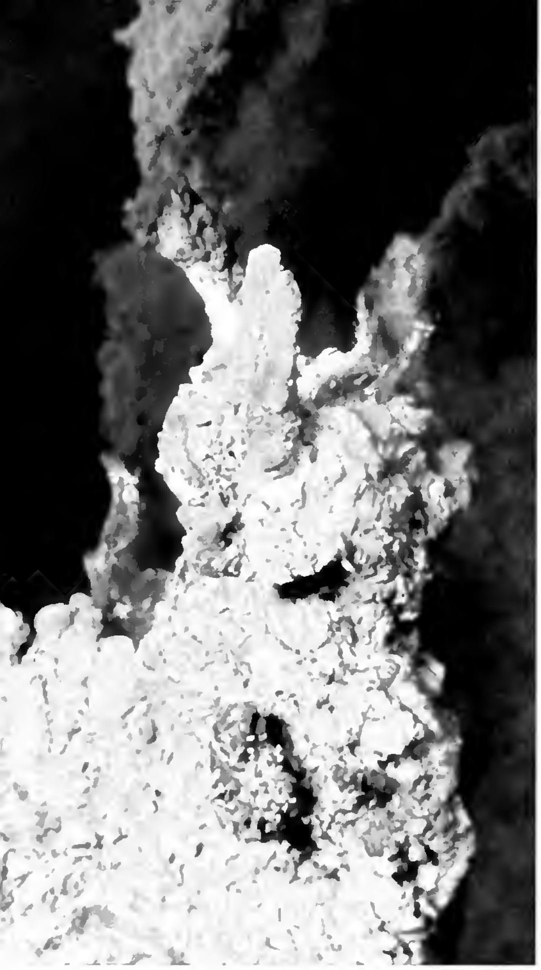
Oceanus

REPORTS ON RESEARCH FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

Vol. 41, No. 2 • 1998 • ISSN 0029-8182

The Mid-Ocean Ridge

Part 2


Patrick Hickey

Dark, particle-rich hydrothermal plumes surge from a black smoker chimney photographed in 1998 at 17°S on the East Pacific Rise.

Oceanus is published semi-annually by the Woods Hole Oceanographic Institution, Woods Hole, MA 02543
508-289-3516 · http://www.whoi.edu/oceanus

A calendar-year *Oceanus* subscription is available for $15 in the US, $18 in Canada. The WHOI Publication Package, including *Oceanus* magazine and *Woods Hole Currents* (a quarterly publication for WHOI Associates and friends), is available for a $25 calendar-year fee in the US, $30 in Canada. Outside North America, the annual fee for *Oceanus* magazine only is $25, and the Publication Package costs $40. To receive the publications, please call (toll free) 1-800-291-6458, or write: WHOI Publication Services, P.O. Box 50145, New Bedford, MA 02745-0005

To purchase single and back-issue copies of *Oceanus*, please contact: Jane Hopewood, WHOI–MS#5, Woods Hole, MA 02543. Phone: 508-289-3516. Fax: 508-457-2182.

Checks should be drawn on a US bank in US dollars and made payable to: Woods Hole Oceanographic Institution.

When sending change of address, please include mailing label. Claims for missing numbers from the US will be honored within three months of publication, overseas, six months.

Oceanus

REPORTS ON RESEARCH FROM THE WOODS HOLE OCEANOGRAPHIC INSTITUTION

Vol. 41, No. 2 · 1998 · ISSN 0029-8182

The Mid-Ocean Ridge

Biologists' First Look at Vent Communities—Galápagos Rift, 1979 1
By J. Frederick Grassle

Deep-Sea Diaspora 6
The LARVE Project Explores How Species Migrate from Vent to Vent
By Lauren Mullineaux and Donal Manahan

Life on the Seafloor and Elsewhere in the Solar System 10
If Volcanism Plus Oceans Can Support Life at the Vents, Why Not on Other Planetary Bodies?
By John R. Delaney

ALISS in Wonderland 14
Imaging Ambient Light at Deep-Sea Hydrothermal Vents
By Sheri N. White and Alan D. Chave

The Cauldron Beneath the Seafloor 18
Percolating Through Volcanic Subsurface Rocks, Seawater Is Chemically Transformed
By Susan E. Humphris and Tom McCollom

How to Build a Black Smoker Chimney 22
The Formation of Mineral Deposits at Mid-Ocean Ridges
By Margaret Kingston Tivey

The Big MELT 27
The Mantle Electromagnetic and Tomography Experiment
By Donald Forsyth

Using Seismic Waves to "See" a Slice of the Oceanic Crust 30
By J. Pablo Canales

A Current Affair 32
Measuring Electrical Conductivity Hundreds of Kilometers within the Earth
By Robert Evans

Hitting the Hotspots 34
New Studies Reveal Critical Interactions Between Hotspots and Mid-Ocean Ridges
By Jian Lin

Editor: Laurence Lippsett · Designer: Jim Canavan

COVER: **This black smoker, among the first ever photographed, was found on the East Pacific Rise during the 1979 expedition on which black smokers were first discovered.** Photo by Dudley Foster


Ruth Turner

J. Frederick Grassle

David Clark

Top (left to right): Scientists from a wide range of disciplines (here pausing for an informal dinner on deck) assembled for the first expedition to study hydrothermal vent ecosystems in 1979. WHOI's submersible *Alvin* was extensively modified to accommodate new equipment for the biological dives. *Alvin* is deployed between the catamarans of its original tender, *Lulu*.

'Nothing Could Diminish the Excitement Of Seeing the Animals for the First Time'

Biologists' First Look at Vent Communities—Galápagos Rift, 1979

J. Frederick Grassle
Director, Institute of Marine and Coastal Sciences, Rutgers University

The scientists who made the surprising discovery of teeming life around hydrothermal vents of the Galápagos Rift in 1977 were geologists and geochemists. They had not expected to find spectacular colonies of previously unknown, large animals on the deep seafloor.

It didn't take long after the first amazing reports arrived for deep-sea biologists to mobilize a Galápagos voyage. Holger Jannasch, Howard Sanders, and I from the Woods Hole Oceanographic Institution, Ruth Turner and Carl Berg of Harvard University, and Bob Hessler of Scripps Institution of Oceanography (SIO) met in Woods Hole and decided to send the National Science Foundation (NSF) a proposal for a return trip. I would coordinate the proposal and be chief scientist of the expedition. After discussions with many colleagues, we devised a cruise on a ship with well-equipped labs, combined with an *Alvin* bottom-station expedition. We would subject the newly discovered communities to the full arsenal of techniques available to modern biology.


Below, a flourishing colony of the red-tipped tubeworm *Riftia pachyptila*.

Biologist Fred Grassle dives to the vents in 1979 aboard *Alvin*.

Al Giddings, © National Geographic Society

The original proposal to NSF, submitted in January of 1978, contained subsections from 19 principal investigators representing many institutions (see box below). We posed three main questions about the biological communities at the vents:
1) What is the basis for the origin and concentration of life at hydrothermal vents?
2) How have large organisms adapted to elevated temperatures, high pressure, and hydrogen sulfide?
3) Do the communities that characterize each vent represent a) stages of succession, b) discrete islands resulting from chance immigration, or c) organisms settling in response to different chemical gradients in each area?

Our three-leg NSF program was combined with a geological study supported by the Office of Naval Research and conducted by Jerry van Andel (Oregon State University), Bob Ballard (WHOI), and Kathy Crane (WHOI). The *Angus* (Acoustically NaviGated Underwater System) team was led by Earl Young (WHOI). Ballard had negotiated with both the National Geographic Society (NGS) and Disney Studios concerning a television special. NGS won and, in return for the privilege of documenting our efforts, provided funds for five additional *Alvin* dives.

Total research funds added up to approximately $600,000, nearly $200,000 of which went to equip and support *Alvin*. In the year that elapsed between submitting the proposal and sailing the following January, *Alvin* was extensively modified to augment its capabilities. NGS agreed to provide a pan-and-tilt system for a new prototype RCA digital television camera, which led to the addition of *Alvin's* much-needed second arm. During 1978, we tested special lights for underwater filming. WHOI's Cliff Winget designed a special basket to hold all the necessary sampling equipment within reach of *Alvin's* arms. We built an elaborate multi-valved system, controlled by the flip of electronic switches, to pump seawater from any of an arsenal of nozzles into sample bottles—through either of two sizes of filters to sample microorganisms, or through a large hose, so that fragile animals could be gently slurped into a large, segregated container. We devised an insulated sampling container; a variety of samplers for microorganisms and particulate organic matter; a 35mm stereo camera with temperature probe; apparatus for incubation experiments; in situ respirometers to measure the animals' oxygen uptake and hence their metabolism; fish, crab, and larvae traps; and a device for deploying plates to learn how larvae are dispersed and settle. Tetrahedrons of thick wire were alternately painted black and white every 2 centimeters to provide three-dimensional markers for photographs.

The 14 members of the biology team who sailed

Early Vent Investigators

The collection of NSF proposals funded in 1978 for the first biological expedition to the vents included:
- *Physiological and morphological description, estimation of chemosynthetic productivity and rates of microorganism activity* Holger Jannasch (WHOI), David Karl (University of Hawaii), Jon Tuttle (University of Texas), and Carl Wirsen (WHOI)
- *Small-scale distribution and community structure of benthic species* Fred Grassle (WHOI), Robert Hessler (Scripps Institution of Oceanography), and Howard Sanders (WHOI)
- *Reproduction, larval dispersal* Ruth Turner and Carl Berg (Harvard)
- *Genetic studies of population differentiation in molluscs* Judy Grassle (Marine Biological Laboratory)
- *Ecological energetics of mytilids* Ken Smith (SIO)
- *Feeding relationships of species including field experiments* Berg, F. Grassle, Hessler, Sanders, and Turner
- *Age structure and rates of mollusc growth* Rich Lutz (Yale), Don Rhoads (Yale), and Karl Turekian (Yale)
- *Effects of temperature, oxygen, and pressure on metabolic rates of invertebrates* Jim Childress (University of California, Santa Barbara)
- *Substrate and cofactor binding, catalytic efficiencies and structural stability of enzymes* George Somero (SIO).

