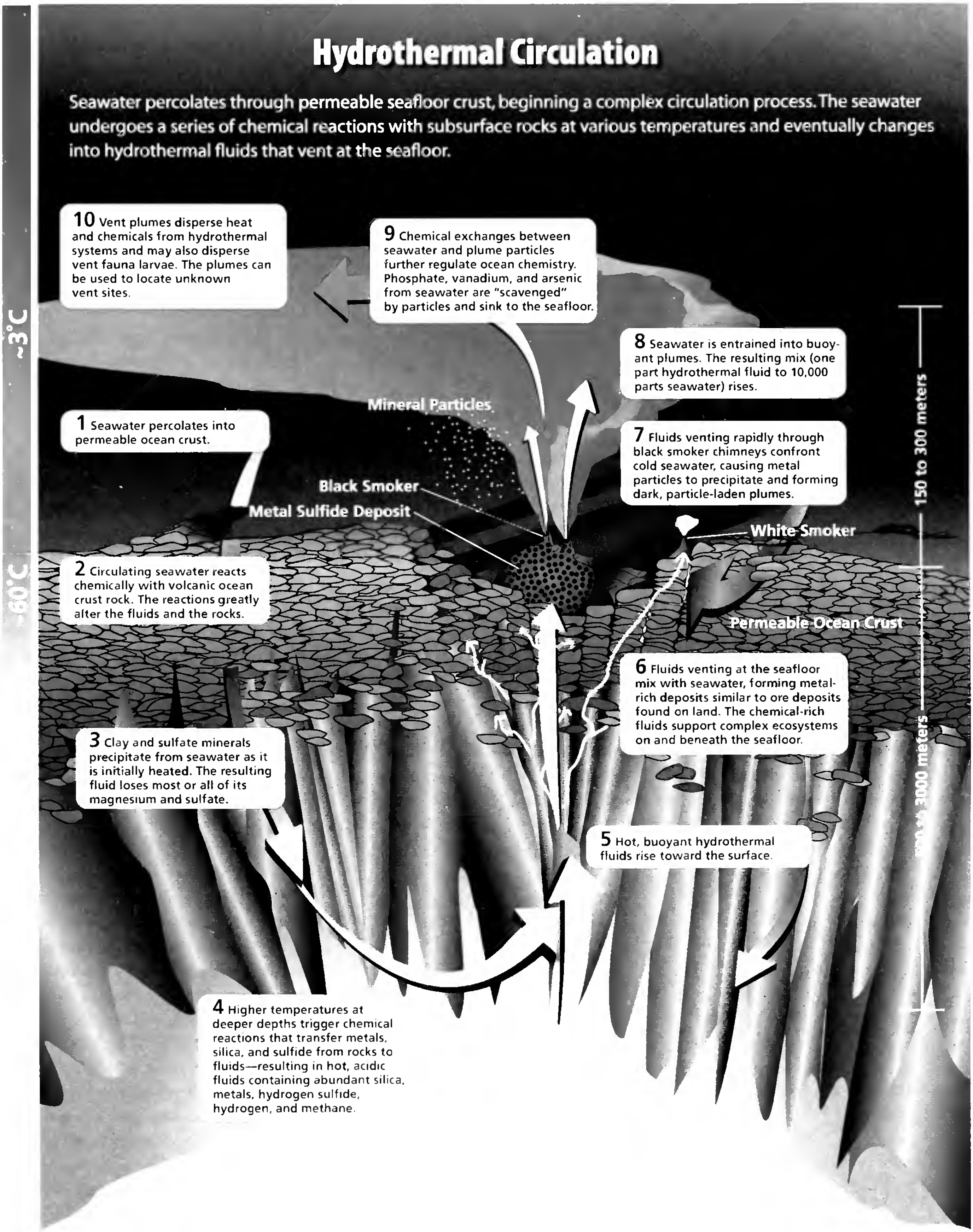
1 *350°C hydrothermal fluid (containing dissolved Ca^{2+} ions) exits the seafloor and mixes with cold seawater (containing dissolved Ca^{2+} and SO_4^{2-} ions). A ring of anhydrite precipitates around a vent opening and the jet of hot fluid.*

2 *Hydrothermal fluid and seawater mix through the nascent anhydrite wall around the vent opening. Sulfide and sulfate minerals precipitate within pore spaces of the wall, which gradually becomes less permeable. The anhydrite wall also provides a substrate, or foothold, on which other minerals can precipitate.*

3 *Different minerals precipitate at different temperatures. Chalcopyrite is deposited against the inner wall, which is adjacent to 350°C hydrothermal fluid. Anhydrite, iron, copper-iron, and zinc-sulfide minerals (such as pyrite, marcasite, bornite, sphalerite, wurtzite) precipitate at lower temperatures within pore spaces of the chimney wall.*

Hydrothermal Circulation

Seawater percolates through permeable seafloor crust, beginning a complex circulation process. The seawater undergoes a series of chemical reactions with subsurface rocks at various temperatures and eventually changes into hydrothermal fluids that vent at the seafloor.



1 Seawater percolates into permeable ocean crust.

2 Circulating seawater reacts chemically with volcanic ocean crust rock. The reactions greatly alter the fluids and the rocks.

3 Clay and sulfate minerals precipitate from seawater as it is initially heated. The resulting fluid loses most or all of its magnesium and sulfate.

4 Higher temperatures at deeper depths trigger chemical reactions that transfer metals, silica, and sulfide from rocks to fluids—resulting in hot, acidic fluids containing abundant silica, metals, hydrogen sulfide, hydrogen, and methane.

5 Hot, buoyant hydrothermal fluids rise toward the surface.

6 Fluids venting at the seafloor mix with seawater, forming metal-rich deposits similar to ore deposits found on land. The chemical-rich fluids support complex ecosystems on and beneath the seafloor.

7 Fluids venting rapidly through black smoker chimneys confront cold seawater, causing metal particles to precipitate and forming dark, particle-laden plumes.

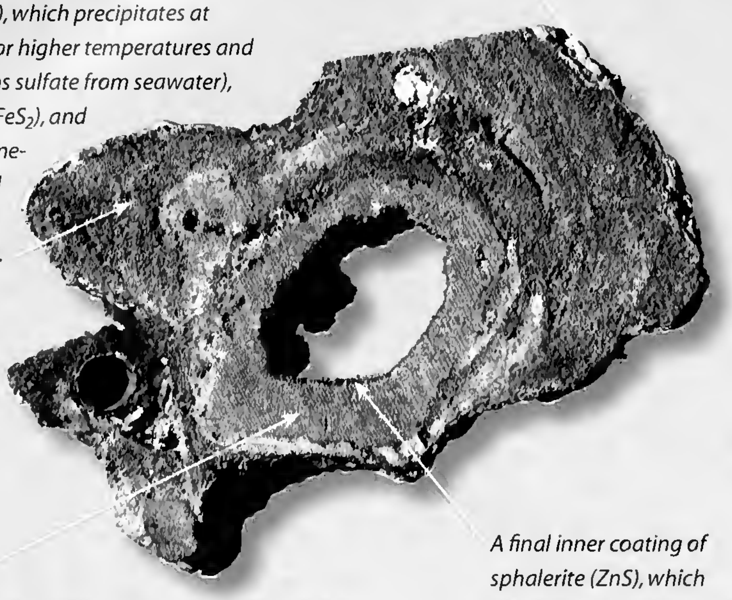
8 Seawater is entrained into buoyant plumes. The resulting mix (one part hydrothermal fluid to 10,000 parts seawater) rises.

9 Chemical exchanges between seawater and plume particles further regulate ocean chemistry. Phosphate, vanadium, and arsenic from seawater are "scavenged" by particles and sink to the seafloor.

10 Vent plumes disperse heat and chemicals from hydrothermal systems and may also disperse vent fauna larvae. The plumes can be used to locate unknown vent sites.

Cross section of a black smoker chimney

As hydrothermal fluid vents from the seafloor and interacts with seawater, different minerals precipitate at different temperatures, creating a multi-layered chimney.



Outer layers contain a mixture of minerals that precipitate at lower temperatures, including anhydrite ($CaSO_4$), which precipitates at 150°C or higher temperatures and contains sulfate from seawater), pyrite (FeS_2), and other fine-grained metal sulfides.

Iron sulfides on the outer wall are exposed to oxygen in seawater and are oxidized to form iron oxides.

The initial chimney structure restricts mixing with cold seawater. Chalcopyrite ($CuFeS_2$), which precipitates at >300°C, is deposited on the inner walls.

A final inner coating of sphalerite (ZnS), which precipitates at ~300°C, can form as hydrothermal fluids cool.

Tom Kleindinst, WHOI Graphic Services

lying mounds of sulfide debris topped by active smokers, we saw steep-sided structures standing 15 meters (50 feet) high.

Why was this site so very different? How could these chimneys stand there like multistory buildings without collapsing?

A fluid environment

Answers to these questions came from studying new samples. We learned that the tall chimneys structures were essentially "cemented"—silica had filled pores in the vent structure walls as the emerging fluids cooled, making the structures sturdy. But why was so much silica precipitating at this site?

The fluid chemistry provided answers: This vent site's fluids were rich in ammonia (NH_3). As the ammonia-rich fluids cool, NH_3 takes up excess H^+ ions to form NH_4, which raises the pH of the fluids. The higher pH likely allows silica to precipitate within Main Endeavour Field structures; at sites with no NH_3, low pH probably inhibits the formation of amorphous silica.

As with almost every visit to a new vent site, our survey of the Main Endeavour Field raised as many questions as it answered. The differences among known hydrothermal systems and the revelations that accompanied each new discovery provoked oceanographers to hunt for new sites. We were explorers trying to learn as much as we could. Hypotheses were advanced, only to be proven wrong by yet another discovery.

More visits to these seafloor hot springs made it clear that all vent fluids are not the same. Rather, the chemical composition changes from ridge to ridge—and from time to time.

Researchers returning to some vents found that the chemistry of vent fluids was not constant, changing on scales ranging from days to years. These vent sites were all associated with sites of recent magmatic activity, with recorded earthquakes and evidence that dikes had been intruded into the ocean crust and, at some sites, that lava had been extruded onto the seafloor. The vent fluid compositions were changing as these dikes cooled, and as fluids penetrated deeper into the crust.

Searching for new vents

In the early 1980s, after a number of vent sites had been found in the Pacific, scientists began to wonder if hydrothermal activity and active black smokers might exist on the more slowly spreading Mid-Atlantic Ridge. The hydrothermal vent systems transfer large amounts of heat from magma or newly solidified hot rock, but on slow-spreading ridges the spreading rate, and magma delivery rate, are much less (about one-third) of those on the northern East Pacific Rise and Juan de Fuca Ridge.

To our surprise, exploration from the mid-1980s through the early 1990s gradually made it clear that hydrothermal systems may be spaced farther apart on the Mid-Atlantic Ridge, but they tend to generate much larger mineral deposits. Expeditions to the Southwest Indian Ridge in 2000 and the Gakkel Ridge (under the Arctic Ocean) in 2001 revealed that hydrothermal venting occurs on even the slowest-spreading portions of the mid-ocean ridge system.

New ways to find vents

Two decades of study have taught us that there is no single type of seafloor hydrothermal vent system. The plumbing systems beneath the seafloor are both diverse and incredibly complex.

Ocean scientists today are posing questions about the dimensions and evolution of the hydrologic systems beneath vent sites. We puzzle over how hot these fluids get, how deep into the crust they descend, and how far they travel before venting at the seafloor. And where does seawater enter these systems?

To answer these questions, we will need to continue exploring, not only over geographic space, but also over time. In the early years, most vents were discovered serendipitously; but as we've explored and learned more about these systems, we've been able to develop systematic methods for pinpointing sites.

For example, a technique of "tow-yowing" has been developed, in which a conductivity-temperature-depth (CTD) sensor is raised and lowered through the water column in a sawtooth pattern above the ridge to map the locations of plumes, and then to home in on and map the buoyant portion of plumes coming directly from active vent sites. This technique was used successfully to find vent sites in the Pacific and Atlantic, and most recently in the Indian Ocean.

Seafloor observatories

The need to explore the dynamics of hydrothermal systems over time has led to new technologies and the development of seafloor observatories. New, more precise and durable instruments allow us to monitor temperature and fluid chemistry at vent sites for hours, days, or months—as opposed to observing those properties for brief moments and grabbing one-time samples.

The future of hydrothermal studies was displayed in a recent series of coordinated experiments. With support from the National Science Foundation's Ridge Interdisciplinary Global Experiments (RIDGE) program, a team of researchers built a seafloor observatory on the Endeavour segment of the Juan de Fuca Ridge.

During the summers of 2000 and 2001, scientists made complementary and continuous observations centered around the Main Endeavour Field (the same site I first visited in 1984) and at vent sites to the north and south. The program goals included making more accurate measurements of the heat and mass flowing from the system, and observing how the hydrothermal plumbing is influenced by tides and by high-temperature reactions that separate elements into saltier liquids and more vapor-rich fluids (a process called "phase separation").

Instruments were deployed to continuously monitor vent fluid temperatures, flow rates, and chemical properties. Scientists also used newly developed samplers to collect fluids at regular time intervals. While these instruments were in place, other researchers made acoustic images of vent structures and venting fluids. Still others used the Autonomous Benthic Explorer (*ABE*) to measure seafloor depths, magnetic signatures, and water column properties above vent fields.

Later in the program, the team deployed a systematic array of current meters, thermistor strings, magnetometers, and tilt meters. Scientists even tested techniques to "eavesdrop" on the data being collected and download it without removing the instrument from the vent. The result of this collective effort was the most comprehensive study of a hydrothermal system to date, and a model for future seafloor observatories.

A continually unfolding story

As we develop these new techniques and instruments, our ability to explore ongoing seafloor processes will grow. More than a quarter-century into our studies, we still find ourselves constantly revising and refining our ideas about hydrothermal systems.

At the same time, as we home in on the fine details of how these systems work, we continue to find new sites that completely break the mold. As recently as December 2000, researchers diving in the Mid-Atlantic discovered "Lost City," a vent site located far away from the ridge axis, on old rather than nascent seafloor crust, and with 15-story-high white minaret-like structures made of carbonate—a mineral that is not found at most other known vent sites.

So after 32 dives to the seafloor to study vents, I am often still surprised, and I am always awed. Even when I return to a vent site that I've visited before, I still find it an unbelievably beautiful sight to watch jets of hot fluid mixing with seawater, and unusual organisms that make their homes near these vents. Like my colleagues, I look for ways to make our studies more precise, more methodical, and more continuous. But 20 years after my first dive, I still enjoy seeing it all live. It's the difference between watching a movie of a waterfall and standing next to one.

Lucinda Gathercole, WHOI

Margaret Kingston (Meg) Tivey, an aqueous geochemist, combines laboratory, theoretical, and field studies to examine the formation of seafloor vent deposits and the transfer of energy and mass through active hydrothermal systems. Born and raised in Lexington, Mass., she majored in geology at Stanford University (after taking a course with five field trips to local beaches and fault zones). As a graduate student at the University of Washington, she was first introduced to seafloor hydrothermal systems when massive sulfide samples with live tubeworms were recovered while dredging along the Juan de Fuca Ridge—only the fifth discovery of an active mid-ocean ridge hydrothermal system. Working on these samples, she received an M.S. in geological oceanography in 1983. In 1984 she had her first opportunity to dive in Alvin, *and shifted her dissertation to develop a theoretical model to link measured vent fluid compositions to observed mineral assemblages in vent deposits. After receiving her Ph.D. in 1988, she came to WHOI, where she is now an Associate Scientist, studying active vent sites throughout the world using both human-occupied submersibles and remotely operated vehicles. Her studies are aided by X-ray computed tomography (CAT scans) to examine samples of mineral deposits in three dimensions; development and use of numerical models to link vent fluid compositions to vent deposit mineralogy; and collaboration with engineers to develop, build, and use instruments capable of making measurements in the high-temperature and low-pH conditions present at vent sites.*

When Seafloor Meets Ocean, the Chemistry Is Amazing

In more and more places, scientists are finding vast amounts of natural gas on the ocean bottom

By Jean K. Whelan, Senior Research Specialist
Marine Chemistry and Geochemistry Dept.
Woods Hole Oceanographic Institution

Far more natural gas is sequestered on the seafloor—or leaking from it—than can be drilled from all the existing wells on Earth. The ocean floor is teeming with methane, the same gas that fuels our homes and our economy.

In more and more locations throughout the world's oceans, scientists are finding methane percolating through the seafloor, bubbling into the water column, collecting in pockets beneath seafloor sediments, or solidifying in a peculiar icelike substance, called methane hydrate, in the cold, pressurized depths of the ocean.

Massive deposits of methane hydrates could prove to be abundant reservoirs of fuel. But in the past, these massive storehouses of methane also may have "thawed" suddenly and catastrophically, releasing great quantities of climate-altering greenhouse gas back into the atmosphere.

In some places, seeping methane sustains thriving communities of exotic organisms that harness the gas as an energy source in their sunless environment. Below the seafloor, an unknown but potentially vast biosphere of microbes

A BUBBLING, LIFE-SUSTAINING BREW—Evidence is steadily growing that methane seeping and bubbling from the seafloor is a widespread, but previously overlooked, natural phenomenon. It can sustain communities of seafloor life, like these mussels in the Gulf of Mexico.

FUEL FROM THE DEPTHS?—Methane, the same natural gas that we use as fuel, solidifies in the cold, pressurized depths. It is encapsulated by frozen water to form an icelike substance called methane hydrate, which could prove to be an abundant source of energy in the future.

may be making the methane that percolates upward. (See "Is Life Thriving Deep Beneath the Seafloor?' page 72.)

Other places on the seafloor show evidence that pockets of gas trapped beneath sediments have exploded to form "mud volcanoes," or may have triggered seafloor avalanches and tsunami waves.

An underestimated phenomenon

Until recently, scientists have largely overlooked seafloor methane and its potentially dramatic impacts. The problem is that methane commonly vents out of isolated cracks in the seafloor—some so small that they are easily missed by oceanic surveillance systems. Once out into the ocean, the methane usually is diluted rapidly by seawater, or it dissolves in seawater and is consumed by microorganisms that convert it metabolically into carbon dioxide. Unless you happen to be looking in the right place at the right time, you'll miss the show.

But evidence has steadily accumulated that natural seepage of methane from the seafloor is a large, continuous, and ubiquitous phenomenon. When oceanographers happen upon these vents (often called "cold seeps"), the scene is often spectacular.

Several researchers have documented large craters or pockmarks on the seafloor, while others have described huge carbonate mounds (formed by organisms that ingest methane and produce carbonate). Both are often relics of past seafloor gas venting. Sometimes gas simply seeps from the ocean floor and sustains communities of unusual tubeworms, mussels, and other creatures like those found at hydrothermal vents. (See "The Evolutionary Puzzle of Seafloor Life," page 78.)