Joining our expeditions were Sandy Williams (WHOI), who collected new physical measurements on currents, John Edmond (Massachusetts Institute of Technology), who took chemical measurements of nutrients, hydrogen sulfide, and oxygen, and scientists of WHOI analytical facilities, who gathered chemical measurements of dissolved and particulate organic carbon. Dan Cohen (NOAA Systematics Laboratory) studied the vent fish, and Meredith Jones of the Smithsonian Institution continued his earlier studies on the vestimentiferan tubeworms. John Baross (Oregon State University), who worked on microbiological material from the 1977 cruise, joined the geochemistry leg of the 1979 cruise.

Much to my chagrin, a proposal to study the food chain relationships of microorganisms was not funded by the NSF—I believe because the oceanographic application of immunological analyses had not been published and was not familiar to reviewers. Perhaps as a consequence, we are still uncertain about how various major microbiological taxa contribute to primary productivity at the vents. — Fred Grassle on the first leg were distributed among WHOI's R/V *Lulu* (*Alvin's* tender), R/V *Gillis*, owned by the Navy and operated by the University of Miami, and *Camelot*, a sailing vessel chartered by NGS. When we arrived in Panama on January 10, *Lulu* was already there. *Gillis* arrived two days later, having run aground in the Panama Canal. *Gillis* was so stuffed with science equipment for subsequent legs of the cruise that we could not enter the labs. In the tropical heat, we unloaded several tons of this equipment onto the dock and then loaded many tons of our own equipment that we had shipped separately—with only one case of heat exhaustion, ably treated by Ruth Turner. *Gillis* was supposed to arrive at the vent site two days before *Lulu* to locate the vents within a patch of seafloor about 50 meters in diameter and 2,500 meters deep, some 380 kilometers northwest of the Galápagos Islands. However, an engine overhaul delayed the ship for two days and *Gillis* arrived at the same time as *Lulu*. As a consequence, *Alvin's* first two dives had to be made away from vents while *Angus*, the 2-ton towed camera sled, searched for them. Ballard estimated that it would take at least 30 hours to locate the vents. The tense moments during a meeting on *Gillis* to plan the field experiments, filmed by NGS cinematographer Jim Lipscomb and shown in the 1979 Emmy-Award-winning NGS special *Dive to the Edge of Creation*, were genuine, as was the relief when a few vent clams showed up on the last few frames of a long series of photos taken by *Angus*.

The work on *Lulu* did not go smoothly. There was difficulty with *Alvin's* hydraulic system and dives often ended abruptly as the alarm for a hydraulic leak sounded—once before we even reached the bottom. After most dives, the hydraulic system was taken apart and the *Alvin* crew worked through the night and into the morning to fix the submersible in time for the next day's scheduled dive. Despite the long hours, the crew's morale remained high, and the pilots would tease "the most concerned scientist" of the day by leaving his—neither Ruth nor Kathy were teased—equipment off the basket until the last minute.

At a precruise meeting near the end of 1978, each investigator had provided written notes specifying minimum needs, and these were invaluable in setting priorities during the first few dives. After six dives out of a projected 10 on the vents, four at a vent site dubbed "Mussel Bed" and two at another called "Garden of Eden," the system that hoisted the *Alvin* cradle to *Lulu's* deck level failed, and we suddenly had to start the long trip back to Panama (an especially long haul for those who had to endure the none-too-gracious accommodations aboard the slow-going *Lulu*).

Even though each dive had been planned as if it were our last, there was still much to do. No one was very happy, even though we had accomplished a significant part of the work. During each dive, we collected many animal specimens and water and microorganism samples. We made in situ metabolic measurements of the animals, placed experiments, and took many photographs with the stereo close-up camera or the prototype RCA video camera. We did have some failures, specifically our current meter and thermistors, which produced no useful measurements. The animals collected during each dive were either sent to *Gillis* for physiological evaluation, preserved, or placed in culture. We were concerned about the effects of decompression as the animals were hauled to the surface and by the long transfer time between ships. We made adjustments: Jim Childress shifted from mussels to crabs for his laboratory physiological studies after our minnow-baited traps proved extraodinarily successful at catching crabs. When a specimen of a delicate orange benthic siphonophore (a relative of the Portuguese man-of-war) fragmented during transit to the surface, we fashioned on board a new sampling container to capture one intact.


Robert Hessler

***Alvin's* meter-long temperature probe extends toward a community of galatheid crabs perched atop pillow lava and a dense field of mussels.**

Each night, we held an intensive debriefing session with each day's divers. By asking questions and recording the conversation, we began to develop a picture of the ecosystem and what was important. NGS photographers Al Giddings and Emory Kristof were full participants in the research and Al's underwater video usually gave us better views of the animals than were available by direct observation through the *Alvin*'s small viewports. Even more important, the video images gave everyone, not only those in *Alvin*, an ability to see the animals.


Howard Sanders

Minnow-baited traps proved quite successful for capturing crab specimens for physiological studies.

Nothing could diminish the excitement of seeing the animals for the first time. But aboard *Alvin* there were few glamorous or even quotable exclamations, as each diver struggled to record everything that happened, operate cameras, and work with the pilot to collect samples. Transcripts of *Alvin* tape recordings often consisted of dispassionate strings of time marks, temperature readings, and names of animals. NGS's Jim Lipscomb did provide a good record of enthusiastic first impressions, such as Bob Hessler's excited commentary as the first person to dissect one of the 2-meter-long *Riftia* tubeworms: The animals I usually work on are about this long, he said, holding two fingers almost together. "To be working with these things, where you could use a knife and fork and spoon for dissection, is absolutely remarkable!"

When we returned to the Galápagos vents for Leg 2 on February 9, the research shifted to Ballard's geology program. But Bob made room for some biology on his five geology dives, and the five NGS-funded dives emphasized biology. These 10 dives on the second leg made a huge difference to the biology program's overall success. When we left the ship on February 26, NGS photographic specialist Pete Petrone, who had discovered how to process color film at sea using seawater, provided each scientist with 20 of the best 35mm photographs taken on the cruise, and Emory Kristof supplied a tape of underwater video highlights, for scientific use only, until after *Dive to the Edge of Creation* aired. Eleven additional dives at the beginning of December 1979 completed experiments begun in the first two legs and added to the sample collections.


Jack Donnelly

Bob Ballard examines a tubeworm several meters long, brought to the surface by *Alvin*.

By the end of 1981, the 1979 Galápagos dives had yielded 32 papers. My lab alone sent information and materials to more than 40 additional investigators. By 1986, the 1979 expeditions to the Galápagos vents had contributed to 79 papers. By then, most of the papers included information from vent systems explored by 1982 expeditions to the East Pacific Rise at 21°N and to Guaymas Basin. The discovery of 350°C+ hydrothermal fluid pouring from "black smoker" chimneys in 1979 added a new dimension to hydrothermal vent biology: a tremendous diversity of microorganisms including Archaea growing above 100°C, and *Alvinella pompejana* worms living at temperatures up to 50°C. The Guaymas vents, spread over a large area of soft sediments, provided yet another set of habitats for new forms of hydrothermal vent life. My greatest regret from these expeditions is that we never had sufficient time to explore the full diversity of life in each area. Basic exploration for smaller organisms and new species took second place to more focused research objectives.

The Galápagos investigators completed most of their work and at least partially answered their original questions: Life at vents was distributed primarily according to the flow and composition of hydrothermal fluid, so that competition and predation among the vent animals were less important than among similarly dense assemblages of animals living in shallow waters. Despite the high pressure and low temperature of the deep, the respiration rates of vent species were generally comparable to those in shallow-water animals. High concentrations of blood pigments, such as hemoglobin, were found in crabs, mussels, clams, and *Riftia pachyptila* tubeworms, compensating for the low partial pressure of oxygen at depth, and, incidentally, giving the animals with hemoglobin their vivid red hues. Karl Turekian's Yale team showed that clams grew large and fast—22 centimeters in 10 years. Ken Smith demonstrated that mussels transplanted close to the vents increased their respiration and growth rates and stopped growing when moved away. All signs pointed to a highly productive ecosystem sustained by the ephemeral, high-energy flow of hydrothermal fluid.

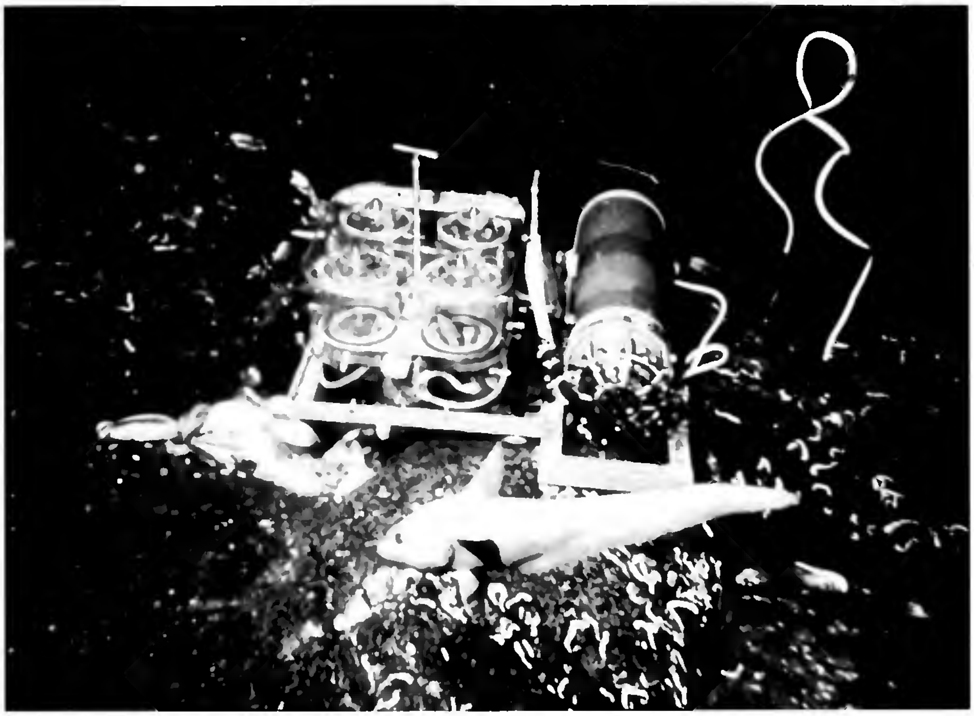
In his experiments, Holger Jannasch filled syringes containing radioactive carbon dioxide combined with vent fluids and incubated them over two days, proving that deep-sea bacteria used hydrogen sulfide from vent fluid to convert carbon dioxide into organic carbon, which they incorporated into their cells. We had not anticipated the presence of these chemosynthetic bacteria in the tissues of *Riftia pachyptila*, clams, and mussels. Discovery of these symbionts explained why these animals grew rapidly to a large size. A surprising variety of free-living chemosynthetic microorganisms was identified, and, per unit area, vents were found to be among the most productive ecosystems known. A central mystery—how larvae were able to find new vents nearly every generation—was partially answered by the early genetic study of mussels: Juvenile mussels were genetically quite different from older classes, indicating larvae arrive in pulses from distant vents.

Although the diversity of species was low in comparison with other deep-sea environments, a remarkable number of new genera, families, and subfamilies was described from the samples collected. In general, life in the deep sea remains grossly undersampled and poorly known, and the mid-ocean ridges are not an exception. After many more expeditions in the two decades since 1979, biological studies have been conducted at 31 vent sites, but the distribution and habitats of most species are still not adequately described.

In a review of the literature through 1998 that appeared in *Advances in Marine Biology*, V. 34, Verena Tunnicliffe (University of Victoria), Andrew McArthur (Marine Biological Laboratory) and Damhnait McHugh (Harvard University) found that 75 percent of the 367 species and 40 percent of more than 200 genera of animals known to occur only at hydrothermal vents have been found at only *one* hydrothermal site. This narrow biogeographic distribution of most of the vent fauna is intriguing, even though the unevenness of sampling and the great distances between sampled sites make any conclusions about faunal distribution uncertain. Many species and genera remain to be discovered from hydrothermal vents. Plankton sampling, further application of molecular techniques to identify and track cohorts of larvae settling at vents, and better understanding of the physical processes associated with vent plumes are making the processes transporting larvae to newly formed vents less mysterious (see article, page 6), and rates of dispersal are beginning to be estimated. The study of vent microorganisms—on surfaces, below the seafloor, in the water column, and in association with other organisms—remains an important frontier. The diversity of microorganisms and their functional roles in the ecosystem are not yet well-described, despite more widespread sampling and the application of molecular techniques.

We have subsequently learned that each segment of mid-ocean ridge has its own characteristic spreading rate and history of volcanic and tectonic activity, which lead to different patterns of hydrothermal flows over time and space, and to differences in chemical composition at various vent sites. This information provides the template for understanding processes controlling the evolution of vent fauna.

The cycle of birth and death of individual vents and vent fields and their spacing along the mid-ocean ridge are not well-understood. Along with increased exploration of new sites, the next few years bring the hope for one or more seafloor observatories at hydrothermal vents. By continuously and simultaneously observing the biological, geological, chemical, and physical processes occurring at these sites, we can learn how all these processes interact. The greatest legacy of the first vent studies has been the collaboration of scientists from the many disciplines of ocean science to learn how a previously unknown ecosystem functions. This will be the model for discovery as other worlds are explored.



Ken Smith

A respirometer measures the oxygen uptake of mussels and hence their metabolism rates. Scientists found that despite the high pressure and low temperature of the deep, the respiration rates of vent animals were generally comparable to those in shallow-water animals.

A summer in a WHOI geology laboratory following his sophomore year in college started Fred Grassle's career studying life on the seafloor. After 20 years on the WHOI scientific staff, he started a new Institute of Marine and Coastal Sciences at Rutgers University. Administrative duties brought an end to his hydrothermal vent cruises, but he still manages time for studying life on the shelf and deep-sea bottom off New Jersey.

Lauren Mullineaux

To learn how deep-sea vent species disperse through the ocean and colonize new hydrothermal sites, researchers in the LARVE Project are investigating the complete life cycles of several species, including three in the photo above: the tubeworm *Riftia pachyptila*, the vent crab *Bythograea thermydron*, and the mussel *Bathymodiolus thermophilus*.

Deep-Sea Diaspora

The LARVE Project Explores How Species Migrate from Vent to Vent

Lauren Mullineaux
Associate Scientist, Biology Department

Donal Manahan
Associate Professor, Department of Biological Sciences, University of Southern California

When spectacular biological communities were first discovered at hydrothermal vents in 1977, biologists puzzled over two main questions: How did these oases of large and abundant animals persist in the deep sea, where food is typically scarce? And how did these unusual species, which occur only at vents, manage to colonize new vents and avoid extinction when old vents shut down?

Efforts to solve the first question have resulted in fascinating insights into the chemosynthetic microbes that form the base of the vent food chain, as well as the physiological adaptations that allow the tubeworms, bivalves, and crabs to thrive. The second question, however, has largely remained an enigma. We do know that most of the species probably disperse between vents in a larval stage that drifts through the water, but we know very little about how this process works. Over the past two decades it has become clear that unraveling this mystery will require an interdisciplinary and cooperative scientific approach. The LARVE (Larvae At Ridge VEnts) Project was created to provide just such a collaborative framework for investigators from many different disciplines.

Lauren Mullineaux

A syntactic foam float marks the location of an experimental block amid a colony of the tubeworm *Riftia pachyptila*.

LARVE is part of a larger program called RIDGE (Ridge Inter-Disciplinary Global Experiments), which is funded by the National Science Foundation to provide a coordinated, interdisciplinary research program aimed at understanding the geology, physics, chemistry, and biology of processes occurring along the global mid-ocean ridge system. At present, 10 principal investigators from eight different universities and research institutions are working in the LARVE team, and others are expected to join over the next few years.

The goal of the LARVE Project is to investigate the processes by which larvae disperse through the ocean from one vent system to another. The LARVE Project aims to understand how these processes determine how far and wide species can migrate, how new vent biological communities are established, and how their populations become increasingly but differentially diverse. Answering these questions requires expertise in a variety of fields, including biology, chemistry, geology, and physical oceanography. The links among these fields are illustrated by following an example species, the vestimentiferan tubeworm *Riftia pachyptila*, through different stages of its life cycle.

A magnified image shows a 22-day-old microscopic embryo of the tubeworm *Riftia pachyptila*. Its actual diameter is about 100 microns (.0001 meters).

Adam Marsh, University of Southern California

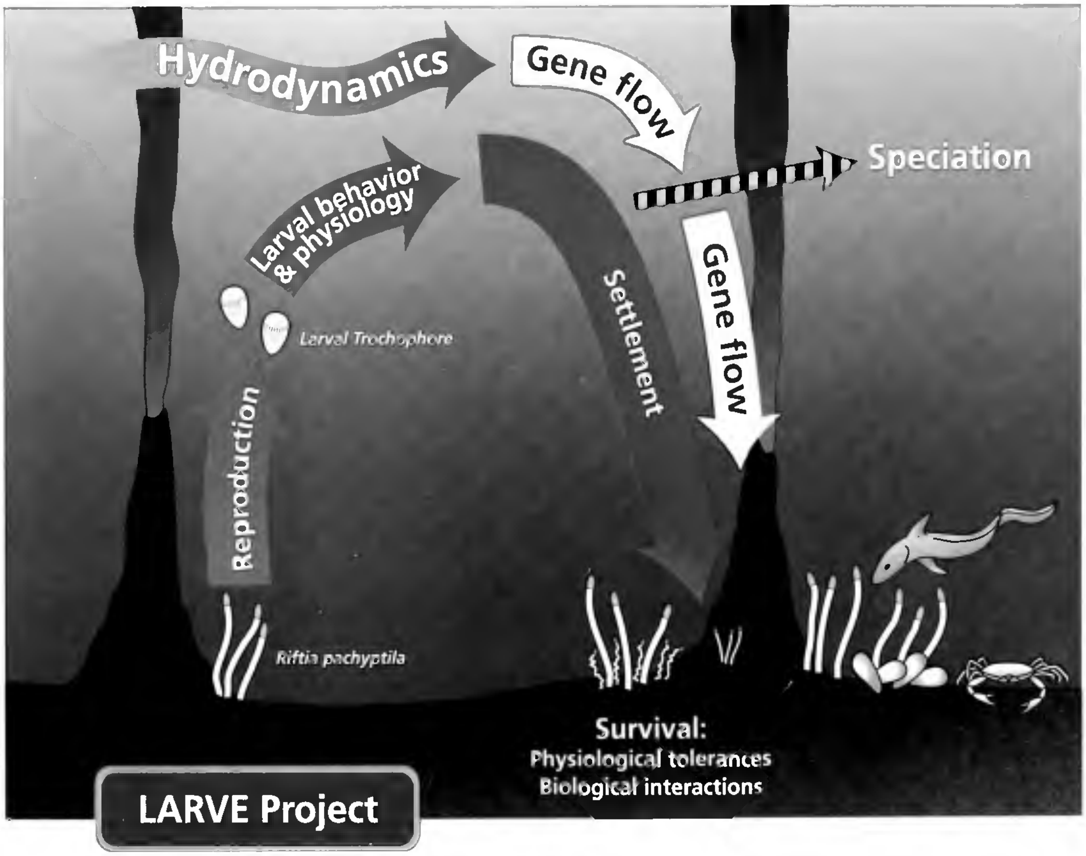
Riftia pachyptila reproduce by releasing eggs and sperm into the water. The fertilized egg then develops into a larva called a trochophore. The length of time a larva can survive in the water depends on its physiology—that is, how much lipid it has and how quickly it metabolizes this stored energy. Although the larvae use their cilia for slow swimming, their horizontal motion is determined largely by hydrodynamics, including fluid flows near the vents and larger-scale oceanic circulation patterns. However, larval behavior, such as vertical swimming, can position the larva in different flows and cause them to disperse at very different speeds and even in opposite directions.

Larvae that survive the perils of predation and starvation in the water column must still locate a suitable vent habitat for settlement—possibly by responding to a chemical cue at a particular vent site. After a larva settles into the vent environment and metamorphoses into a juvenile stage, its survival is controlled by its physiological tolerances, nutritional requirements, and interactions with other tubeworm species, mussels, crabs, and fish that may be competitors or predators.

Successful colonists contribute their genes to the population, and if larval exchange between two populations is frequent, this gene flow keeps the populations genetically similar. If, however, larval dispersal between two populations becomes inhibited, the populations may diverge genetically over time, and speciate (evolve into separate species).