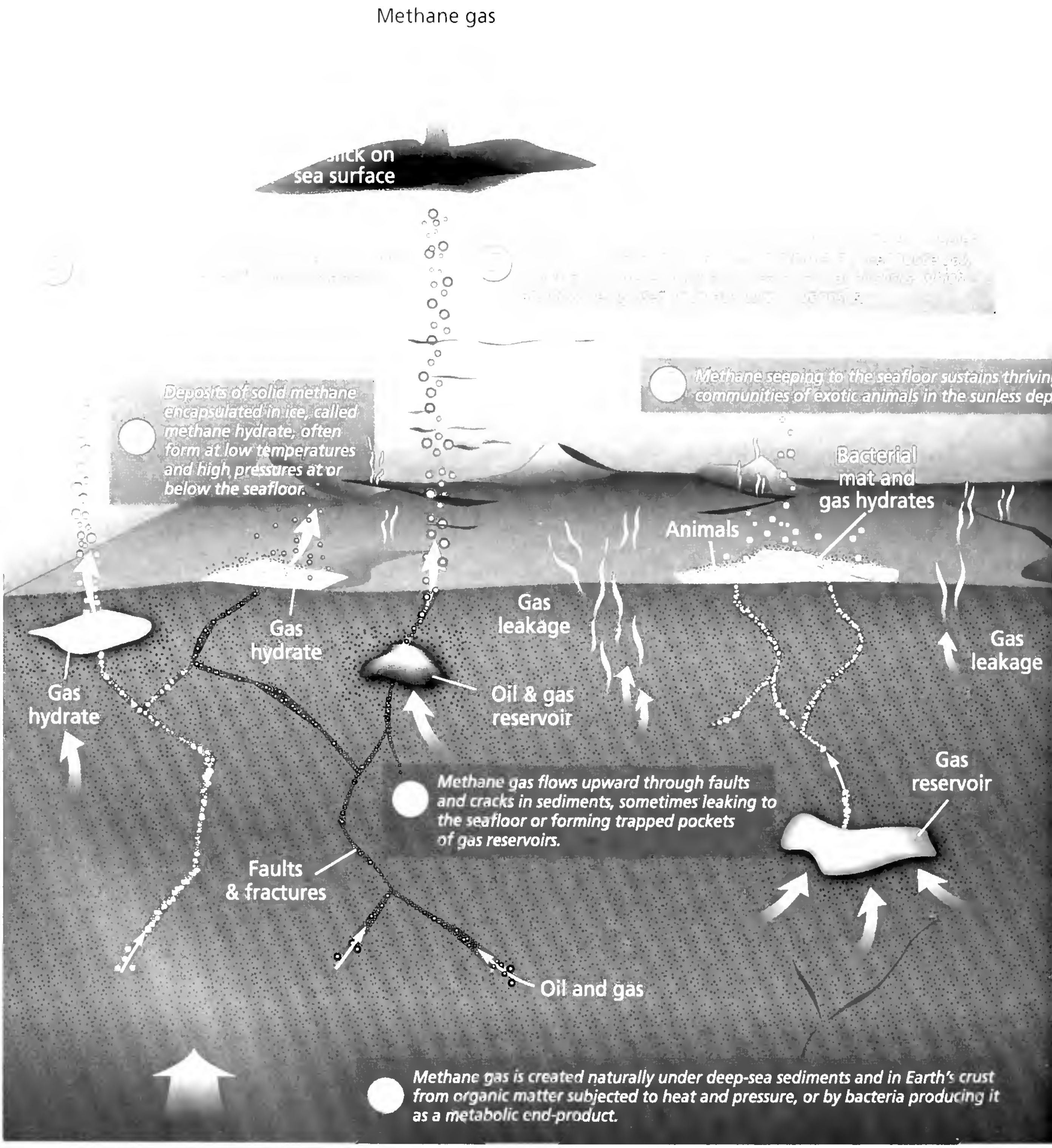
Gas frozen solid at the seafloor

The deep ocean floor around gas seep sites is often covered by methane hydrates. These are solid crystals of methane encapsulated in ice, which form under the low temperatures and high pressures typical of ocean depths greater than about 1,500 feet.

These hydrates look like seafloor car-

Photos in this article Copyright Woods Hole Oceanographic Institution and the BBC Natural History Unit, courtesy of the WHOI Advanced Imaging and Visualization Laboratory and *Johnson-Sea-Link* submersible, Harbor Branch Oceanographic Institution

The seafloor is teeming with methane



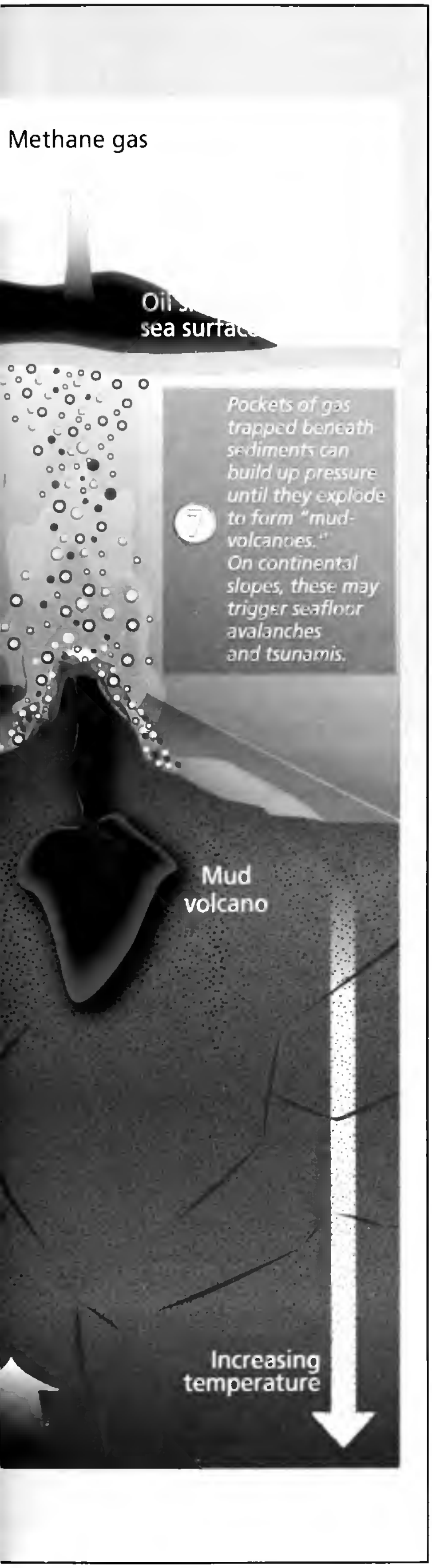
Deposits of solid methane encapsulated in ice, called methane hydrate, often form at low temperatures and high pressures at or below the seafloor.

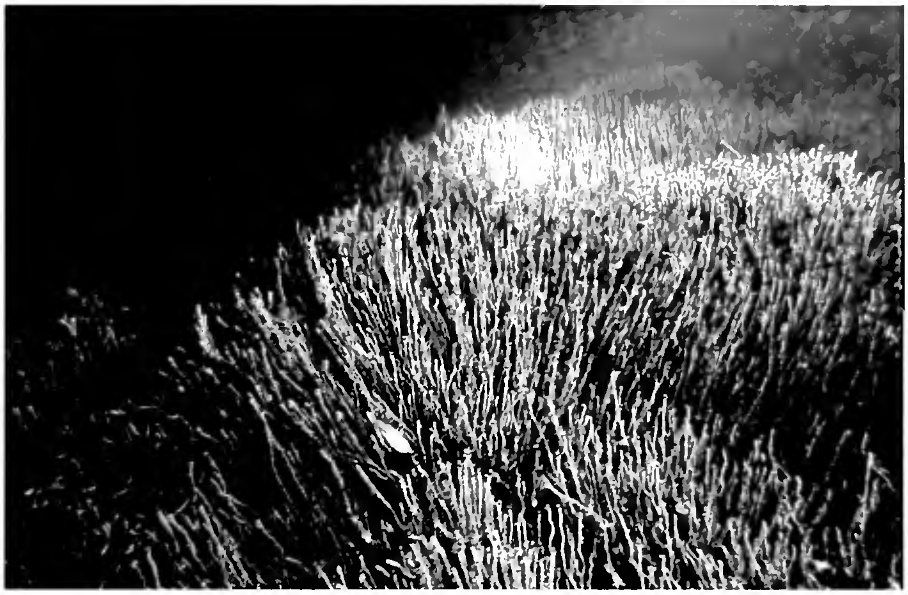
Methane seeping to the seafloor sustains thrivin
communities of exotic animals in the sunless dep

Methane gas flows upward through faults and cracks in sediments, sometimes leaking to the seafloor or forming trapped pockets of gas reservoirs.

Methane gas is created naturally under deep-sea sediments and in Earth's crust from organic matter subjected to heat and pressure, or by bacteria producing it as a metabolic end-product.

Scientists are discovering that abundant quantities of methane gas are continually seeping from the seafloor throughout the oceans. This widespread but overlooked natural phenomenon has potentially dramatic implications on world energy supplies, life in the oceans, and Earth's climate.





FED BY METHANE, LIFE FLOURISHES—Methane seeping from the seafloor sustains microbes that serve as the base of the food chain for communities of animals, like these tubewarms, which thrive in the sunless depths in the Gulf of Mexico.

bonate, but when chunks are broken off, methane hydrates float upward (carbonates sink). As those hydrates rise into higher temperatures and lower pressures, they decompose, releasing methane gas into the ocean—a process akin to releasing the pressure on a bottle of soda.

Energy companies have been eyeing methane hydrates as a potentially tremendous new source of natural gas. Since the 1930s, the use of natural gas has increased fivefold to account for more than 25 percent of the world's energy consumption. With existing technology, the world gas supply is estimated to be 5,300 trillion cubic feet (tcf), Robert Kleinberg of Schlumberger and Peter Brewer of Monterey Bay Aquarium Research Institute reported in *American Scientist*. At the current rate of global consumption (about 85 tcf per year), a 60-year supply remains.

But the amount of gas at various locations around the world varies widely. Russia and the Persian Gulf each have about 1,700 tcf, while the total for North America is about 260 tcf. Japan and Europe import nearly all of their natural gas, while India and China have very small domestic reserves.

A potential new energy resource

The untapped well of methane hydrates holds the promise of energy independence for nations close to oceans or permafrost regions (where conditions and consistently cold temperatures also create methane hydrates). Offshore methane hydrates would provide the U.S. alone an estimated potential natural gas reserve of 300,000 tcf. Projections of hydrate gas reserves in the ocean south of Japan are 2,000 times that country's very small existing natural gas reserves, according to Kleinberg and Brewer.

Most of the world's gas hydrates are sequestered in the deep ocean, presenting great challenges for potential commercial production. Hydrates dissolve quickly when removed from the unique conditions on the ocean bottom, so researchers must figure out how to either stabilize them or produce and transfer fuel directly from the seafloor.

Many known deep-water deposits, such as the Blake-Bahamas Plateau off the Carolinas, are very diluted or spread across relatively thin layers over wide areas, making them very difficult to "mine" economically. And deep-sea hydrates are often associated with complex biological communities

*STANDING TALL—Dense colonies of tubeworms (*Lamellibrachia luymesi*) aggregate around a cold seep site in the Gulf of Mexico. They form the seafloor equivalent of hedges that provide habitat for many other invertebrates, such as mussels, crabs, shrimp, and snails.*

that would be disrupted or destroyed by gas extraction and production.

Recharged oil wells

Recent work by a number of laboratories suggests that free gas streaming through the seafloor or seafloor hydrate deposits may constitute yet another large oceanic methane source. On the northern continental slope of the Gulf of Mexico, for instance, a process known as "gas washing" fills subsurface petroleum reservoirs with natural gas that flows upward from even deeper reservoirs in the Earth's crust.

It has been estimated that less than 2 percent of generated oil and gas ever makes its way into commercial reservoirs. Of the residual oil, about half remains dispersed in the source rock and sediments.

The residual oil and organic matter in deeper sediments is subjected to more heating and natural processing and is broken down into natural gas. The gas streams upward, washing out clogged pore spaces and recharging many fuel reservoirs. Evidence comes from oil wells in the northern Gulf of Mexico, where we have observed significant changes in oil compositions over time scales as short as 10 years. The wells continue to produce long after their expected lifetimes.

The other half of the residual oil leaks upward and out of the sediments into ocean bottom waters. Remarkable satellite photographs of the Gulf of Mexico and other regions reveal slicks extending for miles in areas where no oil production is occurring. Similar photographs are now being used to locate new oil and gas accumulations.

Methane-making microbes

Beyond the geological "cooking and squeezing" processes that produce petroleum and gas, large quantities of gas also are being produced biologically. Many gas hydrate accumulations and ocean-floor gas seeps consist of methane largely derived from microorganisms.

Bacteria living in oxygen-poor areas beneath deep-sea sediments on the seafloor produce methane as a major product of their metabolism. Some models suggest that bacteria in sediments may account for 10 percent of the living biomass on Earth. In addition, microbial communities beneath the seafloor, whose numbers are entirely unknown, may also be producing vast amounts of methane.

Global warming and tsunamis

The pervasive and ongoing movement of methane gas—from seeps, decomposing hydrates, gas washing, and microbial sources—leads to some fascinating phenomena and important questions.

Methane is a greenhouse gas that traps heat about 20 times more effectively than carbon dioxide. If methane deposits and seeps prove to be ubiquitous in the oceans, they are a potentially significant contributor to global warming.

Relatively modest changes in global

PLUMES UNFURLED—Like flower petals atop stems, feather-like red plumes poke out of the tops of the tubeworms' thin, white tubes, which reach about 50 centimeters (20 inches) high. The plumes act like gills, absorbing nutrients from seawater.

ocean temperatures or sea level could trigger a massive release of oceanic methane. If a change in ocean bottom pressure or a rise in water temperatures passes a certain threshold, sizable methane hydrate deposits could decompose rapidly and release a large quantity of heat-trapping gas back into the atmosphere. This scenario has been proposed as a possible cause for some past episodes of rapid global warming.

Evidence from the past suggests that upward-seeping methane may pose another threat: underwater avalanches. Landslides at the edge of the continental slope just off the East Coast of the United States may have been triggered by pockets of methane gas that had built up pressure under a lid of overlying sediments and exploded. Similar landslides today might generate tsunamis that would hit the U.S. coast. An offshore oil-drilling platform that accidentally hit such a gas pocket would also be endangered.

A wide-open new field

Many challenges remain ahead for researchers. Methane seeps are widely distributed around the world's oceans, yet their discovery remains mainly serendipitous. The volume of oil and gas seeping to the floor throughout the world's oceans is also unknown, as most of the seafloor remains unexplored.

Even in the cases of known seeps—especially those found in and around known oil and gas fields—data on the rates of seepage are scarce. Yet evidence suggests that gas seeps and methane hydrate deposits may be even more pervasive than their known extent today and may play a fundamental role in regulating ocean chemistry, sustaining marine life, and shaping seafloor geology.

Tom Kleindinst, WHOI

Jean Whelan earned her bachelor's degree in chemistry at the University of California, Davis, and her doctorate in organic chemistry from the Massachusetts Institute of Technology. Before coming to WHOI, she carried out post-doctoral work at Brandeis University and taught chemistry at Fairleigh Dickinson University in Madison, N.J. She studies how to use organic compounds to deduce geological processes. Among her research focuses are the formation and migration of petroleum, and she and colleagues have shown that large quantities of gas flowing through some of the world's oil and gas fields may be continuously altered and sometimes refreshed by pools of hydrocarbons that lie deep within the Earth. Current research focuses on how this gas seeping also affects the ocean. When she is not in her lab (or sometimes when she is), she loves to sing. A contralto, she has sung both as a choir member and a soloist with many Cape Cod choruses and chamber groups, as well as with her church choir.

Is Life Thriving Deep Beneath the Seafloor?

Recent discoveries hint at a potentially huge and diverse subsurface biosphere

By Carl Wirsen, Oceanographer Emeritus
Biology Department
Woods Hole Oceanographic Institution

In 1991, scientists aboard the submersible *Alvin* were in the right spot at the right time to witness something extraordinary. They had sailed into the aftermath of a very recent volcanic eruption on the seafloor and found themselves in a virtual blizzard.

They were densely surrounded by flocs of white debris, composed of sulfur and microbes, that drifted more than 30 meters above the ocean bottom. The seafloor was coated with a 10-centimeter-thick layer of the same white material.

This vast volume of microbes did not come from the ocean. The eruption had flushed it out from beneath the seafloor.

The discovery was transforming. It strongly suggested that previously unimagined and potentially huge communities of microbial life were thriving in the dark, increasingly hot, oxygen-depleted rocky cracks and crannies below the ocean bottom. An abundance of life apparently flourished in conditions we had considered too extreme. It shattered our narrow preconceptions and stretched our view of the places and circumstances that can harbor life.

'Everything is everywhere'

With our horizons expanded, we have launched new initiatives in the past decade to search for life deep within the Earth—to

Rachel Haymon, UCSB, and Dan Fornari, WHOI/WHOI National Deep Submergence Facility/Alvin Operations Group

A MICROBIAL BLIZZARD—In 1991, scientists aboard the submersible Alvin *witnessed the aftermath of a very recent volcanic seafloor eruption and found themselves in a torrent of white debris. The eruption flushed huge flocs of microbes (and white sulfur filaments created by the microbes) out of subsurface crevices and discharged them from the seafloor. The discovery pointed to previously unsuspected and potentially huge communities of microbes living beneath the seafloor.*

explore the so-called subsurface biosphere. In recent years, scientists have discovered many new subsurface biosphere habitats—reaffirming the principle of the pioneering microbiologist Martinus Willem Beijerinck (1851-1931), who said, "Everything is everywhere, the environment selects." Beijerinck's approach—to study "the relation between environmental conditions and the special forms of life corresponding to them" —certainly applies to the subsurface realm, where biology and microbiology interact with geology and hydrology.

What organisms inhabit this deep biosphere? How deep are they living? How long can they survive under these conditions? How have they adapted to take advantage of energy supplied by the planet, rather than by the sun?

What impact, in turn, does this biosphere have on the oceans and the planet? What can these hardy entrepreneurial organisms teach us about the origin and evolution of life on Earth? How can they guide our search for life on other planetary bodies?

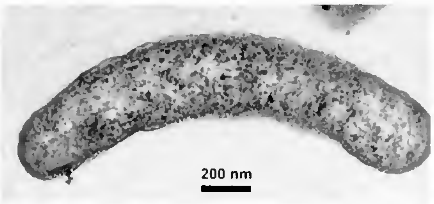
We are at the frontiers of answering these questions.

Better living through chemistry

The amazing discovery of life at seafloor hydrothermal vents in 1977 reminded us that solar energy, oxygen, organic matter, and photosynthesis are not the only fundamental building blocks and chemical processes that foster life.

In place of energy from the sun, certain organisms use chemosynthetic reactions to live and grow. They use inorganic chemicals, such as hydrogen and hydrogen sulfide, rather than organic matter for their energy and carbon dioxide as their source of carbon. Geothermal, rather than solar, energy catalyzes chemical reactions that generate life-sustaining chemicals from rocks and seawater. Water is the only absolutely essential ingredient.

But it was reasonable to assume that conditions below the seafloor and deeper into the subsurface would become more extreme and life would become sparser or nonexistent. Yet in the past decade we have found an extraordinary diversity of subsurface microbes living in a wide range of conditions—buried deep within ocean sediments, in hot ocean crust crevices, in frozen polar soils, and in the subterranean bowels of deep mines.