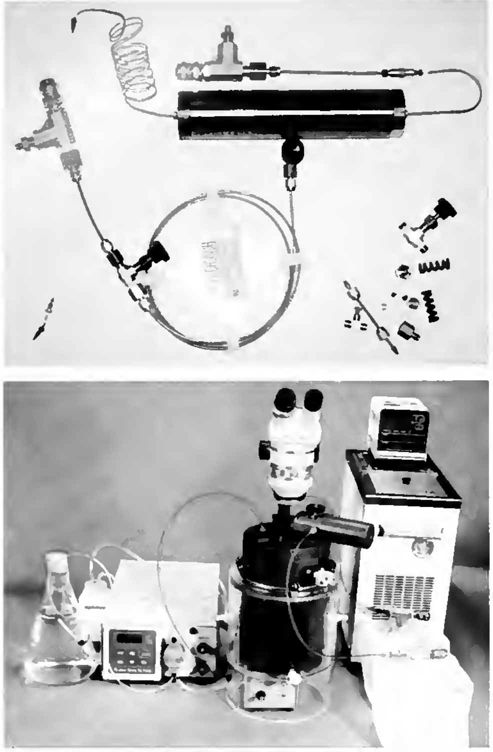
For their initial studies, LARVE Project researchers chose a site near 9°50'N, 104°17'W along an axial summit valley of the East Pacific Rise. The site is ideal because it consists of a chain of vents that support diverse and abundant communities of vent species. The bathymetry of this section of the ridge is well-surveyed, and the geochemistry of the vents has been monitored since 1991, when a well-documented volcanic eruption at the site wiped out the existing community and created a blank slate for a new community to form. Researchers are concentrating on the chain of vents in this area to study how species reproduce, progress through larval stages, settle at vents, and survive. Larger-scale studies of the gene flow and physical oceanography are conducted along the East Pacific Rise and elsewhere.

We presently know a little about stages in the life cycle of a few different vent species, but we do not have a comprehensive picture of how extensively, in both distance and number, any single species can disperse. LARVE researchers have targeted several species for detailed investigations of the species' entire life cycle: how they reproduce, how the larvae's behavior and physiology interact with processes that transport them physically, how larvae settle at new vents in response to chemical or physical cues, how larvae survive in the complex chemical and biological environment of hydrothermal vents and how these processes contribute to gene flow. Selected



The life cycle of *Riftia pachyptila* illustrates the complexity of factors—involving biology, chemistry, geology, and physical oceanography—that all play roles in the migration, resettlement, and speciation of vent species.

Jack Cook



Donal Manahan

Craig Young, Harbor Branch Oceanographic Institution

Newly designed high-pressure systems for culturing vent species' larvae allow scientists to examine the behavior, energy stores, and metabolic rates of larvae, which all contribute to their ability to survive migration to new vent sites.

species include two tubeworms (*Riftia pachyptila* and the smaller jericho worm, *Tevnia jerichonana*), the vent crab *Bythograea thermydron*, the mussel *Bathymodiolus thermophilus*, and several species of gastropods.

The major challenge of the project is adapting techniques used to study shallow-water communities to the remote, deep-sea vent system, with its extreme pressures, high temperatures, and inhospitable chemistry. The field studies require delicate in situ manipulations by submersible, as well as recovery of live, undamaged specimens for shipboard experiments. The laboratory studies require incubating and observing larvae in chambers that must be maintained at ambient deep-sea pressures with precise control over the thermal and chemical environment.

One of the more novel applications for laboratory studies of larvae is the design of two high-pressure systems for culturing larvae (photos above left). The system for behavioral observations consists of a cylindrical chamber outfitted with a viewport and illumination system. The chamber for physiological experiments is a smaller flow-through system that allows researchers to introduce fluid containing chemical tracers or to extract fluid and larvae for experiments and other metabolic measurements. Using these systems, investigators can explore questions about the energy stores and metabolic rates of larvae, and about the behaviors that may affect their hydrodynamic transport.

Bonnie Ripley

A vent colony of the serpulid polychaete *Laminatubus alvini* thrives near a hydrothermal vent.

Currents near mid-ocean ridges are affected by both ridge topography and buoyant plumes of hydrothermal fluids flowing from the vents. Preliminary studies using current meters moored along ridges indicate that currents are "steered" to run parallel to the ridge. Flow speeds, however, can be much faster at some heights above the ridge than others, and currents on the two ridge flanks may be oriented in opposite directions. Therefore, small movements by larvae, up or down, can have a substantial impact on the direction and speed of their dispersal.

The hot, buoyant fluids flowing from the vents further complicate the currents by forming a plume that rises several hundred meters above the ridge. The earth's rotation interacts with the buoyant plume to create a circulation cell within the plume that keeps some of the plume water near the source vent. If a larva becomes trapped in this spinning buoyant plume, it may recolonize the vent where it was spawned. To characterize larval transport in the specific flows near the 9°N East Pacific Rise study site, current meters have been deployed along the ridge axis, and future studies using neutrally buoyant floats are being planned.

One type of larva, the late stage (or *megalopa*) larva of the vent crab *Bythograea*, may not need high pressure for study of some of its behavior. This astonishing larva has been kept alive for more than 10 months at surface pressure by Chuck Epifanio, Anna Dittel, and Craig Cary at the University of Delaware. During that time these researchers have been able to observe individuals metamorphosing into juveniles, providing a potential system for investigating how larvae may settle at potential vent sites in response to physical or chemical cues. Unfortunately, this pressure tolerance is uncommon in most vent species, and settlement cues for other species will have to be investigated under pressure, using laboratory culture chambers or in situ field experiments.

Field experiments to explore how larvae settle at new vent sites and how juveniles survive are conducted with hundreds of simple, inexpensive basalt blocks deployed by the submersible *Alvin*, operated by Woods Hole Oceanographic Institution (WHOI). The blocks are placed within and away from vigorously venting sites for various periods of time to understand the effects of various environments and neighboring colonists on the survival of settling larvae. Some blocks are protected from crabs and fish by cages, and others have partial cages as controls, to examine the effects of predators on colonists (see photos, opposite). Large numbers of vent species' larvae settle onto the blocks in a matter of months. The experimental design has been adapted to the deep-sea vents from classical studies of the rocky intertidal environment by investigators at WHOI (Lauren Mullineaux), Pennsylvania State University (Chuck Fisher and Steve Schaeffer), and the University of North Carolina (Pete Peterson and Fiorenza Micheli).

By necessity, the experimental approach to questions of larval settlement and survival is conducted on small areas over short time periods. But obviously it would be valuable to make observations over many years. Time-series observations of undisturbed faunas are rare in the deep sea, but a 1-kilometer-long vent "sanctuary" was established after the 1991 East Pacific Rise eruption, allowing Rich Lutz's lab at Rutgers University to monitor changes in vent communities for almost a decade. This monitoring is done with time-lapse cameras left at individual vents and repeated camera surveys conducted with *Alvin* and the remotely operated vehicle *Jason*.

Studies of genetic exchange between vents started soon after vents were discovered and continue along the East Pacific Rise and elsewhere in the world's oceans. Studies on the species targeted by LARVE are currently under way as part of the effort by Bob Vrijenhoek's group at Rutgers to understand genetic exchange on a regional and global scale. The intent is to identify vent populations that have significantly different genetic compositions and to characterize how these populations are separated geographically. Are they separated by a few kilometers between neighboring vents? Or by gaps between segments of the ridge? Or by an ocean basin or a continent? This information will then be compared to predictions, based on the larval studies, of which geographic features may pose barriers to dispersal and, therefore, gene flow.

The first cruises specifically associated with the LARVE project went to sea in 1997, and about 10 cruises are expected to visit the East Pacific Rise through the year 2000. The field observations and data are essential ingredients for subsequent theoretical studies that will lead to a cohesive understanding of the complex processes that allow such a wealth of life to thrive on the bottom of the ocean.

Lauren Mullineaux

A few galatheid crabs (*Munidopsis subsquamosa*) wander amid a thriving colony of *Bathymodiolus thermophilus* mussels.

Funding from the National Science Foundation and support from the RIDGE office helped the LARVE Project metamorphose from idea to reality.

Lauren Mullineaux first became interested in the ecology of hydrothermal vent systems during the early 1980s as a graduate student at Scripps Institution of Oceanography in Robert Hessler's lab, a hotbed of pioneering work on vent communities. He (wisely) counseled her to choose a less risky project for a thesis, but the fascination with vents was solidly in place. After arriving at WHOI she jumped at the chance to study larvae of vent species during a cruise along the Juan de Fuca Ridge with Ed Baker (NOAA) and Peter Wiebe (WHOI). Now, many cruises and Alvin *dives later, she still gets a thrill from visiting vents in person, but an even greater satisfaction from witnessing the inspiration and excitement of another scientist on his or her first sojourn to a vent.*

Born and raised in Ireland, Donal Manahan became interested in marine biology and the study of larvae as an undergraduate working on oyster culture in Ireland. As a graduate student at the University of Wales in the UK, he studied larvae metabolism, specifically questions such as how much energy larvae need to grow and how they get that energy from the ocean. He came to America in 1980 as a postdoctoral researcher at the University of California, Irvine. He has expanded his interests to study how animal life develops in extreme environments, such as Antarctica. That naturally drew him to investigate the early stages of animals that survive being cold and hungry at another similarly extreme environment, hydrothermal vents. Although the vents themselves are very hot, the seawater just a few feet away is very cold, and like polar regions, has no obvious source of food.

Lauren Mullineaux

Stacy Kim

Lauren Mullineaux

Scientists have deployed hundreds of basalt blocks (left) within and away from vent areas for various periods of time to learn how larvae settle at these sites. Some blocks are protected by cages (center and right) to determine the effects of predators on colonists. At right, a block has been colonized by vestimentiferan tubeworms after 13 months on the seafloor.

Life on the Seafloor and Elsewhere in the Solar System

If Volcanoes Plus Oceans Can Support Life at the Vents, Why Not on Other Planetary Bodies?

John R. Delaney
Professor of Oceanography, University of Washington

The RIDGE program (Ridge Inter-Disciplinary Globe Experiments) was sharply focused on the global spreading center system, but the program's goals were broadly defined. RIDGE was designed to explore the causes, consequences, and linkages associated with the physical, chemical, and biological processes that transfer mass and energy from the interior to the surface of the planet along the mid-ocean ridges.

That broad mission statement left a lot of room for the "I" in RIDGE. But one lesson of RIDGE is that truly interdisciplinary research is difficult to do. It is difficult to get funding for interdisciplinary research. It is difficult to overcome the language barriers across a spectrum of fields ranging from molecular biology to seismology. Nevertheless, the fields are related, and that is another lesson of RIDGE: Scientists must keep an eye on adjacent fields. Increasingly, a number of researchers believe that communication across fields will spawn some of the major scientific discoveries in the coming decades.

A mosaic of digital images shows the sulfide chimney "Roane" before it was retrieved from the seafloor in 1998. The fluids vented by Roane supported a variety of microorganisms.

University of Washington

With that perspective, the RIDGE program might be considered a work-in-progress. Perhaps it is best viewed in the context of events that happened before it was initiated and activities that may take place as RIDGE evolves. We often look back in order to look forward, and looking back to the late 1970s, two major voyages of discovery occurred within months of one another. One voyage was to the bottom of the ocean and the other to the far reaches of the solar system. These discoveries set the stage for RIDGE.

In 1977, scientists using *Alvin* dove to the ocean bottom near the Galápagos Islands. They found evidence of volcanism, but, unexpectedly, they also discovered a lush animal community. An abundance of crabs, clams, mussels, and worms tipped with brilliant red plumes was found thriving near zones of active seafloor volcanism. Until then, the seafloor had been regarded as relatively barren terrain, where the only nutrient sources were scant dregs that percolated down from the sunlit surface. Distilled to its essence, this first discovery was that volcanic activity in the presence of liquid water can support life without sunlight.

American Museum of Natural History

The 3,000-pound active sulfide chimney "Roane" is retrieved from the seafloor during an expedition in July 1998 led by John Delaney of the University of Washington. Studies of geochemical conditions and microbial communities within the hot, sulfide-rich interiors of the chimneys may shed light on the origin of life on Earth and the possibility of life on other planetary bodies.

Shortly after that *Alvin* dive, the *Voyager I* spacecraft set off to explore the outer solar system. Eighteen months later, it had reached Jupiter and, like *Alvin*, found something unexpected. As *Voyager I* flew past Io, the innermost moon of Jupiter, it photographed nine ongoing, simultaneous volcanic eruptions ejecting material hundreds of kilometers above the moon's surface. Quite unlike the earth's longdead moon, Io turned out to be the most volcanically active body in the solar system. The second fundamental discovery, simply put, was that there were more volcanoes in the solar system than we had ever dreamed.

NASA

Io, a moon of Jupiter (above), where surprisingly active volcanism was detected by NASA's *Voyager I* probe (left) in 1979.

Two ideas, nearly 20 years old: Undersea volcanoes can support life; there are many volcanoes in the solar system. Only now are these two ideas beginning to interact with each other to guide exploration for life in outer space. But these ideas remained worlds apart when the RIDGE program was launched in the 1980s.

A primary goal of the RIDGE program was to look at events taking place on ridge crests in real time, rather than simply to map the products of those processes. From 1986 to 1990, Robert Embley and Edward Baker, from the National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL) in Seattle, Washington, and Newport, Oregon, identified likely volcanic activity associated with large water-column plumes along the southern end of the Juan de Fuca Ridge about 180 miles off the Pacific Northwest coast. But the link between the large plumes and an active eruption was mostly an insightful inference that could not be confirmed by direct observation. At the time, scientists on cruises involved in the area did note the presence of flocculated bacterial mats in the vicinity of fresh seafloor lavas.

In April 1991, researchers exploring the East Pacific Rise off the coast of Mexico found themselves in the right place at the right time. The cruise was led by Rachel Haymon of the University of California, Santa Barbara, and Daniel Fornari of Woods Hole Oceanographic Institution, who listened raptly as divers aboard *Alvin* reported near-whiteout conditions at the dive site. Clumps and clusters of what seemed to be bacterial products billowed up in huge plumes from beneath the seafloor. Through the bacterial haze, they saw tubeworms newly barbecued and folded in fresh lava. The researchers quickly drew the conclusion that the gods of serendipity had delivered them into the midst of either an active or a very recent eruption. These experiences substantially enhanced the resolve of RIDGE and NOAA vent scientists to pursue active events on ridge crests in real time.

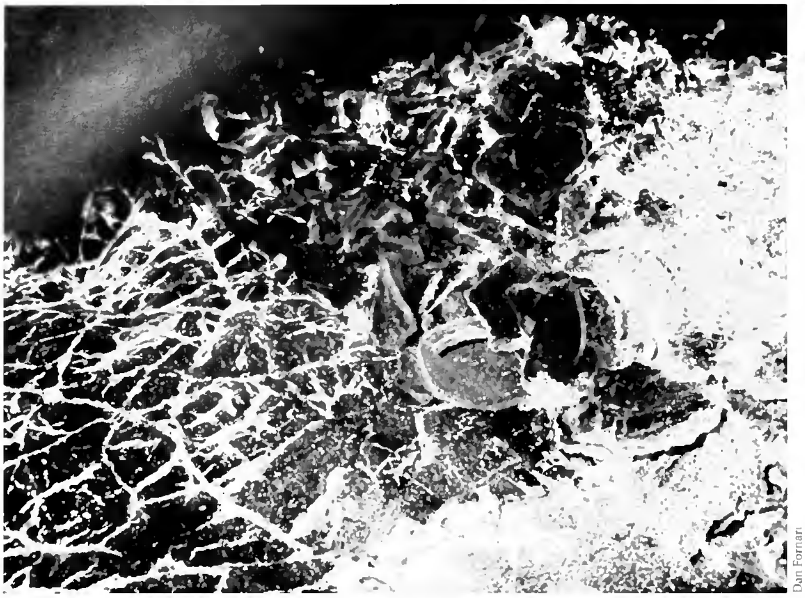
With the end of the Cold War, oceanographers gained an invaluable tool: limited access to selected data from the Navy's classified SOund SUrveillance System. SOSUS was an array of hydrophones originally designed to detect enemy submarines. On June 26, 1993, just four days after gaining access to some SOSUS data, Christopher Fox and colleagues at PMEL in Newport detected a series of earthquakes along the Juan de Fuca Ridge. In two days, the locus of earthquake activity had migrated 50 kilometers northward along the ridge axis.

The opportunity to catch a ridge eruption *in flagrante* finally had presented itself, but taking full advantage of the windfall was not automatic. Some in the scientific community still had doubts about this type of activity and viewed the effort as "fire-engine chasing." Unlike the pursuit of fire engines, however, it is much harder to find ships (and funds) to pursue a possible eruption in the middle of an ocean. To arrive on site within days or weeks of an eruption was not easy. It meant persuading scientists to yield some of their hard-won ship time, usually scheduled more than a year before, to chase a possible chimera and either curtail or ignore their own funded research. Such behavior in the competitive, peer-reviewed world of oceanographic research could jeopardize longer-term funding for more predictable, if less exciting, science.

Nevertheless, within days, following a shore-to-ship call from Fox, Richard Thomson of the Institute of Ocean Sciences in Sidney, British Columbia, a member of the RIDGE Steering Committee, briefly redirected an ongoing cruise operating nearly 120 miles to the north. Thomson and colleagues discovered a major hot-water plume directly above the site where the migrating earthquakes had stalled. Embley and his NOAA colleagues, Baker and Bill Chadwick,

In the late 1970s, two unique research vehicles, WHOI's *Alvin* (below) and NASA's *Voyager I* (above), made separate but complementary discoveries in inner and outer space. By discovering thriving biological communities near seafloor volcanic vents, *Alvin* helped show that water plus volcanism can support life without sunlight. *Voyager I* discovered active volcanism on Jupiter's moon Io, showing that volcanism was more common in the solar system than previously believed. These two ideas have only recently combined to guide scientists' search for life on other planetary bodies.

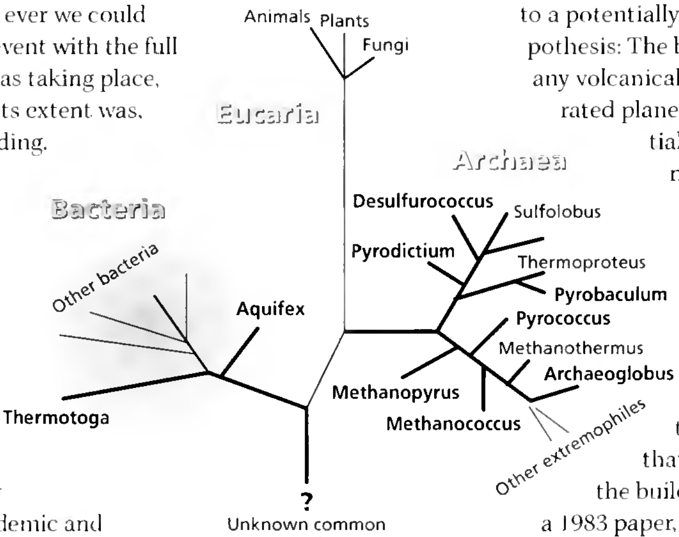
Rod Catanach


Dan Fornari

In 1991, *Alvin* dove onto a recently erupted volcanic zone along the East Pacific Rise near 10°N, where scientists found fresh lava and huge billowing mats and clusters of bacterial products.

also reacted within 10 days and redirected a long-planned cruise to what became known as the CoAxial Segment of the ridge. Using the Canadian vehicle ROPOS (Remotely Operated Platform for Ocean Science), Embley and colleagues found a fresh lava flow that already had been colonized with bright yellow mats of bacteria. Farther south, they discovered massive amounts of bacterial products surging from beneath the ocean floor, in a fashion strongly reminiscent of the East Pacific Rise event in 1991.

As these reports were relayed on shore, two University of Washington (UW) colleagues, Paul Johnson and Russell McDuff, and I worked with dispatch to request support from the National Science Foundation for RIDGE funds to explore the new eruptions with *Alvin* at the earliest possible time. Our argument was that for the first time ever we could approach a seafloor event with the full knowledge of what was taking place, when it began, what its extent was, and how it was unfolding. The submersible is nearly always booked, but there was an opening in October, four long months after Fox first detected the telltale seismic activity. By the time we put to sea with a scientific crew comprising both academic and NOAA researchers, we were already building on the work of many people: Embley, Baker, Haymon, Fornari, Fox, and Thomson. Then two others, Fred Spiess and John Hildebrand of the Scripps Institution of Oceanography, University of California, San Diego, contributed, on very short notice, an eleventh-hour sonar mapping program of the eruption area that helped guide our *Alvin* dives.