Craig Taylor & Carl Wirsen, WHOI

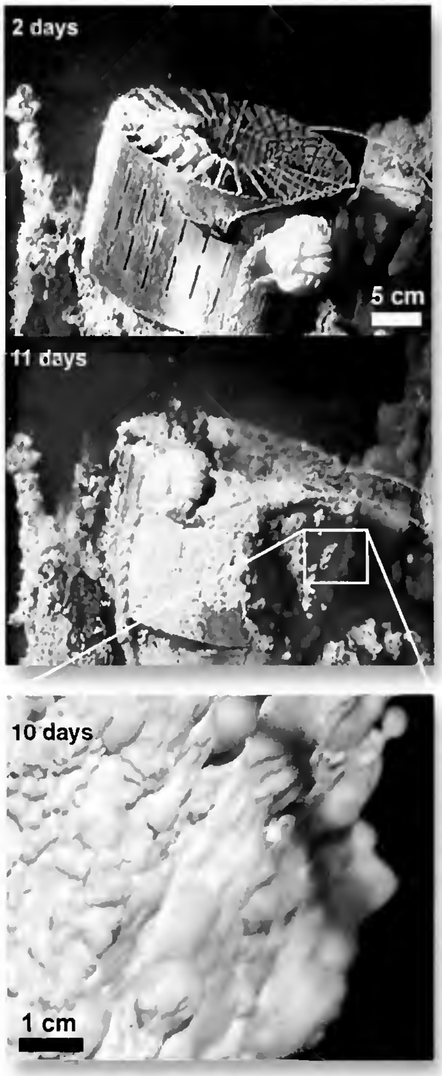
Examining the white flocs discharged from the 1991 seafloor eruption, WHOI scientists discovered a new genus of bacteria called Arcobacter. *It lives in low-oxygen conditions and metabolizes hydrogen sulfide to obtain energy. An end-product of this metabolism is a unique form of sulfur, which the bacteria excrete in the form of solid, white filaments.*

In all these places, individual species have adapted to extreme conditions that include high pressure, high and low temperatures, unusual or toxic chemicals and minerals, or low availability of essential nutrients. Often they take advantage of specific extreme conditions to carve out a niche where they can thrive and other species cannot.

Life finds a way—often cleverly

Take, for example, the mats of white microbial sulfur debris witnessed by scientists aboard *Alvin* in 1991. WHOI Associate Scientist Craig Taylor and I subsequently found that such mats are produced by a genus of bacteria called *Arcobacter*. It lives in low-oxygen conditions and metabolizes hydrogen sulfide (H_2S) to obtain energy. An end-product of this metabolism is a unique form of sulfur, which the bacteria ingeniously excrete in the form of solid, white filaments.

Together, large populations of these bacteria produce crosshatched mats of these filaments. In the face of flowing subsurface hydrothermal fluids, these mats help keep the bacteria anchored to rocky surfaces where *Arcobacter* are perfectly suited. They are bathed in hydrothermal fluids percolating from the ocean crust, which are low in oxygen and high in hydrogen sulfide. In this niche, *Arcobacter* feasts on ample H_2S-rich fluids and outcompetes other oxygen-respiring bacteria.



Craig Taylor and Carl Wirsen, WHOI, and Françoise Gaill, Université Pierre et Marie Curie, Paris, France

A titanium ring deployed at a Pacific hydrothermal vent site indicates the presence of bacteria thriving beneath the seafloor. Within days, Arcobacter *bacteria, discharging from the subsurface, rapidly colonize the ring, producing a white sulfur filament mat up to 3 centimeters thick as they grow.*

It turns out that these discharged bacterial mats may also provide an important carpeting around hydrothermal vents that attracts other animals, such as *Alvinella* tubeworms, and encourages them to settle and grow. And when we looked closer to home, we found *Arcobacter* bacteria in sediments in the shallow depths of Eel Pond in Woods Hole that grow and produce the same sulfur filaments as those at the deep-sea vents.

The world's largest bacterium

Remarkable microbial adaptations like this seem to be common nearly everywhere we look. In 1999, far from any undersea volcanic areas, the world's largest bacteria were identified by an international scientific team that included former WHOI microbiologist Andreas Teske, who is now at the University of North Carolina. They were found in the surface layers of ocean sediments off the coast of Namibia, where they find what they need: hydrogen sulfide for energy and nitrate to respire.

This bacterium, *Thiomargarita namibiensis* ("Sulfur pearl of Namibia") reached sizes up to 750 microns (normal bacteria are only 1 to 2 microns). It was so large it could be seen with the naked eye, and it shattered our conventional wisdom that inherent bacterial physiology prevented them from ever getting so big. Their size is due to a large vacuole in their cells, in which they store nitrate, as do some hydrothermal vent microbes, to survive periods when oxygen is lacking—much the way we might store oxygen in external SCUBA tanks to remain alive under water.

Deep, dark, old, and cold

Arcobacter and *Thiomargarita* are examples of well-adapted bacteria found in the shallow subsurface. But deeper subsurface explorations in the past decade have revealed unique, heretofore unknown microbial habitats.

Some of the first investigations of the deep subsurface were motivated by concerns about pathogens and toxic chemicals in groundwater supplies. The Witwaterstrand Deep Microbiology Project, for example, a multinational effort led by Swedish scientists, sampled groundwater in fractured rock from 3-kilometer-deep gold mines in South Africa and found a wealth of microbial diversity in the deep continental crust.

In 2000, researchers from West Chester (Penn.) University claimed to have discovered the oldest-known living microorganism in an ancient salt deposit in New Mexico, buried 610 meters (2,000 feet) below ground. It was trapped in a tiny brine-filled pocket that formed in a salt crystal 250 million years ago. Long after the dinosaurs became extinct 65 million years ago, it lay in a dormant state, waiting for the right conditions to "awaken" its genetic machinery and resume growing and reproducing, the researchers said.

In the Arctic and Antarctic, scientists have found metabolically active microbes in subsurface permafrost frozen at temperatures of −10°C (14°F) or colder for 2 million to 3 million years. High populations of viable microbes have been found in oceanic sediment cores deeper than a half-kilometer, which would make them older than 10 million years.

Some like it hot

Ultimately, a combination of physical and chemical factors will set the limits at which life can exist. In general, increasing pressure will not limit the depth at which subsurface life is found. Increasing heat is the primary limiting factor, and it is doubtful that we have discovered the maximum temperature at which life can exist.

At hydrothermal vents, volcanic heat has created an environment in which hyperthermophilic (super-heat-loving) microbes thrive. The maximum growth temperature for a microorganism so far was discovered in 2003 by scientists at the University of Massachusetts. They called it Strain 121, because it grows at a 121°C (250°F). But scientists generally agree that life could exist at temperatures as high as 140° to 145°C (284° to 295°F).

In the mid-1990s, scientists found novel hyperthermophilic microbes in hot oil reservoirs 3 kilometers below the North Sea and the North Slope of Alaska. Oil producers had thought that microorganisms, which "sour" or contaminate oil, were introduced into wells, but, in fact, they are naturally occurring and live on organic compounds in oil.

Such discoveries push our understanding of the limits of life and the limits of where to look for it. The largest known biosphere—fully 80 percent of Earth's available living space—is in the deep ocean, yet this may be eclipsed by the subsurface biosphere as research into this realm proceeds.

Drilling down to search for life

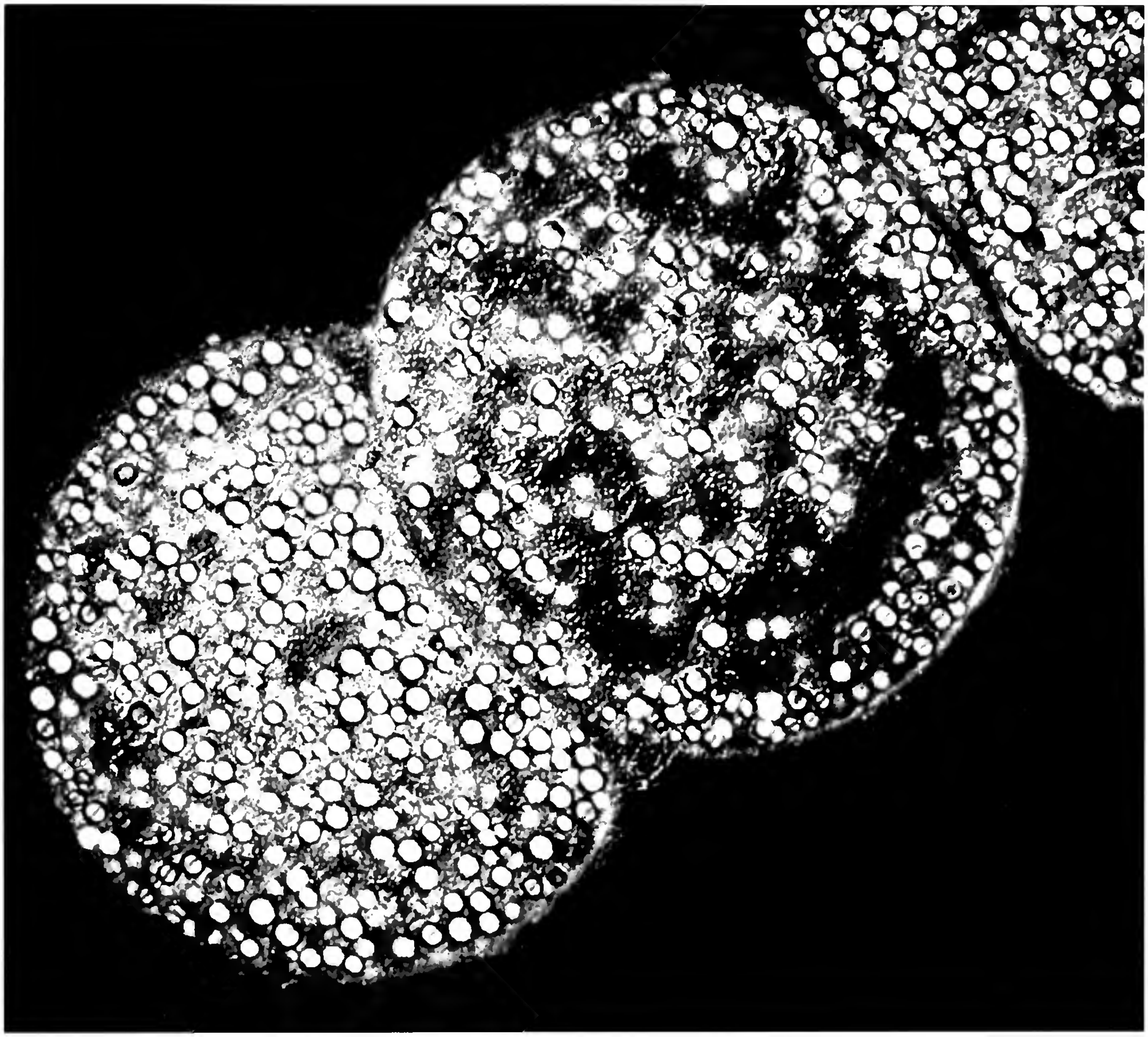
Deep-sea drilling remains the best way to sample the subsurface, though it has limitations. It is costly, and potentially results in contamination of the samples retrieved.

The deep biosphere has been targeted as a major research initiative of the new multinational Integrated Ocean Drilling Program, which operates deep-sea drill ships for the oceanographic community. (See "A Sea Change in Ocean Drilling," page 32.) A new permanent microbiology laboratory was outfitted aboard the *JOIDES Resolution* drill ship.

Scientists have also developed new instrument packages that plug into and seal drilled seafloor holes, where they remain for months. These probes offer potential windows into the interacting chemical, hydrological, geological, and biological processes that occur beneath the seafloor. These long-term observatories have been dubbed "CORKs," which is both an eponym and an acronym (Circulation Obviation Retrofit Kits).

The real challenge is to develop sensors that can be placed in situ in a way that doesn't disrupt the ecosystems they are meant to record and that are sensitive enough to provide continuous, real-time, monitoring of processes occurring on even a molecular scale.

Drilling cruises are scheduled to search for microbial life buried hundreds of meters deep under thick ocean sediments piled atop ocean crust in volcanically quiescent continental slope regions. In 2000, a



WORLD'S LARGEST BACTERIUM—In 1999 scientists discovered a previously unknown bacterium, which is large enough to be seen with the naked eye. Found off the coast of Namibia, the bacteria grow in long lines of single cells, each stuffed with reflective white globules of sulfur. The bacteria resembled a string of pearls to its discoverers, who named it Thiomargarita namibienus *("Sulfur pearl of Namibia"). The bacteria have evolved to live on seafloor sediments, where they find hydrogen sulfide for energy and nitrate for respiration. Their size is due to a large vacuole that fills the interior of their cells like inflated balloons. The vacuole stores nitrate, giving* Thiomargarita *the ability to survive periods when oxygen is lacking—a built-in equivalent of an oxygen-storing SCUBA tank that allows humans to remain alive under water.*

consortium of Japanese scientists launched a several-year project using drill ships, manned submersibles, remotely operated vehicles, and long-term sensors to explore, drill, and monitor the subsurface biosphere beneath hydrothermal vents near Suiyo Seamount, an active subsea volcano in the western Pacific.

Going to extremes

A major research goal of the Deep Ocean Exploration Institute at Woods Hole Oceanographic Institution is to extend our subsurface search into conditions on Earth that are deeper, hotter, and harsher than anything previously studied. We want to learn more about the biological and geochemical interactions that take place within this biosphere.

Any residents we find in these frontiers may well be biochemical pioneers. In their genes, they will still have the original blueprints for a wide range of possible biological processes. Some of these processes—like *Arcobacter's* sulfur filament machinery, or

Thiomargarita's large, nitrate-storing vacuole, or the extreme heat tolerance of Strain 121—we may never have seen before.

Life on Earth and other planets

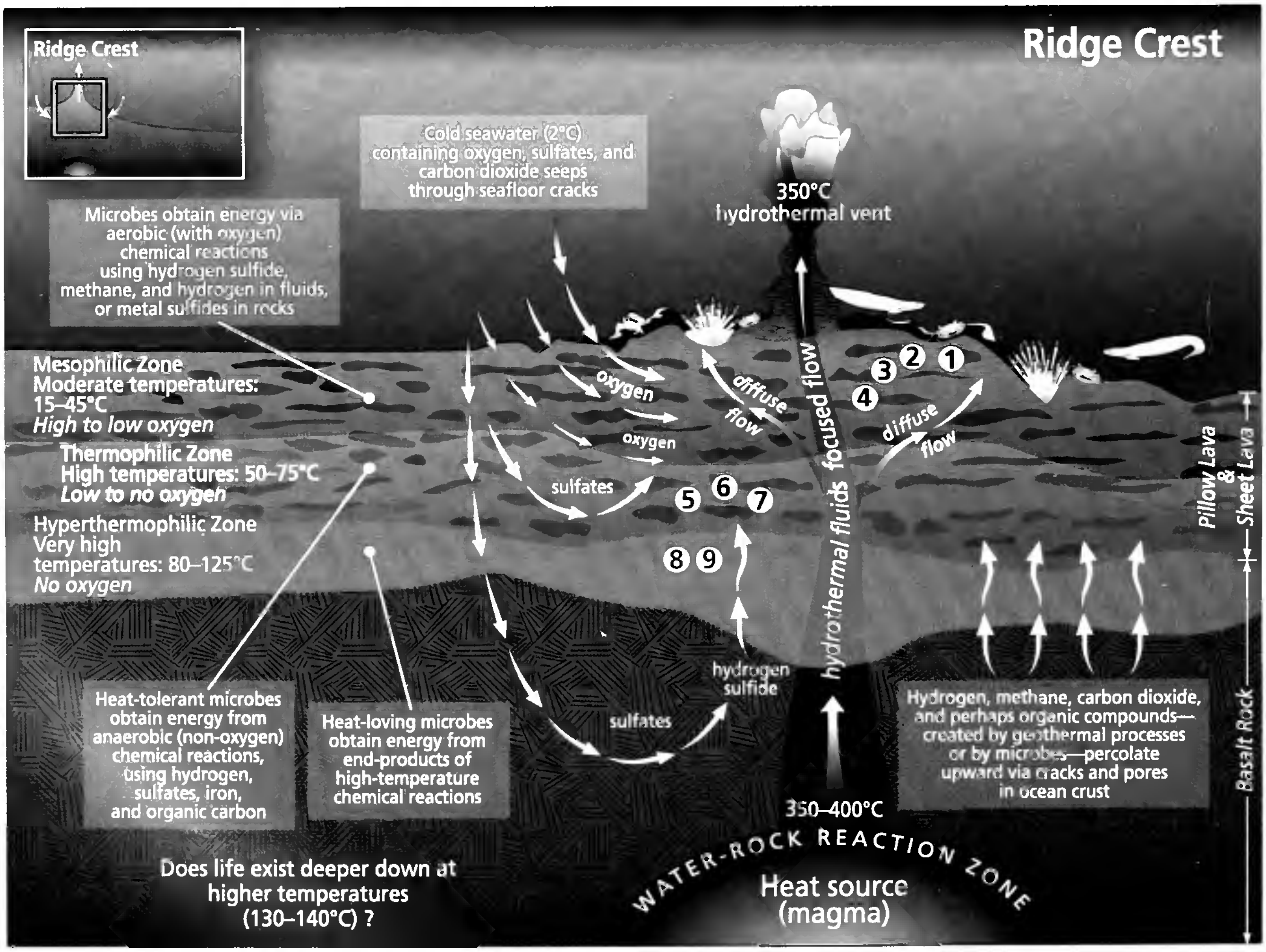
We may never know with complete certainty where and how life originated on Earth, but the hot subsurface around hydrothermal vents is a likely candidate. It is an environment that seems to have all the necessary ingredients to spark critical chemical reactions that could create the precursor building blocks of living organisms—ultimately resulting in amino acids for proteins, the genetic machinery DNA and RNA, sugars for energy, and lipids to make membranes.

In a hot subsurface melting pot, far from solar ultraviolet radiation that can break down complex molecules, these chemicals could find sanctuary in tiny rocky crevices where they could congregate, interact, and perhaps combine eventually with a membrane around them. Below the sea, they would certainly be sheltered from meteor bombardment and other life-threatening conditions that buffeted the early Earth's surface.

Further insights into life's ability to survive harsh conditions will guide our search for extraterrestrial life. New evidence from Mars shows that it once had water, and it may once have had seas

A microbial garden beneath the seafloor

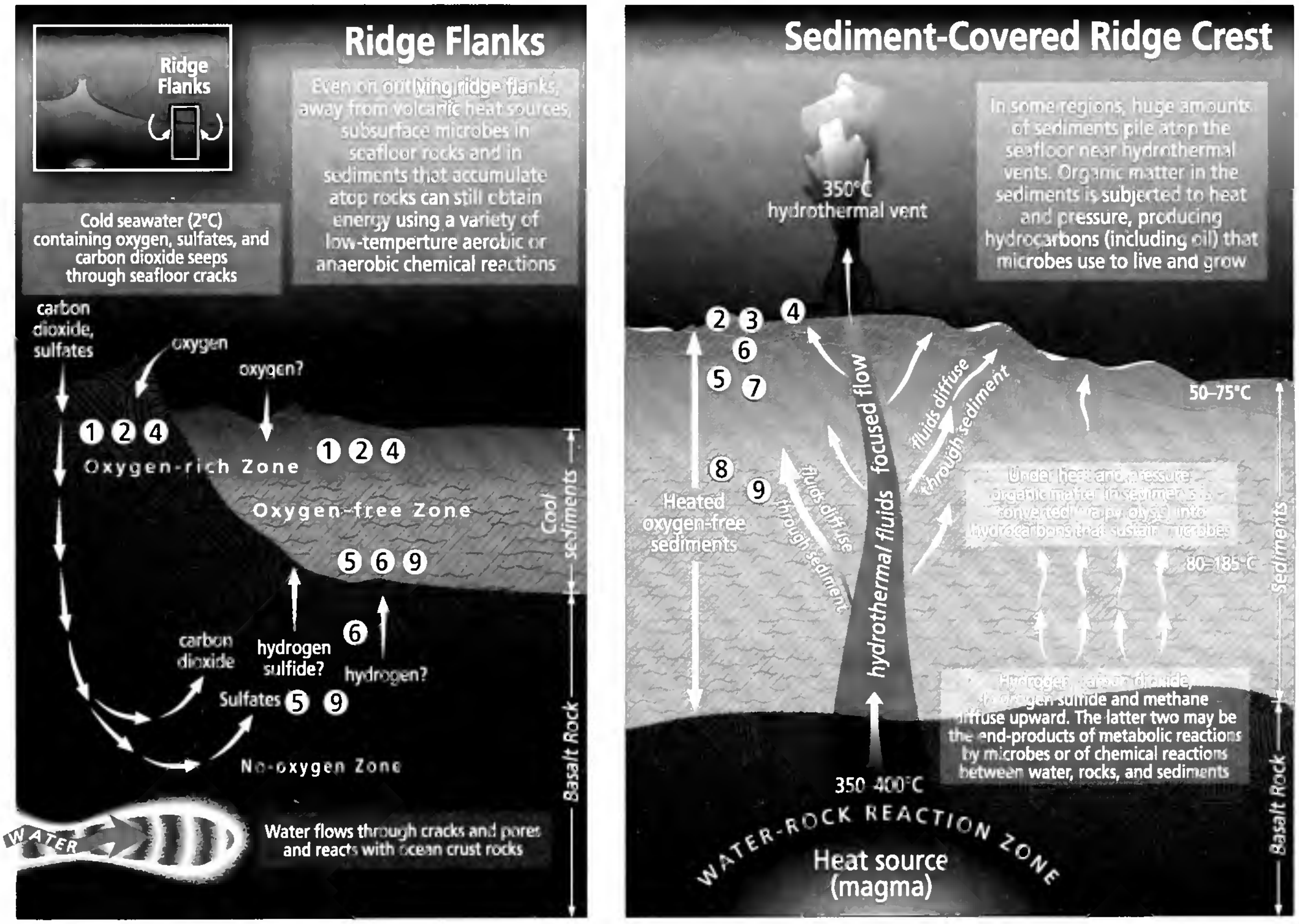
Recent discoveries have raised the possibility of a huge and diverse subsurface biosphere of microbial life. Below the ocean floor, a variety of chemical reactions between seawater and rocks, taking place over a range of temperatures, creates a chemical bouillabaisse. These chemicals diffuse upward and become sources of energy and carbon that sustain a wide variety of microbes. The microbes have evolved to take advantage of specific conditions in particular niches.



that left salt deposits like those in New Mexico. Europa, Jupiter's moon, is probably volcanic, and beneath its ice-covered surface may lie oceans with hydrothermal activity. The same tools and techniques we devise to search for life within and beneath Earth's volcanic oceans will prove useful there.

Our journey into Earth's subsurface biosphere is a quest to find the limits of life.

Carl Wirsen, a Massachusetts native, came to WHOI in 1968 and retired in 2003 as a Senior Research Specialist, having pursued research in marine microbiology over 35 years. Being among the first scientists to dive at the newly discovered hydrothermal vents in the late 1970s and early 1980s, he never lacked novel research opportunities (including "tasting" the lunch preserved for 11 months in Alvin after it sank in 1968 and was recovered in 1969). Now, as an Oceanographer Emeritus, he can pursue some questions that remained unanswered over the years, as well as some favorite outside WHOI activities. For him and his wife Jove, who also retired from WHOI, dogs have always been a big part of their lives, and training them for field and obedience is almost as much fun as rearing a litter. Four grandchildren and all the activities that come with being a grandparent (fishing, camping, science) make life busier now than it ever has been.



A SMORGASBORD OF CHEMICAL REACTIONS—Microbes living in the subsurface at or near deep-sea hydrothermal vent sites exploit a wide range of conditions. Here is a list of known or possible chemical reactions microbes use to live and grow.

① Aerobic metal and metal sulfide oxidation
(Fe^{+2} or Mn^{+2} + $O_2 \rightarrow Fe^{+3}$ or Mn^{+3} + H_2O)

② Aerobic sulfide/sulfur oxidation
($H_2S + O_2 \rightarrow H_2SO_4$)

③ Aerobic methane oxidation
($CH_4 + O_2 \rightarrow CO_2 + H_2O$)

④ Aerobic hydrogen oxidation
($H_2 + O_2 \rightarrow 2H_2O$)

⑤ Anaerobic sulfate reduction
($5H_2 + SO_4 \rightarrow H_2S + 4H_2O$)

⑥ Anaerobic iron reduction
($Fe^{+3} + H_2 \rightarrow Fe^{+2}$)

⑦ Sulfur reduction via organic carbon utilization
(Organic C + elemental S $\rightarrow H_2S + CO_2$)

⑧ Anaerobic sulfur respiration
(Elemental S + $H_2 \rightarrow H_2S$)

⑨ Anaerobic methane production (methanogenesis)
($4H_2 + CO_2 \rightarrow CH_4 + H_2O$)

The Evolutionary Puzzle of Seafloor Life

Scientists are assembling critical pieces to reconstruct the history of life on the ocean floor

By Timothy M. Shank, Assistant Scientist
Biology Department
Woods Hole Oceanographic Institution

From the far reaches of their empire, the Romans brought back all sorts of beasts for their menageries and gladiator spectacles—lions from Africa, bears from northern Europe, and ibexes from the deserts of the Middle East. If the empire had reached Australia, the Romans surely would have imported kangaroos, koalas, and other marsupials found nowhere else on Earth.

Scientists have long pondered why different species are distributed in various places—a field called biogeography. The line of inquiry stretches from Aristotle, through Carolus Linnaeus, the 18th-century father of taxonomy, to Charles Darwin, up to E.O. Wilson, who coined the modern term "biodiversity." Until the latter half of the 20th century, however, biogeography was a strictly terrestrial pursuit.

In 1977, scientists diving on the Galápagos Rift in *Alvin* made a discovery that shook the foundations of biology. They found oases of animals thriving in the sunless depths around hydrothermal vents. Instead of photosynthetic plants, chemosynthetic microbes constitute the base of the food chain at vents. They obtain energy from chemical-rich fluids generated by volcanic processes on mid-ocean ridges, the 75,000-kilometer (45,000-mile) undersea mountain chain that encircles the globe and marks the edges of Earth's tectonic plates.

Since the discovery of vents, scientists have explored hundreds of volcanically active vents in the Pacific, Atlantic, and Indian Oceans. And we have found that on the seafloor, as on land, distinct animal populations have evolved in different regions.

A biogeographic seafloor tour

In the eastern Pacific, tubeworms dominate vent sites, but they are notably absent

Tim Shank, WHOI/Alvin Operations Group

GIANT CLAMS—This vent site on the Galápagos Rift, discovered in 2002, is called "Calyfield" after Calyptogena magnifica, *a clam speices that grows up to 1 foot long. It thrives on chemical nutrients in hydrothermal fluids seeping between crevices around seafloor pillow lava.*

at vents in the Atlantic. Instead, billions of shrimp swarm at vents along the Mid-Atlantic Ridge, which bisects the Atlantic Ocean floor. Both Pacific and Atlantic vents have mussels, but not the same species.

A MIXED COMMUNITY OF VENT LIFE—A cloud of flea-like crustaceans called amphipods hovers around tubeworms encrusted with limpets and mussels at the 9°N vent site in the eastern Pacific.

Advanced Imaging and Visualization Laboratory, WHOI; BBC Natural History Unit, Stephen Low Productions

Scientists today recognize six major seafloor regions—called biogeographic provinces—with distinct assemblages of vent animal species. Beyond the tubeworm-dominated eastern Pacific, there are two provinces in the North Atlantic, where different species of shrimp and mussels predominate at deep vent sites to the south and shallower ones to the north.

The fourth province is in the northeast Pacific, off the U.S. Northwest coast, which shares similar species (clams, limpets, and tubeworms) with the eastern Pacific, but different species of each. Across the ocean in the western Pacific, vents are populated by barnacles, mussels, and snails that are not seen in either the eastern Pacific or the Atlantic.

Scientists got their first chance to search for vents in the Central Indian Ocean in 2001 and found the sixth province. These vents are dominated by Atlantic-type shrimp, but also had snails and barnacles resembling those in the western Pacific.

Evolutionary detectives

All these regions contain the same basic ingredients to support life—chemical nutrients generated by geothermal processes at hydrothermal vent sites. So why do vent fauna differ in the Atlantic and Pacific, or in the eastern and western Pacific? How do we assemble these puzzle pieces to explain the diversity and evolution of vent species throughout the world's oceans?

Evolutionary biologists are detectives, gathering clues and sorting through events and phenomena to reconstruct the processes that generated the patterns we see today. Suspected factors include:

- topographical seafloor features that help or hamper the dispersal of species;
- the movement of Earth's plates, which disconnects underwater mountain chains, and closes and opens gateways between oceans;
- deep-sea currents that aid or hinder the dispersal of vent larvae; and
- migrations of species (over evolutionary history) between vents and other seafloor habitats that foster chemosynthetic ecosystems. These include whale carcasses (called "whale falls") and "wood falls" from shipwrecks or trees cast into coastal regions.

Which combinations of these variables limited or encouraged the dispersal of animal populations along the widely scattered, ephemeral patchwork of active vents on mid-ocean ridges? Which sent some populations down divergent evolutionary pathways, led others to extinction, and created fertile niches for yet others?

Breakthroughs in biotechnology that allow rapid gene sequencing now give scientists powerful new abilities to compare genomes of different species. We can see how closely related they are and examine how far back in time they may have diverged on the evolutionary tree. Determining evolutionary relationships among seafloor species and communities, and their distribution and biodiversity, will help unravel the evolution of life on Earth. And it will guide our search for life on other planetary bodies, where chemosynthesis may reign.

Breaking the mountain chain

Ecosystems on land and the seafloor differ substantially, but terrestrial evolutionary lessons may still apply to the deep sea. For example, as Australia separated from the ancient supercontinent of Pangaea and became an island, its animal population became divorced from other populations (including predators) and began to evolve separately. Did something similar happen on the ocean floor?

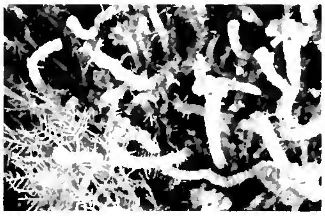
About 40 million years ago, a continuous mid-ocean ridge system existed in the east Pacific, extending from below the equator to the coast of what is now the Northwest United States. In the continuing reorganization of tectonic plates on Earth's surface, however, the North American Plate pushed westward. It began to override the Pacific Plate, forcing a portion of it underneath the North American Plate. Plate tectonics effectively disconnected northeast Pacific ridges from the rest of the Pacific ridge system.

As a result, northeast Pacific vent communities diverged from their equatorial Pacific cousins. Both regions' vents share clams, limpets, and tubeworms, but not

Continued on page 82

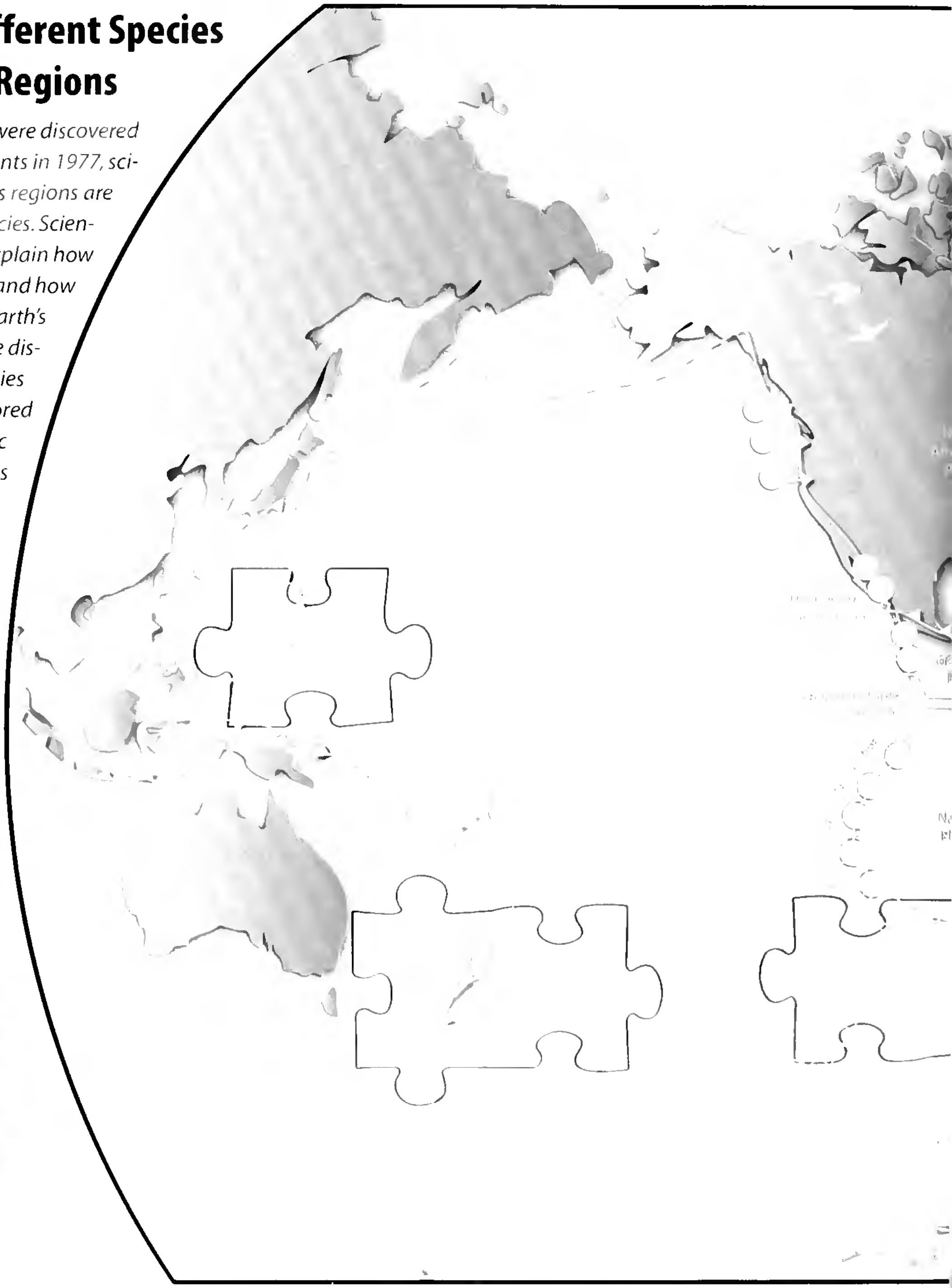
On the Seafloor, Different Species Thrive in Different Regions

Soon after animal communities were discovered around seafloor hydrothermal vents in 1977, scientists found that vents in various regions are populated by distinct animal species. Scientists have been sorting clues to explain how seafloor populations are related and how they evolved and diverged over Earth's history. Scientists today recognize distinct assemblages of animal species in six major seafloor regions (colored dots) along the system of volcanic mountains and deep-sea trenches that form the borders of Earth's tectonic plates. But unexplored ocean regions remain critical missing pieces for assembling the full evolutionary puzzle.



Northeast Pacific vent communities are dominated by "bushes" of skinny tubeworms called Ridgea piscesae.

Western Pacific vent communities are dominated by barnacles and limpets, as well as hairy gastropods, shown above.



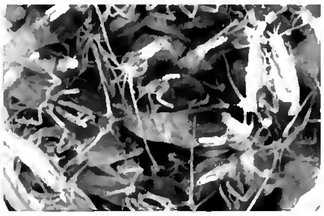
Missing Pieces

Challenger Deep
Unusual life forms may have evolved under conditions of extreme pressure in this 11,000-meter-deep trench, the deepest part of the world's oceans.

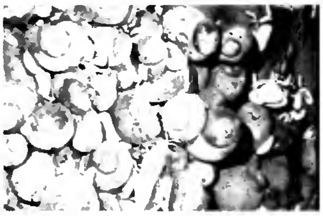
New Zealand
This region has a full spectrum of habitats supporting seafloor life (hydrothermal vents, cold seeps, whale carcasses, and wood from shipwrecks and trees) in close proximity. How have species evolved in these diverse settings?

Chile Rise
This region has a variety of chemosynthetic habitats and geological features in close proximity. How do seafloor populations diverge or converge at this triple junction on the "highway" of mid-ocean ridges?

Shallow Atlantic vents (800-1700-meter depths) support dense clusters of mussels on black smoker chimneys.



Deep Atlantic vent communities (2500-3650-meter depths) are dominated by swarms of shrimp called Rimicaris exoculata.



Central Indian vent communities are populated by Western Pacific-type fauna, but also have North Atlantic-type shrimp species.

Eastern Pacific vent communities are dominated by tall, fat tubeworms called Riftia pachyptila.

Southern Ocean

The Drake Passage may act as a key link or bottleneck for larval dispersal between the Atlantic and Pacific. Whale carcasses and shipwrecks (such as Shackleton's Endurance*) may offer refuges or stepping-stones between vents*

South Atlantic

Powerful currents and huge seafloor chasms (fracture zones) may act as barriers blocking the dispersal of vent larvae and disconnecting vent populations in the North and South Atlantic.

Caribbean

In this region, methane seeping from the seafloor also supports animal communities. Did animals migrate between "cold seeps" and nearby hot vents over evolutionary history?

Arctic Ocean

The Arctic Ocean has never had deep connections with other major oceans. It may harbor fundamentally different vent animals that evolved in isolation over the past 25 million years.

Missão SEHAMA, 2002 (FCT/ PDCTM 1999 MAR/15281)

SWARMING SHRIMP—Like bees around a hive, shrimp aggregate to feed at the Rainbow vent site in the North Atlantic.

Continued from page 79

the same species. Northeastern tubeworms (*Ridgea piscesae*) have skinny tubes, while eastern tubeworms (*Riftia pachyptila*) have fatter tubes.

A ridge too far

The geological evolution of mid-ocean ridges and ocean basins influences biological evolution in other ways.

Hydrothermal vents are typically found in rift valleys at the crests of mid-ocean ridges, but there are striking differences in ridges. On the fast-spreading East Pacific Rise, rift valleys are typically 200 meters (656 feet) wide and 10 meters (33 feet) deep. But on the slower-spreading Mid-Atlantic Ridge, rift valleys are often 1 kilometer (0.6 miles) wide and 2 kilometers (1.2 miles) deep. Such deep valleys may have become "dead-ends" for vent animals inside, whose larvae could not get up and over the valley walls to disperse and colonize new vent sites in other valleys.