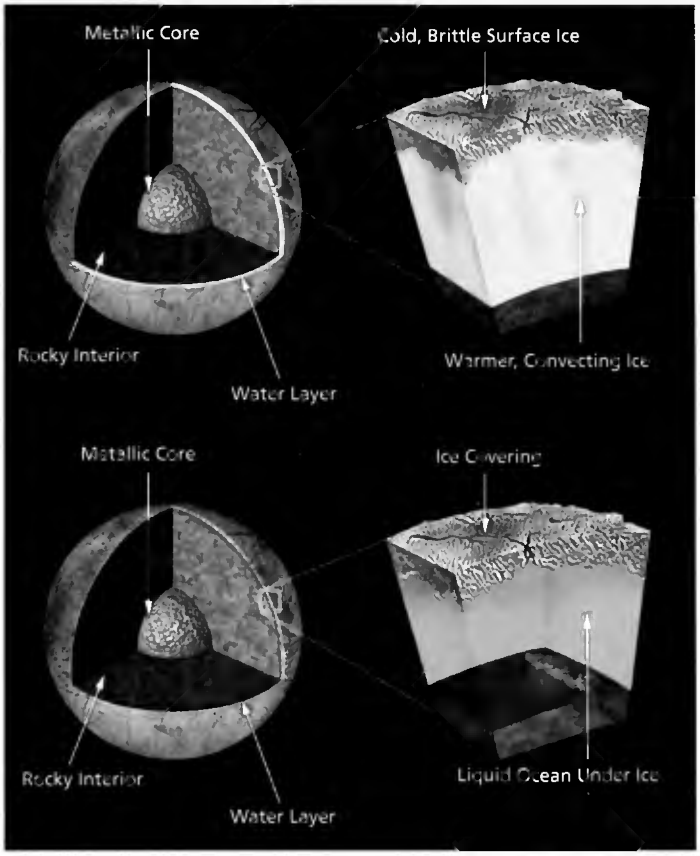


A simplified version of the phylogenetic tree created by Carl Woese (University of Illinois) shows the three domains of life: Bacteria, Eucaria, and Archaea. In 1993, scientists discovered massive outpourings of hyperthermophilic Archaea on erupting mid-ocean ridges.

We found vast volumes of microbial material issuing from the seafloor, as had been observed before. But because of experience on previous expeditions, microbiologists from John Baross' laboratory at UW were on board to culture bacterial samples that we collected. Then-graduate-student Jim Holden established that the volcanic microbes belonged to an ancient group of organisms that are so genetically distinct that they represent a separate and fundamental branch on the tree of life distinct from bacteria, plants, and animals. They are known as Archaea, or ancient ones, and they are hyperthermophilic, meaning they survive, in fact thrive, at temperatures greater than 90°C. We don't know yet whether the eruptions flush pre-existing microorganisms inhabiting the subseafloor or whether the eruptions release nutrients that trigger a volcanic microbial bloom that simply overflows the available space in seafloor rocks. But it was clear that, as hypothesized earlier by Baross and his colleague Jody Deming of UW, the rocks below the seafloor are populated with microbial communities that we need to explore.

Discovering the outflow of Archaea along erupting spreading centers has been one of RIDGE's major successes. It required long-term commitment and cooperation of many scientists in the face of considerable difficulty. Since the Coaxial Event, a number of similar rapid responses have been mounted to document these types of events, and in each case, high-temperature microbes have been cultured from the effluent associated with the volcanic-tectonic activity.

These observations are giving rise to a potentially controversial hypothesis: The brittle outer shell of any volcanically active, water-saturated planet may harbor a potentially vast subsurface microbial biosphere. Indeed, this deep, hot, chemically rich environment within the earth's volcanic shell appears to have the necessary ingredients to foster the critical reactions that could have created the building blocks of life. In a 1983 paper, Baross, Sarah Hoffman, and Jack Corliss, all then at Oregon State University, first suggested that life may have originated on the earth not in warm, shallow pools struck by lightning, but rather in sunless, deep-sea volcanic vents. And if such an evolution can occur on the earth, perhaps something similar has occured elsewhere in the solar system where active volcanism and liquid water are juxtaposed.



Pam Engebretson. Courtesy of NASA's Jet Propulsion Laboratory

These drawings depict two proposed models of the subsurface structure of Jupiter's moon Europa. No conclusive proof has yet been found that an ocean exists on Europa, but geologic features on its surface, imaged by NASA's *Galileo* spacecraft, might be explained either by the existence of a warmer, convecting ice layer, located several kilometers below a cold, brittle surface ice crust (top model), or by a layer of liquid water with a possible depth of more than 100 kilometers (bottom model). If an ocean 100 kilometers (or 60 miles) deep existed below a Europan ice crust 15 kilometers (10 miles) thick, it would be 10 times deeper than any ocean on the earth and would contain twice as much water as the earth's oceans and rivers combined.

One of the most intriguing solar bodies likely to support such life forms may be Io's nearest neighbor, Europa—Jupiter's second moon and one of the most beautiful planetary bodies in the solar system. It has a smooth, highly reflecting, almost pearl-like appearance from a distance because its surface is completely covered with ice and nearly devoid of large craters. Recent close-up images of Europa's surface taken from the *Galileo* spacecraft display a more chaotic texture, which has been interpreted by the *Galileo* imaging team as a cluster of blocklike icebergs. The tops of these striated blocks appear to be "floating" about 200 to 250 meters above a surrounding slurry of much smaller ice fragments, much the way a large ice cube would float in a slush of crushed ice. The height of the ice block suggests that only one-ninth of its bulk projects above the surface. That implies that the blocks, which clearly have floated away from a solid ice "shoreline," are about 3 to 5 kilometers thick. With a calculated bulk density of nearly 3.0 grams per centimeter, Europa must have a rocky interior, and the best estimates indicate that the water layer (whether liquid or solid) above the more dense rocky material is about 100 kilometers thick. If that is true, a relatively thin outer layer of ice may float atop a much thicker layer of liquid water, which directly overlies Europa's higher-density interior. In other words, there may well be another ocean in the solar system, and it may be maintained by volcanism within the rocky interior.

Some scientists speculate that to maintain a liquid water body on a frigid satellite that is slightly smaller in diameter than the earth's moon, Europa, like its neighbor Io, may harbor volcanic activity within. In Roman mythology, Jupiter, king of the gods, and the maiden Europa conducted a torrid affair. In a modern scientific parallel, the tidal relationship between the huge planet and its diminutive moon creates significant heat. Jupiter's enormous gravitational embrace, combined with the resonant interplay of nearby satellites, alternately squeezes and stretches Europa, generating internal friction and possible volcanism, as it clearly does on Io. The possibility of a planetary body hosting both an ocean *and* submarine volcanoes makes similar systems on the earth useful analogs for searching for life elsewhere in the universe. By designing innovative strategies to learn more about the relationships between volcanoes and life here on Earth, we not only learn a great deal about how our own planet functions. We also gain valuable new insights into how to approach similar systems in our solar system and beyond.

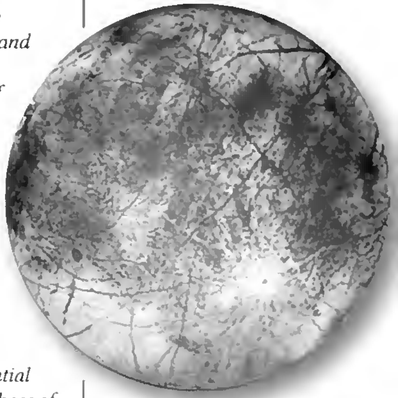
John Delaney completed a degree in geology at Lehigh University in Bethlehem, Pennsylvania, before going to the University of Virginia for a master's degree. As an ore deposit geologist in Maine, he became fascinated with processes that concentrate metals. Gravitating to the heart of the copper mining industry, he searched for base and precious metals in Colorado, Utah, Nevada, and Arizona, while studying economic geology at the University of Arizona in Tucson. After six months living in and working on active volcanoes of the western Galápagos Islands, he decided to study active volcanism for the rest of his life, and completed a dissertation on submarine volcanic gases.

His research and teaching have focused on active submarine volcano-hydrothermal systems along the global spreading-center network. In 1980 a unique set of rocks from the Mid-Atlantic Ridge recovered aboard Alvin *provided clear evidence that seafloor fracturing and mineral deposition was identical to quartz veins beneath massive copper-iron sulfide deposits on land—bringing Delaney full circle to his original geological interests. The recognition that submarine volcanic gases provide an essential nutrient source for the microbial communities that are the base of the chemosynthetic food chain at ridge crests took another of his original research pursuits in an exciting, unanticipated direction.*

Delaney enjoys the poems of haiku poet Matsuo Basho (1644-1694)—a master at capturing the essence of an experience in very few words:

Breaking the silence of an ancient pond,
A frog jumped into water.
Deep resonance!

Whether the pond is only a pond, or the pond is a mind and the frog is an idea, is left to the reader. In many ways, the simplicity and elegance of such a distillation is akin to what scientists strive to extract from their observations.



The icy exterior of Europa, a moon of Jupiter, may be hiding a deep ocean and interior volcanism—two necessary ingredients for life. The gravity field on Europa is about one-seventh that of the earth.

NASA Voyager Image

ALISS in Wonderland

ALISS (Ambient Light Imaging and Spectral System) collects data at "F" vent at 9°N on the East Pacific Rise. To focus the camera on a vent, two lasers mounted on ALISS cross at a distance of 50 centimeters (red dot at center) from ALISS's pressure window.

Imaging Ambient Light at Deep-Sea Hydrothermal Vents

Sheri N. White
WHOI/MIT Joint Program Student
Alan D. Chave
Senior Scientist, Geology & Geophysics Department

In 1985, Cindy Van Dover, then a graduate student in biology in the MIT/WHOI Joint Program, discovered a novel light-sensing organ on a unique species of shrimp that lives at high-temperature, black smoker chimneys on the Mid-Atlantic Ridge. If this photoreceptor were indeed some sort of primitive "eye," the question instantly arose: At depths of some 3,600 meters, where sunlight cannot penetrate, what are these shrimp looking at? The search for a source of light in deep-sea hydrothermal environments began.

The shrimp that Van Dover investigated, *Rimicaris exoculata*, lack normal eyes and eyestalks; hence the name *exoculata*, which means "without eyes" in Latin. This fact did not seem surprising considering the pitch-black depths where these shrimp dwell. But ensuing anatomical investigations revealed the existence of a large, reflective organ on the shrimp's dorsal side beneath the thoracic shell. Subsequent studies of its structure and pigment supported Van Dover's hypothesis that it was some type of eye. The organ does not create images, but it is a very sensitive photoreceptor. It is uniquely adapted to maximize the absorption of light at about 500 nanometers, in the blue-green part of the spectrum. But what

The vent shrimp *Rimicaris exoculata* swarm near a hydrothermal vent site on the Mid-Atlantic Ridge.

kind of light were these shrimp "looking" at and where was it coming from?

The most plausible light source is thermal radiation from the extremely high-temperature (above 350°C) fluids discharging from the vents. Thermal radiation is the light emitted from a hot, dense object—the same phenomenon that causes the heating element, or burner, on an electric stove to glow. In 1988, on a cruise to the Juan de Fuca Ridge in the northeastern Pacific, Van Dover persuaded John Delaney of the University of Washington to take a picture of a black smoker vent with a charge-coupled device (CCD) camera while all of the submersible *Alvin's* external lights were turned off and the portholes blocked. Indeed, the image revealed a glow emanating from the vent orifice (photo below). Since that time, a group of marine geophysicists, chemists, biologists, and physicists has been studying the phenomenon to learn what causes the light, what the light can tell us about vent properties, and how biological communities at the vents respond to the light.

The first confirming image of "vent glow" offered no data to characterize the light. In an effort to obtain a rough spectrum of the light, OPUS (Optical Properties Underwater Sensor) was built at Woods Hole Oceanographic Institution. OPUS is a simple photometer that measures light intensity at various wavelengths. OPUS consisted of four to eight photodiodes covered with individual optical bandpass filters, which together cover the spectrum from 400 nanometers (in the blue part of the visible) to 1,000 nanometers (well into the near infrared). The visible region of the electromagnetic spectrum (that is, what humans are capable of seeing) ranges from 400 nanometers (violet) to 750 nanometers (red), with the infrared region extending on to about a million nanometers. The search for light is limited to the 400- to 1,000-nanometer region because below and above that range, light intensity greatly decreases as it passes through water. This phenomenon is called attenuation; light is attenuated the least at approximately 500 nanometers, allowing blue-green light to travel the farthest and giving the ocean its characteristic color.

Delaney, Smith, Van Dover, Cann, & Foster

The first image of vent glow taken on the Juan de Fuca Ridge in 1988.

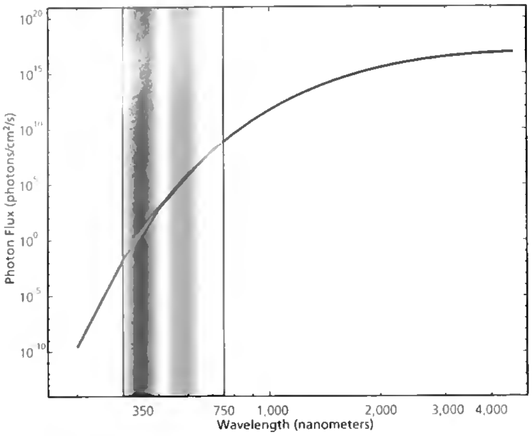
OPUS was deployed using *Alvin* at black smoker chimneys on the Mid-Atlantic Ridge and the East Pacific Rise during four cruises between 1993 and 1997. The OPUS data revealed that most of the vent glow is in the infrared region of the spectrum (greater than 750 nanometers), which suggests that the light is primarily due to thermal radiation. The OPUS data were consistent with the spectrum of a theoretical "black body"—an ideal body that absorbs and emits all the radiation falling on it. Light emitted from a black body is dependent only on the temperature of the body. For a 350°C black body, a graph of light emission would peak at long wavelengths (about 4,600 nanometers), with a tail extending down into the 400- to 1,000-nanometer region (see figure on page 16). OPUS recorded light emitted in this tail region.

Dave Brenner, University of Alaska, Fairbanks

Sheri White checks the alignment of the ALISS filter array during a fall 1997 cruise.

OPUS successfully provided a rough spectrum of the light emitted at vents. That is important in determining possible light sources, since certain mechanisms can cause light emission at certain wavelengths. However, OPUS lacked an imaging capability, and knowing *where* the light is emitted at a black smoker (at the orifice or higher in the plume, for example) may also hold important clues to which sources are more likely. To obtain both images and spectral information, a special charge-coupled device (CCD) camera was commissioned by WHOI. It is called ALISS (Ambient Light Imaging and Spectral System).

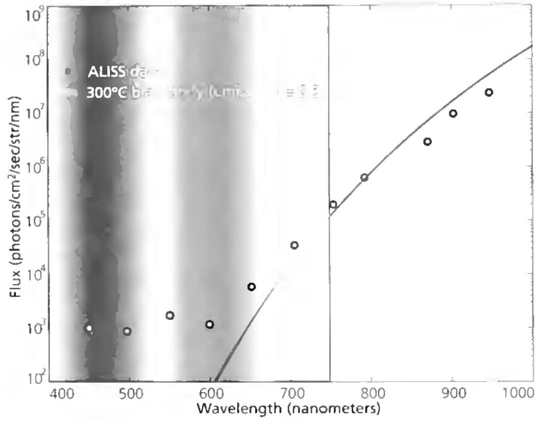
The development of CCD technology in the 1970s was of great interest to astronomers who measure very faint sources of light—stars billions of light-years away. A CCD is basically a silicon chip that is divided into a number of pixels (picture elements), each of which acts like a bucket holding incoming photons. The advantage of a CCD is that it can digitally image very faint objects by using long exposures to increase the number of photons captured in each pixel. Long exposure times are necessary for ALISS to capture vent glow, which is too faint to be seen by the human eye.



Light emission from a "black body" (an ideal body that absorbs and emits all radiation falling on it) peaks at 4,600 nanometers with the tail extending downward in the region of the light spectrum visible to the human eye (400 to 750 nanometers).

The ALISS camera, built by Princeton Instruments Inc. of Trenton, New Jersey, contains a CCD chip with a 1,024-by-1,024-pixel grid. It has a set of optics, designed by Truax Associates of Southington, Connecticut, consisting of nine individual lenses that divide the CCD plane into nine smaller tiles, each roughly 340 by 340 pixels. The nine lenses in front of the chip are each covered by individual optical bandpass filters with wavelength bandwidths of roughly 50 nanometers and 100 nanometers. Thus, ALISS can obtain nine separate and simultaneous pictures—each in a different wavelength band. Equipped with two separate nine-filter arrays, ALISS can obtain images in 18 wavelength bands per dive.

ALISS is controlled by a scientist inside *Alvin* using a personal computer, which also stores the ALISS data. Two lasers mounted on top of ALISS cross at a distance of 50 centimeters in front of the camera to aid the *Alvin* pilot in positioning the camera within its focusing range of 50±25 centimeters. Because the light emanating from vents is so faint, ALISS must take a number of long exposure images (5 minutes each), which can then be added together and/or averaged electronically. This requires the submarine to remain stationary and in the dark (all external lights and lasers turned off and all viewports blacked out) for 5 minutes at a time—not a completely comfortable prospect when you are a mere half a meter from water hot enough to melt *Alvin's* viewports.



Plot of actual data (blue dots) collected at "P" vent on the Mid-Atlantic Ridge and the data expected from a theoretical black body at 300°C (red curve).

A number of corrections are made to the ALISS images during processing to account for variations in the response from one pixel to the next, as well as for surplus charge buildup in the pixels that is unrelated to the incoming light. The camera was calibrated between cruises at the California Institute of Technology with the assistance of Palomar Observatory scientists, who have extensive experience with CCD devices used, in their case, to explore outer space.

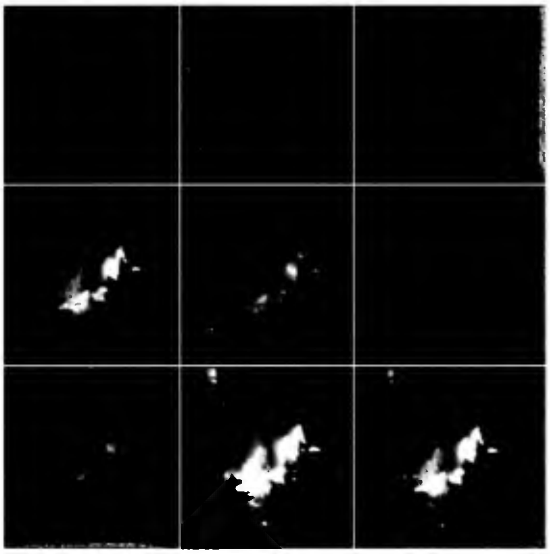
ALISS has been deployed at deep-sea hydrothermal vents in the 9°N area of the East Pacific Rise (November–December 1997) and in the main Endeavour vent field of the Juan de Fuca Ridge off the Pacific Northwest coast (June–July 1998). Images have been collected from black smokers and flange pools whose venting fluids range in temperature from 250° to 375°C. Black smokers and flange pools are very distinct types of hydrothermal venting. At some large chimney structures (particularly on the Juan de Fuca Ridge), flanges are formed on the sides of the chimneys, much like the eaves on a house. Exiting hydrothemal fluid collects underneath these flanges, forming high-temperature, relatively stationary, clear pools.

ALISS's images tell us a lot about the light emitted at hydrothermal vents. The light's intensity is highest at the vent orifice and decreases farther from it. Because of rapid mixing with seawater, the temperature of hydrothermal fluids drops from about 350°C at the orifice to about 10°C at a distance of some 20 centimeters above the orifice. Therefore, the higher light intensities appear to correspond to the higher temperatures. An example of the spectra derived from the ALISS images is shown in the figure below left. The greatest amount of light is seen in the far red and near infrared region of the spectrum (greater than 700 nanometers). This matches the spectrum of an ideal black body at similar temperatures. Thus, both the spatial and spectral observations suggest a large component of thermal radiation.