Pacific and Atlantic ridges differ in other ways, too. Mid-ocean ridges are broken into segments by extensive faults, called fracture zones, which intersect the ridges at roughly perpendicular angles. Ridge segments move apart along fracture zones, breaking the otherwise straight line of the ridge and creating a zigzag pattern of alternating ridges and fracture zones.

In the Pacific, two ridge segments may be separated by 10-kilometer (6 mile)-long fracture zones. But in the Atlantic, fracture zones typically span hundreds of kilometers—perhaps an unbridgeable gap for vent larvae trying to disperse into an adjacent ridge segment to the north or south.

Closing ocean gateways

Plate tectonics may have played an evolutionary role in another way—by opening and closing passages between oceans. As Pangaea began to break up 200 million years ago, and North America and Europe separated from Africa, the ancient Tethys Ocean formed between them. It was the precursor of the Mediterranean Sea, and it allowed a free flow of waters from the proto-Atlantic Ocean to the Indian Ocean.

Perhaps this bygone oceanic route links Atlantic and Indian Ocean shrimp populations, which are diminished at shallow Atlantic vents (800–1,700 meters/2,625–5,577 feet), more abundant at deeper Indian vents (2,400 meters/7,874 feet), and swarming by the hundreds of thousands at even deeper Atlantic vents (2,500–3,650 meters/8,202–11,975 feet). The shrimps' predilection for greater depths may have allowed their larvae to disperse via deep currents from the Atlantic to the Indian Ocean—an avenue unavailable to other species—rather than via a route along the mid-ocean ridge, through the South Atlantic and around the Horn of Africa.

Perhaps the explanation for distinct North Atlantic fauna—with its swarming shrimp and no tubeworms—involves other ocean gateways. The North Atlantic Ocean basin began to form about 180 million years ago, but South America and Africa remained connected until about 110 million years ago. That means that North Atlantic populations evolved for some 70 million years before the South Atlantic existed. Further, the Drake Passage between Antarctica and the tip of South America, a crucial oceanic gateway connecting the Pacific and Atlantic, did not open until about 21 million years ago.

Genetic comparisons of shrimp populations throughout these oceans will allow us to reconstruct the pathways of shrimp migration over evolutionary history and answer these questions.


Craig R. Smith and Amy Baco, University of Hawaii

A WHALE OF A MEAL—Orange microbes coat the skeleton of a whale that fell to the seafloor off California. Craig Smith (University of Hawaii) and colleagues found that microbes decompose whale tissue and bones, producing hydrogen sulfide nutrients that sustain thriving animal populations. Whale-fall communities share many species with other chemosynthetic seafloor communities, such as hydrothermal vents and seeps, and may act as stepping-stones between them.

The rise of the Isthmus of Panama

A similar combination of geological and oceanographic factors may also explain the Logatchev vent site. Discovered in 1994, it is the only Atlantic vent site where clams are known to exist. Logatchev, the southernmost known vent site in the Atlantic, is located just east of the Caribbean Sea.

Did clams originally migrate from the Pacific via an ancient seaway that connected the Pacific and Atlantic—before the Isthmus of Panama rose about 5 million years ago to block it? Or did clam populations from western Pacific vents migrate around South America until they were impeded south of Logatchev by ocean currents or seafloor topography? Or perhaps clams thrive in other Atlantic vents that we haven't discovered yet.

Chasms and currents

Complex processes create the patterns of vent populations we have seen. But we can't truly begin to assemble this evolutionary puzzle without having all the pieces. Major regions of the seafloor remain unexplored.

We have not yet located vent sites in the South Atlantic, for example. The puzzle pieces we do have indicate a disconnection between most fauna in the North Atlantic and on other mid-ocean ridges.

The most intriguing explanation may involve the Romanche and Chain Fracture Zones located near the equator, which are particularly large—1,000 kilometers (620 miles) long and almost 8 kilometers (5 miles) deep. A strong, deep current flows along and through these fracture zones, almost straight across the South Atlantic (pushing a volume of 1 million cubic meters of water per second at an average speed of 10 centimeters per second). We think that the combination of these currents and fracture zones may act as physical barriers blocking the transport of vent fauna between the North and South Atlantic—a subsea equivalent of a Berlin Wall.

Islands in the seafloor stream

Other topographical factors may also explain the existance of unique biological communities found at seamounts—submerged extinct or active volcanoes that typically are isolated from mid-ocean ridges. Vent communities at Loihi Seamount, an active subsea volcano near Hawaii, and at Edison Seamount, off the coast of Papua, New Guinea, each have their own set of endemic species.

Are vent larvae from these isolated seamount communities too far away to reach mid-ocean ridges or other hydrothermal vent locations? Or do seamounts, towering miles above the seafloor, cause deep-ocean currents to swirl around them—creating impenetrable vortices that dispersing larvae cannot breach?

Despite their isolation, seamounts may play a vital role in the evolutionary history of seafloor life. Standing high above catastrophic seafloor events, such as mass extinctions, they might have offered critical refuges for vent fauna. Or they may have provided fortuitous stepping-stones between mid-ocean ridge vent sites.

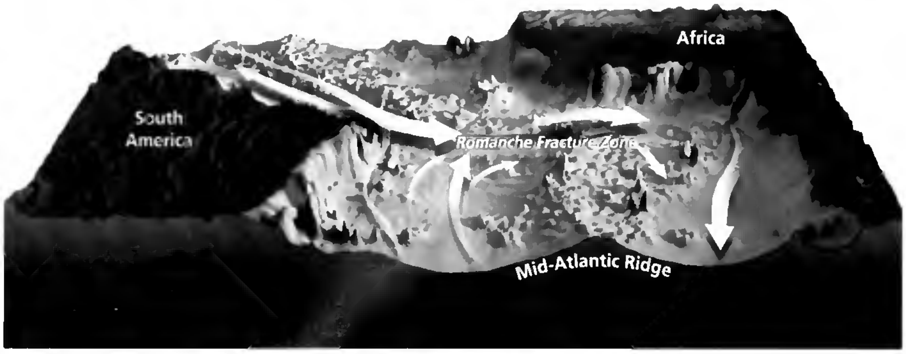
Deep-sea seeps and sanctuaries

Into this complex equation, scientists have added new variables by discovering other deep-sea habitats that foster chemosynthetic life.

In shallower seafloor regions on continental margins, for example, naturally created methane and hydrogen sulfide seep from the seafloor. These so-called "cold seeps" support chemosynthetic ecosystems (including tubeworms, mussels, and shrimp) that are different but analogous to vents. (See "When Seafloor Meets Ocean, the Chemistry Is Amazing," page 66.)

Genetic studies have shown that tubeworms at seeps and vents are not the same specie, but the two habitats do share 13 species. Over evolutionary history, did species migrate back and forth between seeps and vents?

Fossil records show that ancestors of



E. Paul Oberlander, WHOI

A WALL OF WATER—The Mid-Atlantic Ridge near the equator is offset by long, deep faults, called fracture zones. A strong deep current flows along and through these fracture zones, almost straight across the South Atlantic. The combination of currents and fracture zones may act as a physical barrier blocking the transport of vent fauna between the North and South Atlantic Oceans—a subsea equivalent of a Berlin Wall.

vent tubeworms, barnacles, and limpets are as old as the dinosaurs. Several mass extinctions, like the one that annihilated the dinosaurs, have occurred in the deep sea. Could seeps or vents act as deep-sea refuges, where colonies of animals survived catastrophes and subsequently reseeded populations?

Whale falls and shipwrecks

In 1987, Craig Smith of the University of Hawaii and colleagues found a thriving, diverse animal community on a whale carcass that had fallen to the ocean bottom. Microbes decomposing the whale's soft tissue and bone lipids produced hydrogen sulfide nutrients similar to those that sustain vent communities. To date, more than 20 whale-fall ecosystems have been found. They share 10 species with vents and 19 with seeps.

Similarly, wood—from trees discharged into the coastal ocean by rivers and mudslides, or from shipwrecks in coastal and more far-flung areas—also provides chemical nutrients from decaying organic matter to support chemosynthetic animals.

Like seamounts and cold seeps, whale and wood falls likely play important evolutionary roles. Whale falls along migratory routes, and trees deposited near river mouths, may serve as stepping-stones to help disperse seafloor fauna. Wooden shipwrecks may have introduced more recent seafloor stepping-stones.

Recent evidence indicates that wooden shipwrecks began earlier than suspected in history, were not confined to coastal areas, and occurred more frequently than previously believed. Between 1971 and 1990 alone, an estimated 3,000 wooden ships were wrecked.

Finding the right niche

We can add other possibilities to this expansive list of factors that may have influenced the evolutionary process. For starters, the proliferation of certain animals in certain locations is probably encouraged or discouraged by subtle differences in the chemistry of vent fluids, seafloor rocks, larval swimming behaviors, or other unknown factors.

Tubeworms may have an advantage over shrimp at fast-spreading Pacific mid-ocean ridges where eruptions occur more frequently than they do in the Atlantic. Eruptions destroy vent communities. Animals stand a far greater chance of avoiding extinction caused by frequent eruptions if they have evolved with the abilities to colonize sites, mature, and reproduce quickly. On the other hand, as these sites mature or become more stable, other animals may seize the advantage and overwhelm the original colonists.

According to one theory, the newly forming Atlantic Ocean—small, shallow, and more susceptible to evaporation—was more saline than it is now. Shrimp may have been more salt-tolerant and may have settled first at nascent Atlantic vent sites. Once they took hold, species such as tubeworms could never attain a foothold. Shrimp assiduously scrape the surfaces of vent chimneys to harvest bacteria and, the theory continues, they would have consumed any tubeworm larvae that happened to settle long before the worms could mature.

Filling in the critical gaps

To assess the critical factors that redirected evolutionary pathways, the first step is to locate and sample what's living in key places for making evolutionary comparisons. Is South Atlantic vent fauna similar to that in the North Atlantic or Pacific? We will find out during an expedition in 2005, funded by the National Oceanic and Atmospheric Administration's Ocean Exploration program, to search for vents in the South Atlantic.

Proposed expeditions aim to add missing pieces to the puzzle from the largely

E. Paul Oberlander, WHOI Graphic Services

A NEW HYBRID ROBOT—Scientists hope to use the Hybrid Remotely Operated Vehicle (HROV), now being designed and built at Woods Hole Oceanographic Institution, to explore Challenger Deep—a 35,800-foot-deep seafloor trench in the Pacific. They will search for unusual life that may have evolved under conditions of extreme pressure.

unexplored Southern Hemisphere. In 2006, we hope to explore the seafloor off New Zealand, which offers a natural laboratory to investigate relationships among the full spectrum of habitats supporting seafloor life (vents, seeps, whale falls, and shipwrecks) that exist in close proximity there.

Expeditions proposed for 2006 to the Chile Rise offer a similar opportunity to examine—all in one region—a diversity of chemosynthetic communities, along with a wide range of plate tectonic processes, from mid-ocean ridge spreading to an oceanic plate being subducted back into the mantle. It also includes a triple juncture of mid-ocean ridges, where vent populations may converge or diverge.

In 2006, NOAA's Ocean Exploration program will fund expeditions to search for vents near Antarctica, on the East Scotia Rise and in the Bransfield Strait, which is strategically located at a narrow but critical juncture linking the Pacific and Atlantic Oceans. The powerful Antarctic Circumpolar Current, rushing easterly through the Drake Passage, may prove to be a magic carpet dispersing Pacific vent larvae to the Atlantic, a wall of water preventing the westward flow of Atlantic larvae, or a bottleneck choking flow in both directions.

The region also has a large whale population, giving us opportunities to explore whale falls. And the tempestuous Drake Passage and Southern Ocean ice have populated the seafloor with wood falls from shipwrecks that we will search for—including Sir Ernest Shackleton's famous ship *Endurance*.

Under the ice and in the trenches

There is another icy, unexplored ocean that we are eager to explore—the Arctic Ocean. In 2001, the spectacularly successful maiden voyage of the U.S. icebreaker *Healy* found evidence from water samples and seafloor rocks of far more volcanism and hydrothermal venting than was predicted on the ultra-slow-spreading Gakkel Ridge in the Arctic Ocean. (See "Earth's Complex Complexion," page 36.)

Reproduced by permission of the Scott Polar Research Institute

An Antarctic cruise in 2007 will search for the wreck of Ernest Shackleton's ill-fated ship Endurance *and test the theory that wooden wrecks play an important role in sustaining and dispersing seafloor populations.*

Are Arctic vent species similar to those in the Atlantic, the Pacific, or to neither? Our current knowledge suggests that the Arctic Ocean has never maintained deep-water connections with neighboring oceans. We theorize that Arctic fauna has evolved in isolation—producing fundamentally different kinds of species. Perhaps species dwelling on the remote Gakkel Ridge are "living fossils"—relicts of ancient species that continue to thrive today just as they have for tens of millions of years.

In 2007 we will return to the Gakkel Ridge on an expedition funded by the National Science Foundation (NSF) and the National Aeronautics and Space Administration's Astrobiology Science and Technology for Exploring Planets (ASTEP) program. To explore beneath the ice, we will employ new autonomous underwater vehicles built at Woods Hole Oceanographic Institution to work in ice-covered oceans. (See "Unique Vehicles for a Unique Environment," page 25). We also hope to use the cutting-edge Hybrid Remotely Operated Vehicle (HROV), now being designed and built at WHOI. The HROV will be able to operate at depths up to 11,000 meters (36,000 feet) in two modes: as an autonomous, or free-swimming, vehicle for wide area surveys, and as a tethered, or cabled, vehicle for close-up sampling and other tasks.

When the HROV is ready in 2006, we plan to take it on a cruise funded by the NSF to the Challenger Deep, a trench off the Marianas Islands in the western Pacific that is 10,923 meters (35,838 feet) deep—deeper than Mount Everest is tall. In a place where the pressure reaches 16,000 pounds per square inch, we will test our hypothesis that these extreme conditions have spawned uniquely adapted life forms on the seafloor.

Dan Fornari, WHOI

Tim Shank grew up on the North Carolina coast and has been fascinated with marine life for as long as he can remember. In the mid-1980s, his professors at the University of North Carolina discovered hydrocarbon seeps, sparking his interest in the evolution of life and chemosynthetic ecosystems. Shank heeded the advice of his marine geosciences professor and mentor, Dr. Conrad Neumann, who recommended that he study other passions, such as genetics or chemistry, and then apply them to marine science research. After graduation, he worked in the molecular genetic environmental toxicology lab at the Environmental Protection Agency in Research Triangle Park, N.C., honing his molecular skills for three years before entering graduate school at Rutgers University. He came to WHOI as a Postdoctoral Scholar in 1999. Shank's research focuses on understanding the ecological factors that affect the structure of diverse populations of deep-sea chemosynthetic species. He combines molecular genetic approaches and ecological field studies to understand the conditions and adaptations that allow various species to migrate, evolve, and thrive in deep-sea habitats throughout the world's oceans, including, more recently, seamounts. He has participated in more than 20 research cruises, using Jason *and* ABE, *and has had more than 50 dives in* Alvin. *Shank's thirst for evolutionary history extends into another passion: genealogical and American history.*

Living Large in Microscopic Nooks

Newly discovered deep-sea microbes rearrange thinking on the evolution of the Earth—and life on it

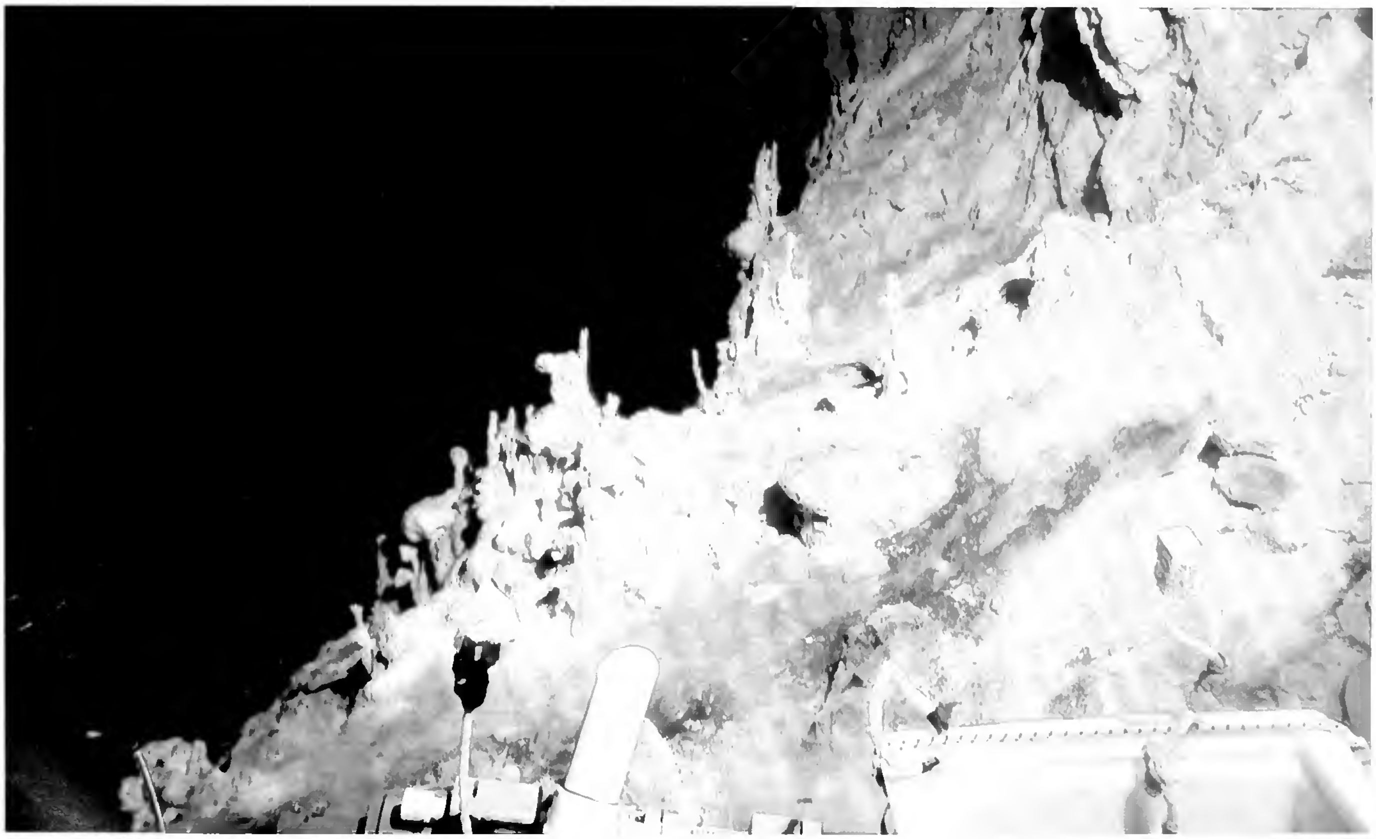
By Katrina Edwards, Associate Scientist
Marine Chemistry & Geochemistry Dept.
Woods Hole Oceanographic Institution

Between a rock and a hard place is the proverbial worst spot for people to find themselves in. But for certain deep-sea microbes, it's the place to be. In 2000, to our surprise, we found that microscopic nooks and pits within volcanic seafloor rocks harbor abundant colonies of previously unidentified microbes.

These microbes are different from other microorganisms living in the sunless depths. They do not obtain the energy they need to grow and multiply by metabolizing chemicals dissolved in seawater or in hydrothermal fluids venting from the seafloor. Instead, these newly discovered microbes are living directly off minerals in solid seafloor rocks.

The microbes are oxidizing iron in the rocks, chemically altering the rocks, and harnessing the energy produced by this chemical reaction to live. Their discovery has raised a slew of intriguing questions:

- Does our planet sustain abundant and ubiquitous populations of these microbes?
- Do they play a pivotal role in chemically altering Earth's crust?
- Were they pioneering life forms on an early Earth, which was largely devoid of oxygen but full of iron?
- Do they exist on other iron-rich, oxygen-



Terry Kirby, University of Hawaii

RUST IN DAVEY JONES' LOCKER—Reddish-orange iron oxide (the same chemical compound we commonly refer to as "rust") coats the seafloor on Loihi Seamount, an active underwater volcano 25 miles off the island of Hawaii. The material is made by an abundance of microbes that live and grow by oxidizing iron directly from solid seafloor rocks. To study these newly discovered microbes, scientists have established FeMO—the Iron (Fe)-oxidizing Microbe Observatory—on Loihi.

Katrina Edwards, WHOI

TRANSFORMING ROCK—Rusty-orange iron oxide coats the left side of this sample of seafloor rock, where microbes have oxidized iron in the rock. They harness the chemical energy from this reaction to live and grow. The microbes did not progress to the right side of the rock, which remains its normal gray color.

poor planetary bodies such as Mars?

These previously inconspicuous microorganisms may turn out to have starring roles in shaping the evolution of life on Earth and other planets, and shaping the evolution of the planet itself.

So why didn't we notice them before? Beyond the inherent difficulties and expense of searching for microorganisms at the bottom of the ocean, the answer is that we hadn't really looked for them before. But now these easy-to-overlook microbes have become hard to ignore.

Pumping iron on the seafloor

More and more, we are learning how life on the Earth and the Earth itself—biology and geology—are intimately intertwined and evolve together. Microbes are ubiquitous catalytic agents, sparking chemical reactions that alter the physical and chemical properties of their surroundings. Beyond our scope of vision, their cumulative metabolic activities play a fundamental role in shaping and regulating our environment. (Our world would be completely different, for example, if microorganisms did not continuously decompose organic matter and transform it back into inorganic material.)

A new field of study has arisen called geomicrobiology. Scientists are now taking a closer look at many unexplored regions of our planet, and other planets, searching for populations of unknown microbes that may play major roles in cycling chemicals through planetary systems.

In geomicrobiology, the borders between rocks and living things are not so ironclad. Many rocks are, however, and the microbes we found steal electrons from iron atoms in the rock, changing them from ferrous (Fe^{+2}) to ferric (Fe^{+3}). With the energy produced by this chemical reaction, they convert carbon dioxide (from seawater) into organic matter—much the way plants and plankton use solar energy and photosynthesis to accomplish the same.

Microscopic, but mighty

Iron is one of the most abundant and reactive elements in the environment near Earth's surface, so the discovery of iron-oxidizing microbes raises the potential that massive communities of them may exist on Earth. If so, they could continually extract huge amounts of carbon dioxide from seawater and microscopically exert a huge influence on ocean chemistry over geologic time.

Does this large-scale drawdown of carbon dioxide from seawater help the oceans absorb carbon dioxide, a critical greenhouse gas, from the atmosphere? If so, it would revise our understanding of how carbon cycles through the planetary system—perhaps giving iron-oxidizing microbes an important, previously unknown role in the evolution of Earth's climate.

In their own way, the rise of microscopic photosynthetic plants caused one of the most devastating, permanent alterations in all of Earth's history. They changed the chemical composition of the near-surface environment that all life depended on, by simply pumping oxygen into Earth's atmosphere.

Before then, neither the atmosphere nor the oceans contained much oxygen, but the oceans were filled with iron-rich rocks and tons of dissolved iron. In such an iron-rich, oxygen-poor environment, iron-oxidizing microbes may have been dominant, pioneering life forms—a concept that compels us to reassess our thinking about the evolution of life on early Earth.

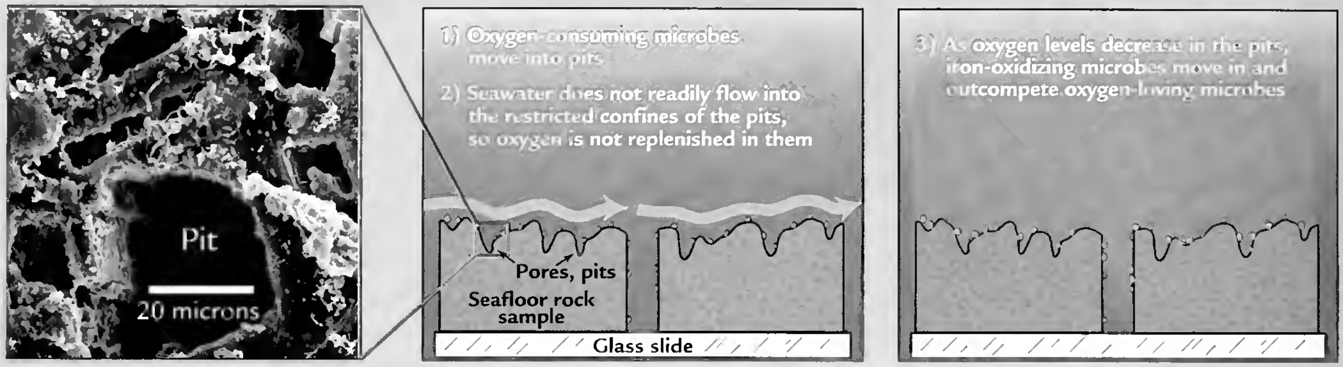
The existence of iron-oxidizing microbes also redirects our search for life elsewhere in the universe. Similar microbes could have thrived, or still thrive, in other iron-rich, oxygen-poor locales—such as Mars, with its red, iron-rich soil, or on the volcanic seafloor below the ice-covered ocean of Jupiter's moon, Europa.

A search for unknown life

These unexpected new lines of inquiry began in 2000 when former WHOI Postdoctoral Scholar Tom McCollom and I, with funding from the Mellon Foundation and the National Science Foundation, joined a research cruise aboard R/V *Atlantis* off the Oregon coast.

Since the late 1970s, when hydrothermal vents were discovered, scientists have focused on deep-sea chemosynthetic microbes that derive energy from dissolved hydrogen, hydrogen sulfide, and methane emitted from these sites. Though it is easier for microbes to draw

An experimental sample of seafloor rock is put back on the seafloor ...



energy from chemicals dissolved in seawater, WHOI biologist Carl Wirsen and others found evidence of sulfur-oxidizing bacteria that used solid minerals as their only source of energy. (See "Is Life Thriving Deep Beneath the Seafloor?" page 72.)

Enormous amounts of sulfur and sulfides are found in vent chimney rocks, in broken chimney rubble on the seafloor, and in fine-grained mineral particles that precipitate and "rain" out of plumes of hydrothermal fluids spewing out of chimneys. We speculated that this little-recognized but potentially large source of chemical energy may sustain important microbial communities, which, in turn, could play pivotal roles in altering the chemistry of seafloor rocks and the ocean itself.

Our goal in 2000 was to try to identify unknown microbes that live off solid minerals and that might be mediating large-scale geochemical changes on Earth.

The perfect niche for microbes

To explore what might be down there, we used the submersible *Alvin* to place a variety of microbe-free samples of natural seafloor rock back on the seafloor. Our aim was to see what might "grow" on these "blank slates."

WHOI geochemist Meg Tivey retrieved our experimental samples for us during an *Alvin* dive two months later (See "The Remarkable Diversity of Seafloor Vents," page 60). To our surprise, we found that many of the samples had thick burnt-orange coatings of oxidized iron (or "rust").

Using a scanning electron microscope, we saw that the surfaces of the samples were scarred with abundant pits and pores less than 20 microns (0.0004 inches) deep and wide. In these tiny pits were large accumulations of corkscrew-shaped stalks made of iron oxide, which created the thick rusty coating.

Here's what we believe is happening: Iron-oxidizing microbes exploit a niche where the chemistry is just right. At first, oxygen-loving microbes move into the pits. They consume the available oxygen, which is not replenished because seawater does not readily flow into the restricted pit areas.

That creates an ideal situation for the iron microbes, which need low-oxygen conditions. The tiny sheltered coves within seafloor rocks contain just enough oxygen from seawater for the iron microbes to respire, but not an overwhelming amount that would oxidize all the iron—without microbial intervention—before the microbes could use it.

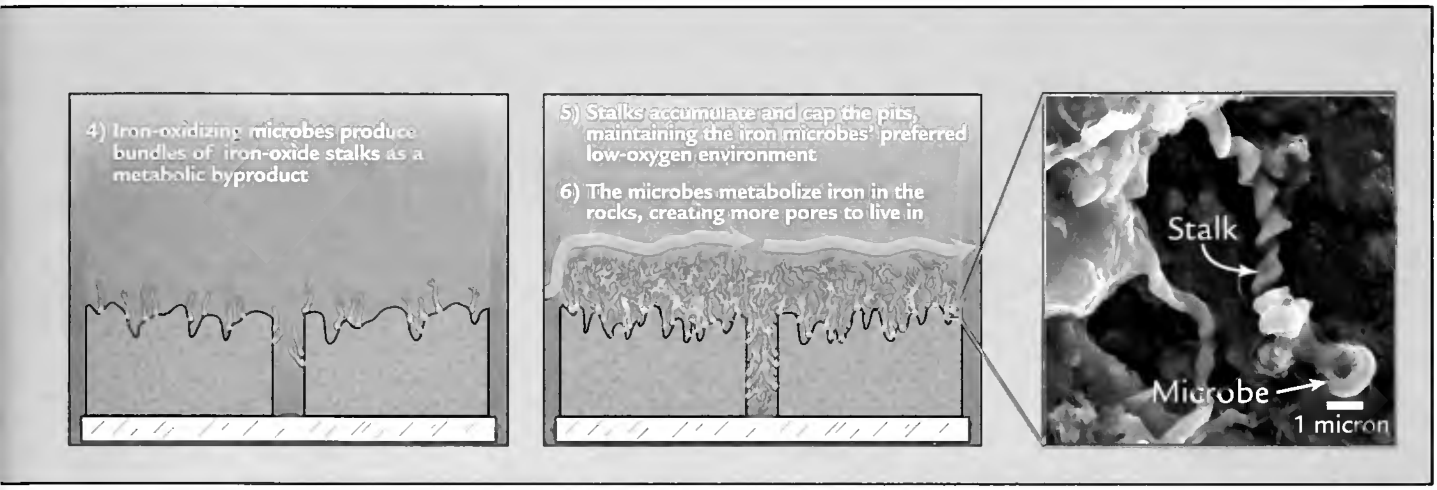
As a byproduct of their iron-oxidizing process, the microbes produce bundles of iron-oxide stalks that resemble a little girl's ringlets. These stalk accumulations effectively cap the pits, maintaining the iron microbes' preferred low-oxygen environment and securing their turf.

FeMO—a microbial observatory

The rapid proliferation and sheer abundance of these iron microbes and


Katrina Edwards, WHOI
Katrina Edwards, WHOI

A BUCKETFUL OF DATA—WHOI scientists prepared plastic buckets filled with thin, microbe-free samples of natural seafloor rock and placed them back on the seafloor. The experiment sought to find out what might "grow" on these "blank slates." To their surprise, the scientists found that the samples were quickly colonized by intriguing microbes. (See diagram above.)



Jack Cook, WHOI Graphic Services

the quick chemical transformation of the rocks they lived on were eye-opening. Now we have mobilized research that combines biology, chemistry, and geology to explore many intriguing aspects of these iron microbes.

Among the initial questions are: What kinds of iron-oxidizing microbes are out there? How many are there? How are they making a living?

These species have been notoriously difficult to grow in the laboratory and therefore difficult to learn about. But in our lab Dan Rogers and I, along with WHOI biologist Eric Webb and others, have made strides recently to culture and interrogate these elusive microbes, and we have begun to identify various species of microbes and reveal their biochemical machinery and metabolic capabilities.

Toward this end, we have just established "FeMO"—an Iron (Fe)-oxidizing Microbe Observatory—to study these microbes at a site where they are diverse and prolific. It is located at Loihi, an active, submerged volcano, relatively conveniently located only 25 miles southwest of the big island of Hawaii.

To investigate the potential abundance of iron microbes, WHOI geochemist Wolfgang Bach and I analyzed rock samples retrieved from an assortment of holes drilled by the Ocean Drilling Program into the exposed volcanic rock that spreads out on both sides of the mid-ocean ridge mountain chain encircling the globe. We found that older rocks were depleted of Fe^{+2} and full of Fe^{+3}—exactly what iron-oxidizing microbes use up and leave behind. The finding suggests that mid-ocean ridge flanks represent millions of square miles of fertile habitat for iron microbes.

Life on early Earth and elsewhere

We have also begun to sequence genomes of these microbes, in a project with Mitch Sogin and Ashita Dhillion at the Marine Biological Laboratory in Woods Hole, funded by the National Aeronautics and Space Administration's Astrobiology Institutes Program (NAI). These microbes are pioneers that probably lived billions of years ago on Earth and may exist on other planetary bodies. Identifying their genes, the enzymes they produce, and the metabolic pathways these enzymes catalyze will reveal an evolutionary heritage that will help us unravel the emergence and development of life on Earth and guide our search for life elsewhere in the universe.

A key to reconstructing the evolution of life on Earth and other planetary bodies lies in the ability of scientists to read the records, or "biosignatures," that long-dead microbes leave behind in ancient or extraterrestrial rocks. To do that reliably, scientists must be able to distinguish changes caused by microbial activity from those caused by abiotic oxidizing processes such as rusting.

With this goal, scientists in our group, including Bach, Postdoctoral Scholar Olivier Rouxel, and graduate student Cara Santelli, are advancing a range of new approaches to gain understanding of how microorganisms affect the microtextures, isotopic chemistry, and history of the rocks they interact with.

If we can unravel their story, these long-neglected microbes will reveal a profound tale about the co-evolution of Earth and life.

Katrina Edwards grew up in central Ohio, where she pursued an initial early career in the family business of running a small municipal airport just north of Columbus. She spent several years assisting her father and siblings in general airport operations (graduating to the role of chief flight instructor), which she continued as she pursued a bachelor's degree in geology at Ohio State University. Edwards then "retired" to attend the University of Wisconsin, Madison, where she earned a Ph.D. in geomicrobiology—the first degree in this field ever awarded by the university. Edwards and her family moved to Massachusetts in 1999 to join WHOI, where she established a geomicrobiology lab. It focuses on "the tooth decay of the solid Earth," she says, or more specifically, the transformation and degradation of Earth materials (rocks, minerals, organic matter) by microbes. Edwards now enjoys deep-sea exploration, as long as someone else "flies" the submarine and she can focus on geomicrobiological research.

Continental drift closed an oceanic gateway that once connected the Atlantic and Pacific Oceans, creating the Isthmus of Panama. The continental shift led to changes in ocean circulation and Earth's climate.

The collision of the Indian and Eurasian Plates uplifted the Himalayas and the Tibetan Plateau, which scientists believe resulted in the rise of the Asian monsoons.

Shifting Continents and Climates

Sixty-five millions years ago, dinosaurs had just become extinct, and mammals were starting to dominate the planet. Tropical conditions extended to Northern Spain and the heartland of North America. Large trees grew in Greenland and Antarctica, and alligators and primates could be found on Ellesmere Island in Arctic Canada. Global temperatures were 6° to 10°C (11° to 18°F) warmer than today, and the polar regions were free of ice.

Since then, Earth's history has been marked by a sustained and nearly continuous cooling trend, punctuated by abrupt shifts and transitions. Today, *Homo sapiens* dominate the landscape, the poles are blanketed in ice, and over the past 3 million years, massive continental glaciers have waxed and waned in an ongoing era of ice ages. Our modern climate is a brief, temperate respite from an otherwise cold cycle in Earth's geologic life.

So how did our hothouse planet turn into an icehouse planet?

Tectonic causes, climatic effects

One explanation for the change is the steadily and substantially decreasing levels of carbon dioxide and other greenhouse gases in the atmosphere (at least until the anomalous and very recent post-Industrial Revolution era). Less greenhouse gas means that less heat is trapped in Earth's atmosphere.

But changes in Earth's atmosphere cannot explain the full extent of global cooling or periods of acute change. Nor can scientists fully explain the causes of the atmospheric changes themselves.

So what other forces or processes might have rearranged Earth's climate so dramatically?

In recent years, scientists have been building a persuasive but still controversial case that changes in the solid Earth (the crust and mantle) spurred changes in the liquid Earth (the oceans and atmosphere). In other words, so-called tectonic forces—the drifting and collisions of Earth's tectonic plates—may lead to climate changes.

Rising mountains, closing gateways

The following articles outline two theories that link tectonic and climatic changes. One theory, outlined by Gerald Haug of the Eidgenossiche Technische Hochschule (ETH) in Zürich, Switzerland, and colleagues, proposes that the opening and closing of oceanic gateways between land masses—a result of continental drift—may have altered global ocean circulation patterns, which, in turn, led to climate changes. According to another theory, outlined by Peter Clift of Woods Hole Oceanographic Institution, the uplift of great mountain belts—caused by continental collisions—may have disrupted atmospheric circulation and triggered a cascade of other climate changes.

"Understanding the links between solid and liquid Earth systems is a first-order scientific problem for the 21^{st} century," says Clift, a marine geologist.

The best evidence to reveal those links, he notes, is buried under the seafloor.

—*Mike Carlowicz*

Moving Earth and Heaven

Colliding continents, the rise of the Himalayas, and the birth of the monsoons

By Peter Clift, Associate Scientist
Geology and Geophysics Department
Woods Hole Oceanographic Institution

Therefore will not we fear, though the Earth be removed, and though the mountains be carried into the midst of the sea. —Psalm 46

As a geologist, I do not fear the processes that carry Earth and mountain into the sea. I rejoice in them.

The mountains rise, are lashed by wind and weather, and erode. The rivers carry mud and debris from the mountains into the ocean, where they settle onto the relatively tranquil seafloor and are preserved. The sediments bear evidence about where they came from, what happened to them, and when. By analyzing and dating these seafloor sediments, scientists can piece together clues to reconstruct when and how fast their mountain sources rose to great heights millions of years ago, and how the climate and other environmental conditions may have changed in response.

Linking mountains and monsoons

Tens of millions of years ago, a geological process was set in motion that changed the planet. It produced some of the world's most dramatic and extensive mountain ranges. It probably created one of the planet's most intense and important climate phenomena—the Asian monsoons—which today pace and undergird the health and welfare of billions of people in South and East Asia, two-thirds of the total population on the planet. And it may have provoked large-scale environmental changes in the past that brought hominids out of trees and upright onto two feet.

All of these developments in recent Earth history ultimately may be attributed to the land masses now known as India and Arabia, which began moving north some 100 million years ago, on a collision course with what is now Eurasia. According to plate tectonic theory, Earth's crust is composed of interlocking, moving oceanic and continental plates. Scientists consider the collision of the Indian and Eurasian Plates the classic example of how plate tectonics can alter the circulation of the oceans and atmosphere. Here's the hypothetical sequence of events:

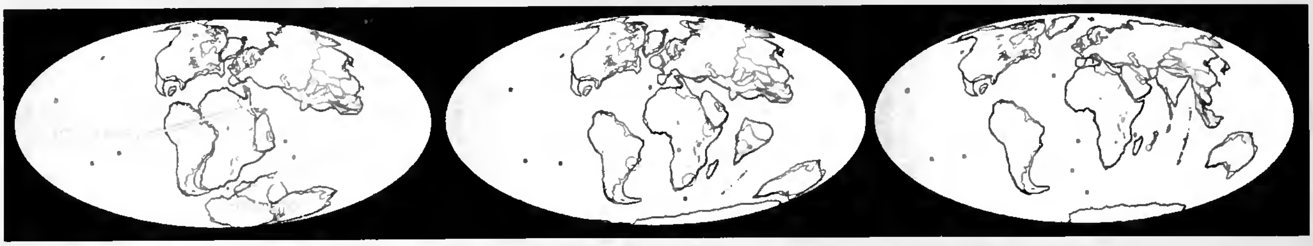
The birth of the monsoons

Before the Indian and Eurasian Plates collided, an ancient ocean called the Tethys, lay between Eurasia and Africa. By about 55 million years ago, the continents squeezed out the ocean, and some research suggests that the resulting rearrangement of ocean currents may have provoked the strong global warming that came shortly after.

As India smashed into Asia, the world's tallest mountain ranges were thrust up like the hood of a car in a head-on collision. On the Indian Plate, the Himalaya Mountains were formed, spanning Pakistan, India, Nepal, and Bhutan. The Indian

HIGH AND MIGHTY—A view of Pangong Lake in the Ladakh region of Northern India, taken at an altitude of 18,000 feet, shows the great flat, 2-mile-high expanse of the Tibetan Plateau, extending in the background as far as the eye can see.

Colliding continents



120 million years ago
The Indian subcontinent was part of a supercontinent called Gondwana. The ancient Tethys Ocean existed between the South American/African and Eurasian supercontinents.

60 million years ago
The Indian subcontinent, moving toward Asia at a speed of 10 centimeters per year, heads toward a collision about 50 million years ago.

Today
The India-Asia collision has closed the ancient Tethys Ocean, created the Himalayan, Karakoram, and Hindu Kush mountain ranges, and uplifted the great Tibetan Plateau.

Plate was shoved under the Eurasian Plate, uplifting the Karakoram and Hindu Kush Mountains in Afghanistan and Pakistan, as well as the great Tibetan Plateau—an expanse about 4.5 kilometers high and half the size of the continental United States. The creation of this dramatic continental topography launched a cascade of planetary changes.

The Tibetan Plateau acts like a gigantic exposed brick, absorbing summer heat and heating the atmosphere above it. Hot air rises, and cool, moist air—drawn in from over surrounding oceans—rushes in to replace it. That moist air is the source of monsoon rains.

New evidence suggests that between 22 million and 15 million years ago, the Asian monsoons may have begun to strengthen. The onset of the monsoons may have been triggered when the Tibetan Plateau reached a threshold height of 2 to 3 kilometers (1.2 to 1.8 miles).

Removing CO_2 from the atmosphere

As the mountains rose upward, the land became more exposed to the forces of weather and gravity. Rainwater contains acids that chemically react with rocks. In the process, called chemical weathering, carbon dioxide is drawn out of the atmosphere and converted into carbonate in rocks. As the monsoons strengthened, chemical weathering increased.

As the mountains rose and monsoon rains increased, rivers also swelled and cut more deeply into the mountains, increasing erosion and carrying more sediments into the oceans. To give a sense of scale, the Indus River today deposits about 1,000 million tons of mud and sand each year onto the Indus Submarine Fan in the Arabian Sea. Relieved of such massive sedimentary weight, the mountains could be thrust up higher, in a reinforcing cycle that continued to increase monsoons, erosion, and uplift.

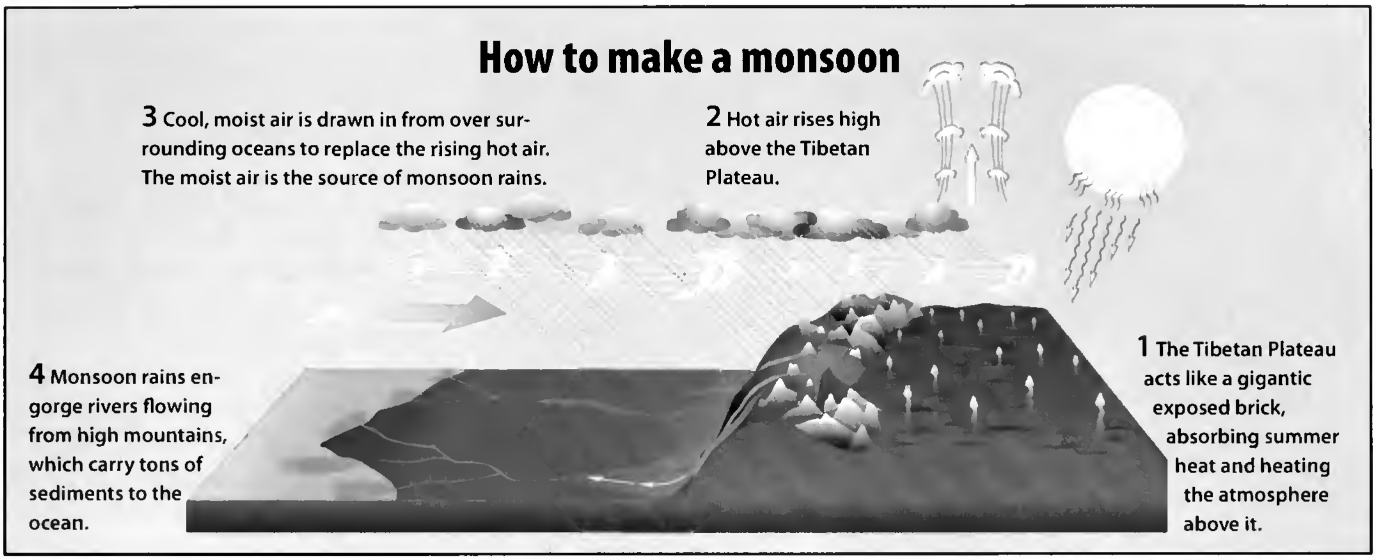
Evolving climates

Climatically, research suggests that the increasing rates of weathering and erosion of the mountains converted large volumes of carbon dioxide from the atmosphere into carbonate sediments that eventually were deposited on the ocean bottom. As carbon dioxide was drawn out of the atmosphere, the global greenhouse effect

The rise of the Himalayas and the Tibetan Plateau

In the India-Asia collision, the Eurasian Plate was compressed and thickened to uplift the Tibetan Plateau. The bulk of the Indian Plate continues to be thrust under the Eurasian Plate, further uplifting Tibet. Slices of the Indian Plate were scraped off to form the Himalayas.

Jayne Doucette, WHOI Graphic Services



was reduced, setting the stage for long-term cooling of the planet that culminated in the ice ages of the last 2.7 million years.

In addition, an influx of chemical nutrients into the ocean may have sparked blooms of phytoplankton. Microscopic marine plants also extract atmospheric carbon dioxide via photosynthesis and convert it into carbonate organic matter that settles to the seafloor when the plankton die.

As monsoon winds strengthened, they blew waters laterally across the ocean surface. To replace these waters, cooler, nutrient-rich waters upwelled from the depths to the sunlit surface, providing all the ingredients plankton need to thrive. Evidence from seafloor sediment cores shows an abundance of preserved microscopic shells of plankton (and, by inference, a strengthening of the monsoons) beginning about 8.5 million years ago in the Arabian Sea, though the situation in other parts of Asia is less clear.

Evolving humans

Curiously, that same time period marks crucial events in human evolutionary history. The cumulative effects of decreasing atmospheric carbon dioxide reduced the global greenhouse effect, creating a much colder and drier Earth.

About 8 million years ago, paleontological evidence shows that the great apes became extinct in Europe and Asia—victims of a colder, drier climate. They maintained populations only in Southeast Asia and Africa.

About 7 million to 8 million years ago, humans began to diverge from great apes in Africa, which, though still equatorially warm, began to dry out. Jungles and forests turned into grasslands and deserts. The climate shift provided evolutionary advantages for bipedal hominids with larger brains to cope with environmental changes.

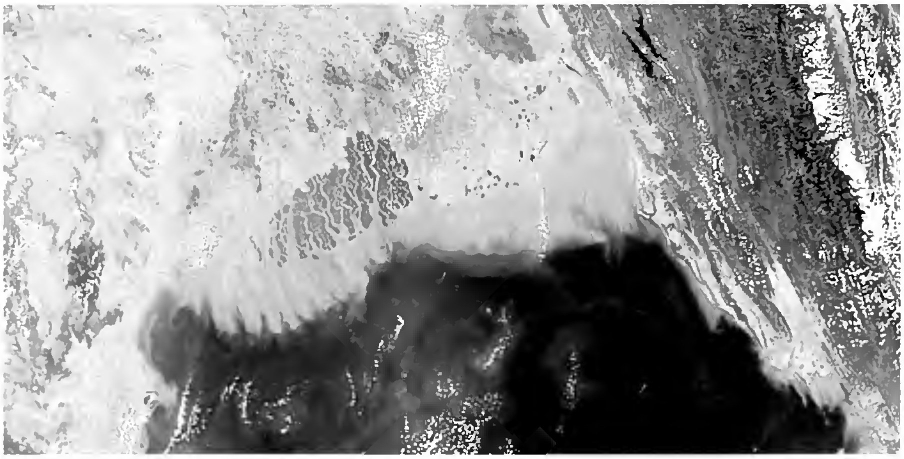
Continental clues are erased

All this is an intriguing, but speculative, theory.

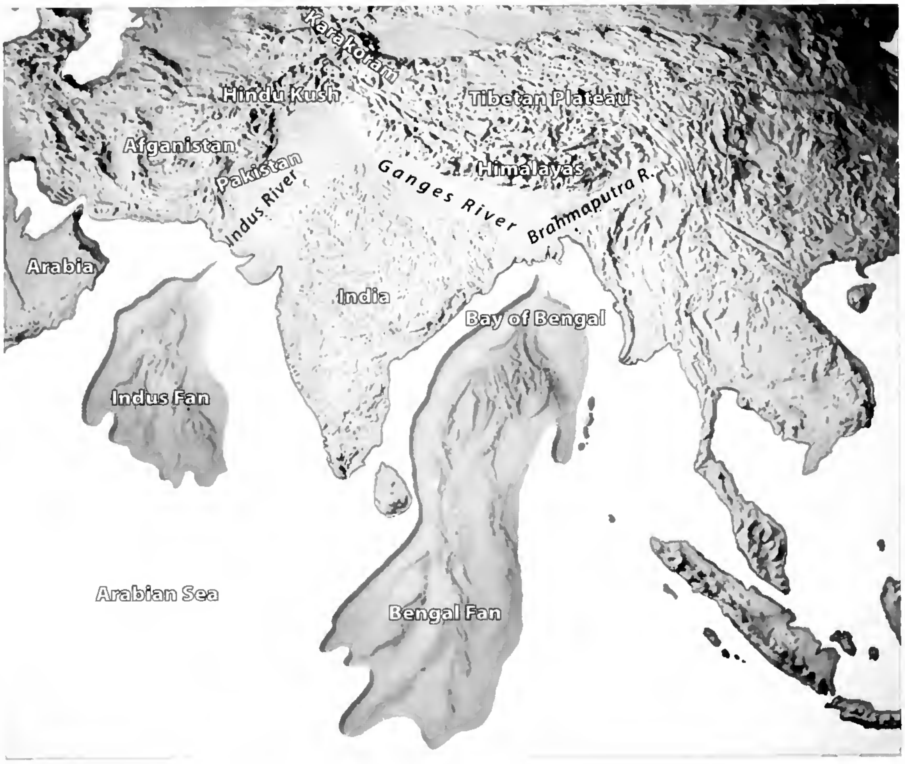
Unfortunately, our detailed theoretical understanding of Earth's climatic evolution is not matched by a sufficiently detailed record of the evolution of Tibetan and Himalayan uplift and erosion. Theories concerning the uplift of Tibet set the start date anywhere from 65 million years ago to as recently as 2 million years ago.

This lack of consensus principally reflects the lack of a good continental geological record to chart the growth of the mountains. Because of chemical weathering, continental sediments are difficult to date, and erosion often wipes away large and critical portions of the record, destroying any hope for a continuous chronology.

Fortunately, marine sediments preserve robust, continuous records that can link tectonic and climatic evolution. From deep-sea cores, marine geologists



FLOWING TO THE SEA—An aerial view of the Ganges River Delta shows tons of sediments being poured into the northern Bay of Bengal off India.



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FROM THE MOUNTAINTOPS TO THE BOTTOM OF THE OCEAN—Great rivers (the Ganges, Brahmaputra, and Indus) transport large volumes of sediments from great mountains (the Himalayas, the Hindu Kush and the Karakoram) into the ocean. The Bengal Fan extends 2,500 kilometers (1,535 miles) south into the Bay of Bengal and is 22 kilometers (13.5 miles) thick. The Indus Fan is 10 kilometers (6 miles) thick and extends 1,000 to 1,500 kilometers (610 to 915 miles) into the Arabian Sea.

have pieced together a detailed record of environmental change in Asia and Africa. Many of those cores have come from the Arabian Sea, the South China Sea, and the Bay of Bengal, which offer fertile territory for examining the interacting histories of the solid Earth and its climate.

The Tibet-Himalaya region is drained by some of the most vigorous rivers on Earth. The Ganges and Brahmaputra River systems transport large volumes of detritus from the rapidly eroding Himalayas and deposit them in the Bengal Fan in the Indian Ocean. The Bengal Fan is the largest sediment body on the planet; it runs 2,500 kilometers (1,535 miles) south into the Bay of Bengal and is 22 kilometers (13.5 miles) thick.

The modern Indus River system drains sediments from the high peaks of the Karakoram, Hindu Kush, and Western Tibet. It has created the 10-kilometer-thick Indus Fan, which extends 1,000 to 1,500 kilometers into the Arabian Sea.

Located between the land masses of Arabia and the Indian subcontinent, the Arabian Sea is ideally placed to record the effects of India's collision with the Asian mainland. New data now suggest that the Indus River and Fan system was initiated shortly after the India-Asia collision about 55 million years ago, probably in response to the initial uplift of Tibet. This long history makes it a natural storehouse of information on how the mountains developed over long time periods.

An archive buried on the seafloor

Studying this rich store of deep-sea sediments, I have been able to estimate that erosion increased around 16 million years ago, somewhat earlier than the start of the monsoon pattern. That pulse of erosion appears to have been the result of mountain building in the Karakoram.

Conversely, the record shows a decrease in sedimentation rates about 5 million to 7 million years ago. Some researchers have proposed this may be related to the strengthening of the monsoons. Increased monsoon rainfall, they speculate, might have promoted the growth of vegetation, stabilizing the slopes and reducing erosion. Other scientists, including me, believe this period was drier, with less rainfall, less erosion, and less seafloor sedimentation.

The marine sediments of the Arabian Sea and the Bay of Bengal hold the promise of allowing ocean scientists to make direct correlations among the evolution of the monsoon, the uplift of the Tibetan Plateau, and the erosion of the plateau by heavy monsoonal winds and rains. With further deep-sea scientific drilling and marine seismic research to reveal sub-seafloor sedimentary layers, we can expose this record in detail and discover how Earth's tectonic, climate, and perhaps human, evolutions are all linked.

Tom Kleindinst, WHOI

Peter Clift grew up far from the Himalayas, just outside London, England. After degrees at Oxford and Edinburgh Universities and some very pleasant field research in Greece to escape the English rain, Peter spent time exploring in central Asia, traveling overland from Pakistan to Beijing. Smitten with the travel bug, he made his first expedition to the Indian sub-continent where he began to reconstruct the history of mountain growth from the sediments he found there. Shortly after, an invitation to sail on a cruise in the Southwest Pacific led to a new love of sea-going science and an interest in the interactions between the land and oceans. He worked with the Ocean Drilling Program at Texas A&M University before coming to Woods Hole in 1995 as an Assistant Scientist. When he is not tending to his fuzzy family of cats and birds and cycling around town, Clift continues to do fieldwork in remote parts of Asia more often associated these days with CNN than scientific journals.

How the Isthmus of Panama Put Ice in the Arctic

Drifting continents open and close gateways between oceans and shift Earth's climate

By Gerald H. Haug, Geoforschungszentrum Potsdam (GFZ), Germany; Ralf Tiedemann, Forschungszentrum für Marine Geowissenschaften, Germany; and Lloyd D. Keigwin, Woods Hole Oceanographic Institution

The long lag time has always puzzled scientists: Why did Antarctica become covered by massive ice sheets 34 million years ago, while the Arctic Ocean acquired its ice cap only about 3 million year ago?

Since the end of the extremely warm, dinosaur-dominated Cretaceous Era 65 million years ago, heat-trapping greenhouse gases in the atmosphere have steadily declined (with the anomalous exception of the last century), and the planet as a whole has steadily cooled. So why didn't both poles freeze at the same time?

The answer to the paradox lies in the complex interplay among the continents, oceans, and atmosphere. Like pieces of a puzzle, Earth's moving tectonic plates have rearranged themselves on the surface of the globe—shifting the configurations of intervening oceans, altering ocean circulation, and causing changes in climate.

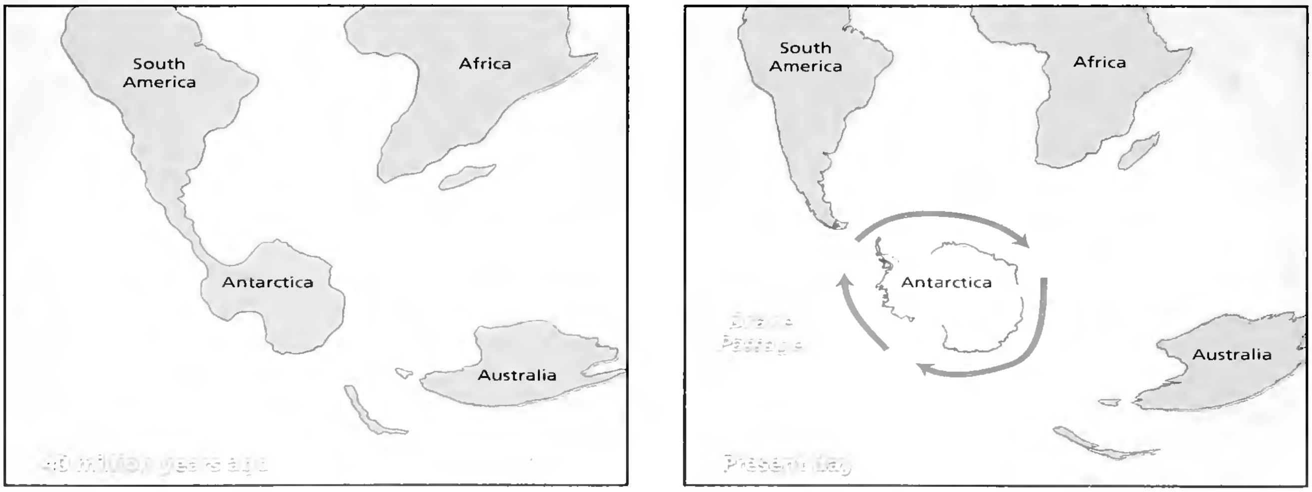
The development of ice sheets in the Southern Hemisphere around 34 million years ago seems fairly straightforward. The supercontinent of Gondwana broke apart, separating into subsections that became Africa, India, Australia, South America, and Antarctica. Passageways opened between these new continents, allowing oceans to flow between them.

When Antarctica was finally severed from the southern tip of South America to create the Drake Passage, Antarctica became completely surrounded by the Southern Ocean. The powerful Antarctic Circumpolar Current began to sweep all the way around the continent, effectively isolating Antarctica from most of the warmth from the global oceans and provoking large-scale cooling.

The Northern Hemisphere is more problematic. From sediment cores and other data, we know that until about 5 million years ago, North and South America were not connected. A huge gap—the Central American Seaway—allowed tropical water to flow between the Atlantic and Pacific Oceans.

A growing body of evidence suggests that the formation of the Isthmus of Panama partitioned the Atlantic and Pacific Oceans and fundamentally changed global

How Antarctica got its ice sheets



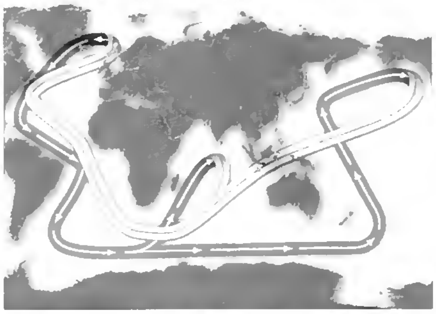
In the continual movement of Earth's tectonic plates, Antarctica was severed from the southern tip of South America about 34 million years ago, creating the Drake Passage. Antarctica became completely surrounded by ocean. The powerful Antarctic Circumpolar Current began to sweep around the continent, isolating Antarctica from the warmth of the global oceans and provoking large-scale cooling.

ocean circulation. The closing of the Central American Seaway initially may have warmed Earth's climate, but then set the stage for glaciation in the Northern Hemisphere at about 2.7 million years ago.

The Ocean Conveyor

A fundamental element of today's climate system is a conveyor-like ocean circulation pattern that distributes vast quantities of heat and moisture around our planet. This global circulation is propelled by the sinking of cold, salty—and therefore dense—ocean waters.

In today's ocean, warm, salty surface water from the Caribbean, the Gulf of Mexico, and the equatorial Atlantic flows northward in the Gulf Stream. As the warm water reaches high North Atlantic latitudes, it gives up heat and moisture to the atmosphere, leaving cold, salty, dense water that sinks to the ocean floor. This water flows at depth, southward and beneath the Gulf Stream, to the Southern Ocean, then through the Indian and Pacific Oceans. Eventually, the water mixes with warmer water and returns to the Atlantic to complete the circulation.



Today's climate system is influenced by the ocean's conveyor-like global circulation. Cold, salty waters sink to drive the conveyor, and warm surface currents complete the loop.

The principal engine of this global circulation, often called the Ocean Conveyor, is the difference in salt content between the Atlantic and Pacific Oceans. Before the Isthmus of Panama existed, Pacific surface waters flowed into the Atlantic. Their waters mixed, roughly balancing the two oceans' salinity.

About 5 million years ago, the North American, South American, and Caribbean Plates began to converge. The gradual shoaling of the Central American Seaway began to restrict the exchange of water between the Pacific and Atlantic, and their salinities diverged.

Evaporation in the tropical Atlantic and Caribbean left ocean waters there saltier and put fresh water vapor into the atmosphere. The Trade Winds carried the water vapor from east to west across the low-lying Isthmus of Panama and deposited fresh water in the Pacific through rainfall. As a result, the Pacific became relatively fresher, while salinity slowly and steadily increased in the Atlantic.

As a result of the Seaway closure, the Gulf Stream intensified. It transported more warm, salty water masses to high northern latitudes, where Arctic winds cooled them until they became dense enough to sink to the ocean floor. The Ocean Conveyor was rolling, drawing even more Gulf Stream waters northward.

How does this make ice in the north?

Peter Weyl of Oregon State University hypothesized in 1968 that the closure of the Central American Seaway and the intensification of the Gulf Stream would

The rise of the Isthmus of Panama and the closing of the Central American Seaway

Surface waters flowed from the Pacific into the Atlantic 10 million years ago via an ocean gateway called the Central American Seaway, and both oceans had the same salinity.

About 5 million years ago, the North American, South American, and Caribbean Plates converged. The rise of the Isthmus of Panama restricted water exchange between the Atlantic and Pacific, and their salinities diverged. The isthmus diverted waters that once flowed through the Seaway. The Gulf Stream began to intensify.

Today, evaporation in the tropical Atlantic and Caribbean leaves behind saltier ocean waters and puts fresh water vapor into the atmosphere. Trade Winds carry the water vapor westward across the low-lying isthmus, depositing fresh water into the Pacific through rainfall. As a result, the Atlantic is saltier than the Pacific.

have brought a critical ingredient for ice sheet growth to the Northern Hemisphere—moisture. Weyl's theory assumed that the closure of the Central American Seaway and the buildup of salt in the Atlantic coincided with the growth of northern ice sheets between 3.1 and 2.7 million years ago.

But doubts about this hypothesis surfaced in 1982, when Lloyd Keigwin of WHOI found evidence in ocean sediments that the closing of the Isthmus of Panama had influenced ocean circulation more than a million years earlier. He demonstrated that the salinity contrast between the Atlantic and Pacific had already started to develop by 4.2 million years ago.

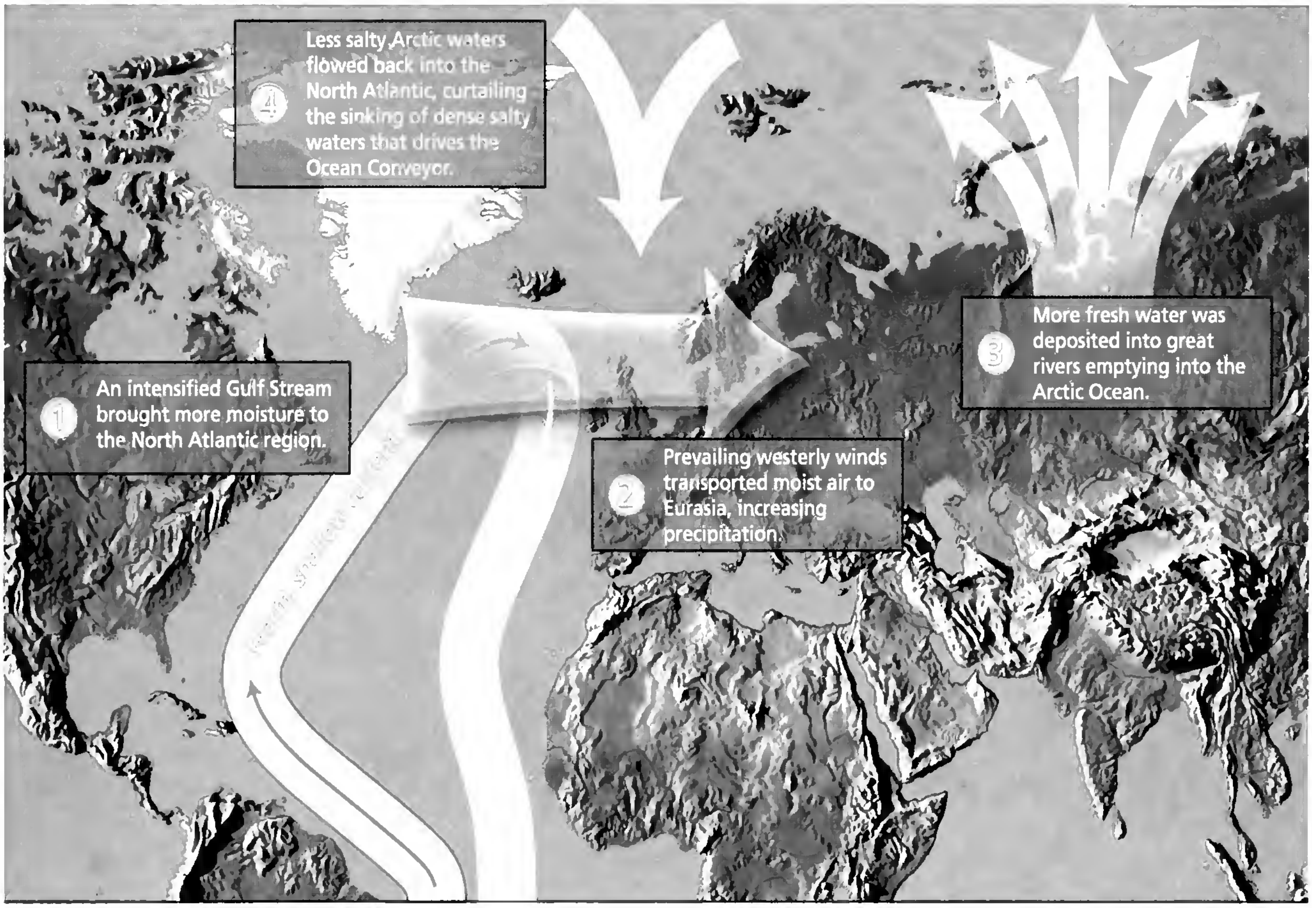
In 1998, Gerald Haug and Ralf Tiedemann confirmed Keigwin's research with higher-resolution data from sediment cores. If the salinity had already changed by 4.2 million year ago, why didn't glaciation start until 2.7 million years ago? On the contrary, the Earth experienced a warm spell between 4.5 million and 2.7 million years ago.

That global warm spell, called the Mid-Pliocene Warm Period, may also have been related to the closing of the Central American Seaway and the consequent rearrangement of global ocean circulation. An invigorated Ocean Conveyor could have driven a stronger flow of deep waters from the Atlantic to the North Pacific Ocean, which is the end of the line for deep-ocean circulation.

On their journey to the North Pacific, these deep waters became enriched in nutrients and carbon dioxide. In the Subarctic Pacific, these deep waters could have upwelled, rising to the sunlit surface to provide the ingredients to spark enormous blooms of phytoplankton. Great abundances of silica and opal (the preserved material from the phytoplankton shells)

Short-circuiting the Ocean Conveyor

What factors caused the Northern Hemisphere to develop sea ice and glaciers about 3 million years ago? The closing of the Central American Seaway intensified the Gulf Stream, the upper limb of a conveyor-like global ocean circulation called the Ocean Conveyor. The Gulf Stream transported salt to the North Atlantic, making waters there dense enough to sink and drive the lower limb of the Conveyor. According to one theory, the Gulf Stream also transported moisture to the North Atlantic region and encouraged ice formation. But the Gulf Stream also conveys heat, which would deter glaciation. Neal Driscoll and Gerald Haug proposed a solution to this apparent contradiction (below).



in seafloor sediments are evidence of both the blooms and the strong upwelling.

The upwelling may have been so strong, however, that the phytoplankton did not keep pace; that is, more carbon-dioxide-rich water from deeper ocean regions upwelled than the phytoplankton could use. Consequently, the excess carbon dioxide "leaked" back into the atmosphere, adding a greenhouse gas that warmed the planet.

Short-circuiting the Conveyor

What shut down the Mid-Pliocene Warm Period about 2.7 million years ago? And what finally caused Northern Hemispheric glaciation at about the same time—but nearly 2 million years after the Isthmus of Panama formed?

Weyl's original theory of a stronger, moisture-laden Gulf Stream raised another nettlesome question: How could the Gulf Stream—which transports not only moisture but also heat to the North Atlantic—lead to major Northern Hemisphere cooling and the formation of ice?

Gerald Haug and Neal Driscoll of Scripps Institution of Oceanography proposed one solution. They postulated that moisture carried northward by the Gulf Stream was transported by prevailing westerly winds to Eurasia. It fell as rain or snow, eventually depositing more fresh water into the Arctic Ocean—either directly, or via the great Siberian rivers that empty into the Arctic Ocean.

The added fresh water would have facilitated the formation of sea ice, which would reflect more sunlight and heat back into space. It would also act as a barrier blocking heat stored in the ocean from escaping to the atmosphere above the Arctic. Both these phenomena would further cool the high latitudes. In addition, Arctic waters flowing back into the North Atlantic would have become less cold and salty—short-circuiting the efficiency of the Ocean Conveyor belt as a global heat pump to North Atlantic regions.

The tilt toward glaciation

These preconditions—moisture plus an Arctic nucleus for cooling—would have made the climate system highly susceptible to ice sheet growth. Even modest changes in the global environment would have been sufficient to tip the scales and lead to the onset of major Northern Hemisphere glaciation.

Just such a change occurred between 3.1 million and 2.5 million years ago, as Earth's axis fluctuated so that the planet's tilt toward the sun was less than today's angle of 23.45 degrees. Less tilt to the Earth would have reduced the amount and intensity of solar radiation hitting the Northern Hemisphere, leading to colder summers and less melting of winter snows.

The onset of Northern Hemisphere glaciation also affected the Subarctic Pacific. It led to the formation about 2.7 million years ago of a freshwater lid at the surface of the ocean, called a halocline. This Arctic halocline would have created a barrier to upwelling, which blocked deep carbon-dioxide-rich deep waters from rising to the surface. The "leak" of heat-trapping carbon dioxide into the atmosphere was stemmed, further cooling the planet.

Many other ocean-atmosphere feedback mechanisms, resulting from the opening and closing of oceanic gateways, remain imperfectly understood. And scientists are also exploring the ramifications of other oceanic gateways.

Mark Cane of Columbia University and Peter Molnar of the University of Colorado, for instance, have suggested that the uplifting and movement of the Indonesian Islands between 5 million and 3 million years ago would have fundamentally redirected a smaller amount of warm South Pacific water and a greater amount of cooler North Pacific water through the Indonesian Seaway. The consequence might have been that the Pacific changed from more permanent El Niño-like conditions (which move heat from the tropics to high latitudes) to a more La Niña-like state (which would have curtailed the heat transfer and cooled the Northern Hemisphere).

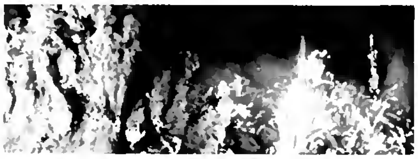
The lessons from these vast geologic and geographic changes are both elegantly simple and excruciatingly complex. The opening and closing of seaways has a profound influence on the distribution of fresh water, nutrients, and energy in the global ocean. The coupling of these changing oceans with a changing atmosphere inevitably means a changing climate.

Gerald Haug studied marine geology at Kiel University, Germany. He was then a postdoctoral scholar at the University of British Columbia, in Vancouver, Canada, and at WHOI in Lloyd Keigwin's lab. In 1998-99, he was a researcher at the University of Southern California in Los Angeles. Between 2000 and 2002, he did his 'Habilitation' at ETH Zürich, Switzerland, and was an adjunct scientist at WHOI. Since 2003, he has been a scientist at Geoforschungszentrum Potsdam with a joint appointment as professor at Potsdam University, Germany. Gerald benefited tremendously from his time at WHOI, both scientifically and in his passion for old cars, which he shares with co-author Keigwin

Lloyd Keigwin studied geology at Brown University and oceanography at the Univeristy of Rhode Island. At Brown he was in the ROTC and after graduation, served on active duty for two years as a line officer on a destroyer escort in Newport, R.I. He maintained his affiliation with the Naval Reserve, retiring after 30 years as Captain USNR. At Brown, his interest in geology was stimulated by Leo Laporte, and his introduction to oceanography was through John Imbrie. Keigwin's research interests have evolved from studying ocean and climate changes that occurred millions of years ago to those that occurred in recent centuries. Noting this progression, a National Science Foundation program manager quipped, "Soon he will be studying the future, and we won't have to fund him any longer!" When not busy with family or having fun doing science, Keigwin works in his barn, trying to keep old sports cars running.

The Ocean Institutes

In 2000, Woods Hole Oceanographic Institution established four Ocean Institutes to accelerate advances in knowledge about the oceans and to convey discoveries expeditiously into the public realm. The Ocean Institutes' goals are to catalyze innovative thinking that can open up new scientific vistas, to spur collaboration among scientists in different disciplines, and to stimulate a rich and productive educational environment that will engage future leaders of oceanography. Concurrently, the Institute's mission is to shorten the time between acquiring knowledge and making it accessible to decision-makers who can use this information to benefit society and steward the Earth.



The Deep Ocean Exploration Institute investigates Earth's dynamic processes—beneath the oceans where more than 80 percent of all earthquake and volcanic activity occurs and where the clues to understanding the inner workings of our planet lie. The seafloor is our window into the dynamic, fundamental processes that generate natural disasters, produce oil and mineral resources, create and destroy oceans, rend continents, build mountains and islands, and foster life.

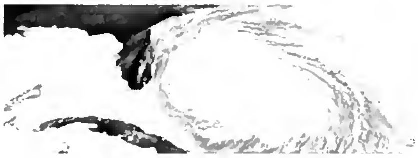
The Deep Ocean Exploration Institute:

- explores how our dynamic planet evolves and changes
- examines the basic forces that create earthquakes and volcanoes
- develops technology related to seafloor observatories and deep-submergence vehicles
- investigates unusual chemosynthetic communities of life on and below the seafloor
- explores potential new energy and mineral resources in the oceans

The Ocean Life Institute explores the ocean's extraordinary diversity of life—from microbes or whales—to identify ways to sustain healthy marine environments and to learn about the origin and evolution of life on Earth. The more we look into the oceans, the more we find remarkable life forms thriving in environments ranging from Antarctic sea ice to the volcanic crust below the seafloor.

The Ocean Life Institute:

- explores biodiversity in the oceans
- finds ways to monitor and sustain the health of marine ecosystems
- studies marine life's physiological and ecological adaptations
- investigates the evolution of life in Earth's oceans
- develops new techniques and instruments to explore ocean life



The Ocean and Climate Change Institute seeks to understand the role of the ocean in regulating Earth's climate and to improve our ability to forecast future climate change. The ocean stores vast quantities of heat, water, and carbon dioxide and works with the atmosphere in regulating global and regional climates—on time scales ranging from days (storms and hurricanes), seasons (monsoons), years (El Niños), to centuries and longer.

The Ocean and Climate Change Institute:

- identifies the climatic effects of ocean circulation patterns
- develops an ocean-monitoring network to forecast climate changes
- examines geological records to better understand ocean behavior
- studies ocean dynamics that may trigger large, abrupt climate shifts
- evaluates the ocean's response to the buildup of greenhouse gases

The Coastal Ocean Institute examines one of the most vital—and vulnerable—regions on Earth: the coast. Our planet's exploding population has begun to put stress on the fragile coastal ocean and has exposed more people to coastal hazards such as storms, beach erosion, and pollution. Understanding the complex, delicately balanced processes at work in coastal areas is the key to ensuring that they remain productive and attractive.

The Coastal Ocean Institute:

- reveals basic processes underlying the coastal ocean's fertility
- provides sound science to guide coastal management policies
- examines uses of coastal resources, such as wind, oil, and fisheries
- identifies strategies to mitigate coastal hazards and natural disasters
- promotes awareness of the coastal zone's importance to society

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