The data collected from black smokers and flange pools on both the East Pacific Rise and the Juan de Fuca Ridge show very similar results at the longer wavelengths. In all cases, thermal radiation appears to dominate, with hotter vents emitting a greater amount of light. However, while flange pools show no light in the visible range, some of the black smoker data do show a very low level of visible light. Given the temperatures of the vents, the existence of visible light cannot be explained by thermal radiation. Thus, it is still possible that other mechanisms are also contributing to vent light. These mechanisms include, but are not limited to, such phenomena as sonoluminescence (the emission of light due to the implosion of small bubbles) and crystallo- and triboluminescence (the emission of light due to the crystallization and fracturing of crystals, respectively).

At some hydrothermal vents, the extremely high temperatures and relatively low pressures (with respect to those at the ocean floor) can allow hydrothermal fluids to boil. Under these circumstances, bubbles will form and sonoluminescence remains a possibility. At all vents, minerals crystallize and precipitate rapidly as the hot, metal-rich hydrothermal fluids mix with colder seawater. As these minerals form, thermal shock might cause them to fracture and emit light. Many of the minerals present at hydrothermal vents emit light in this way under laboratory conditions. Further examination of existing ALISS data and new data to be collected on the Mid-Atlantic Ridge should help to verify what sources contribute to vent light.

In calculating the contribution of thermal radiation to vent light, three factors must be known: the temperature of the fluids, the intrinsic attenuation of light by water in the hydrothermal vent environment, and the emissivity of vent fluids. *Alvin* temperature probes can measure the temperature of the vents, so these are well-documented. Attenuation experiments, using both OPUS and ALISS with an external light source, have helped to determine how much light is attenuated as it passes through the water between the vents and the ALISS instrument. Emissivity is a measurement of how much light is actually emitted by an object. The emissivity of vent fluids is related to the reflection, scattering, and transmission of light through them. Thus, measuring emissivity is not an easy task. An experiment planned for a year 2000 cruise to hydrothermal vents on the Mid-Atlantic Ridge will help ascertain reasonable values of emissivity. An external light source will be directed at the vents at angles of 0° to 180° from ALISS. The reflection, scattering, and transmission of light through the vent fluid can be measured by the camera and then used to calculate the emissivity. In situ measurements of temperature, attenuation, and emissivity will greatly enhance our analysis of the ALISS images and will help to elucidate just how big a role thermal radiation plays in the phenomenon of vent glow.



At left, ALISS recorded nine images of "P" vent in nine different wavelengths of light. The image in the shortest wavelength (about 450 nanometers) is in the upper righthand corner. The image in the longest wavelength (some 950 nanometers) is in the lower lefthand corner.

Understanding what causes vent glow and characterizing the light is just the first step. At present, it appears that long-wavelength light at vents is dependent on temperature, which offers some intriguing potential applications. Images of vent light could be used to create thermal maps of vent plumes, which may help elucidate processes by which vent fluids and seawater mix at vents. If light in a certain wavelength band can be found to relate to the chemistry of the vent, imaging vents may provide an in situ way of analyzing vent chemistry.

Then there is the question of biological response to light. While we know that the vent shrimp *Rimicaris exoculata* can detect vent light, it has not yet been proven whether they actually do or how they use that information. Do they use their photoreceptor to "see" the vents and thus locate food? Or do they "see" the vents only to avoid the high-temperature fluids that could cook them?

Patrick Hickey

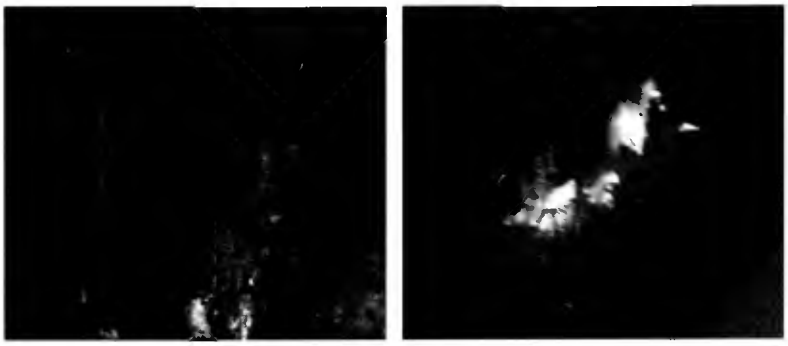
The ALISS camera, mounted on *Alvin's* science basket, looks at "P" vent at 9°N on the East Pacific Rise.

The shrimp are not the only fauna living at vents, and perhaps we will find that other organisms can also detect vent light. While some scientists speculate that life may have begun in hydrothermal vent environments, others take it a step further and wonder if photosynthesis could have originated at vents, as well. The discovery of a nonsolar source of light at the ocean floor adds to the list of amazing vent phenomena that were once thought impossible.

Development of the ALISS camera system was funded by the National Science Foundation Oceanographic Instrumentation Program.

Sheri White is a Ph.D. candidate in the Department of Geology & Geophysics. While she once dreamed of being an astronaut, Sheri now sets her sights down instead of up—some 2,500 meters down to deep-sea hydrothermal vents. When she's not at sea or in front of her computer, she is a force to contend with on the rugby pitch.

Alan Chave is a Senior Scientist in WHOI's Department of Geology and Geophysics, where he says 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.

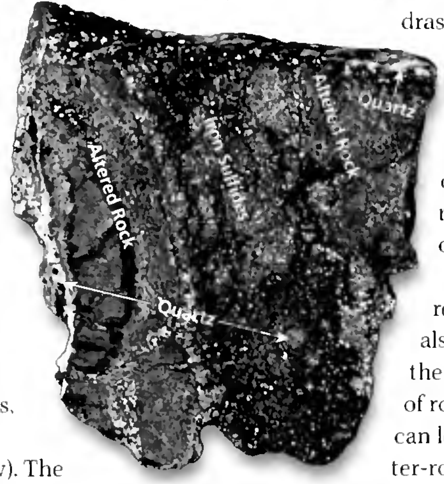


These two photos show "P" vent illuminated by *Alvin's* lights (left) and imaged with ambient light in the 870-nanometer band (right).

The Cauldron Beneath the Seafloor

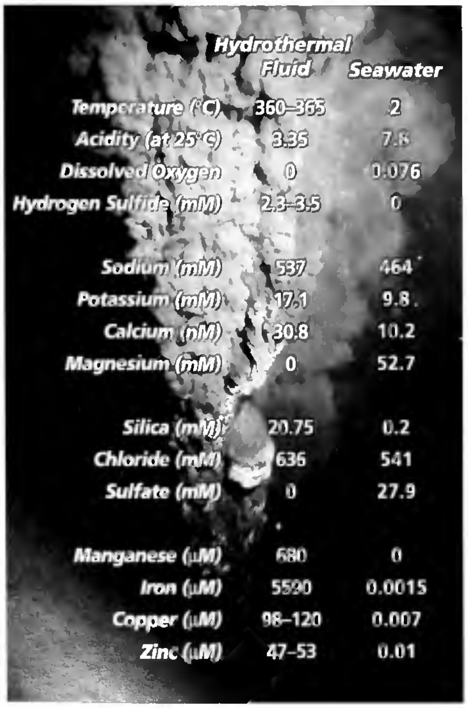
Percolating Through Volcanic Subsurface Rocks, Seawater Is Chemically Transformed into Hydrothermal Fluid

Susan E. Humphris
Senior Scientist, Geology & Geophysics Department
Thomas McCollom
Postdoctoral Fellow, Marine Chemistry & Geochemistry Department



A rock sample, recovered by drilling 116 meters below the active seafloor hydrothermal vent site at 26°N on the Mid-Atlantic Ridge, shows how the rock has been altered by reactions with seawater at temperatures of about 300°C. Pieces of highly altered rock (gray) are cemented together with minerals such as iron sulfides (gold-colored) and quartz (white).

Just over 20 years ago, scientists exploring the mid-ocean ridge system first made the spectacular discovery of black smokers—hydrothermal chimneys made of metal sulfide minerals that vigorously discharge hot, dark, particulate-laden fluids into the ocean. The ultimate source of the fluid venting from these smokers is seawater, but a comparison of chemical compositions shows that seawater and hydrothermal fluid are distinctly different. The vent fluids are not only far hotter than surrounding seawater, they are also more acidic and enriched with metals, and have much higher concentrations of dissolved gases, such as hydrogen, methane, and hydrogen sulfide (see table below). The metals transported by the fluids frequently form ore deposits at the seafloor, and the dissolved gases support a prolific biological community that derives its energy from chemical reactions rather than sunlight. By what processes is seawater turned into this remarkable fluid that emanates from black smokers?



	Hydrothermal Fluid	*Seawater*
Temperature (°C)	360–365	2
Acidity (at 25°C)	3.35	7.8
Dissolved Oxygen	0	0.076
Hydrogen Sulfide (mM)	2.3–3.5	0
Sodium (mM)	537	464
Potassium (mM)	17.1	9.8
Calcium (nM)	30.8	10.2
Magnesium (mM)	0	52.7
Silica (mM)	20.75	0.2
Chloride (mM)	636	541
Sulfate (mM)	0	27.9
Manganese (µM)	680	0
Iron (µM)	5590	0.0015
Copper (µM)	98–120	0.007
Zinc (µM)	47–53	0.01

Jayne Doucette (Data from von Damm, 1995, Von Damm et al., 1997)

A comparison of characteristics and chemical composition shows the distinct differences between seawater and hydrothermal vent fluid, in this case fluid from the TAG hydrothermal site on the Mid-Atlantic Ridge at 26°N.

The answer lies beneath the seafloor, within the oceanic crust. The mid-ocean ridge system, which forms where the earth's tectonic plates are spreading apart, is volcanically active and the site of numerous heat sources, which induce seawater to circulate through the permeable oceanic crust. It is estimated that the equivalent of an entire ocean's worth of water circulates through the mid-ocean ridge hydrothermal systems every 10 million years or so. As the seawater percolates through subseafloor rocks, a complex series of physical and chemical reactions between seawater and volcanic rocks drastically changes the chemical composition of both the seawater and the rocks. These chemical reactions not only influence the composition of the oceanic crust, they also play a role in regulating the chemistry of the oceans.

The history of these chemical reactions is recorded in the minerals and chemical composition of the rocks. By investigating samples of rocks that have been altered, we can learn about the sequence of water-rock interactions taking place in the subsurface. We can then begin to understand the processes responsible for the chemical composition of vent fluids, the formation of sulfide-rich mineral deposits, and the existence of biological communities at hydrothermal vents.

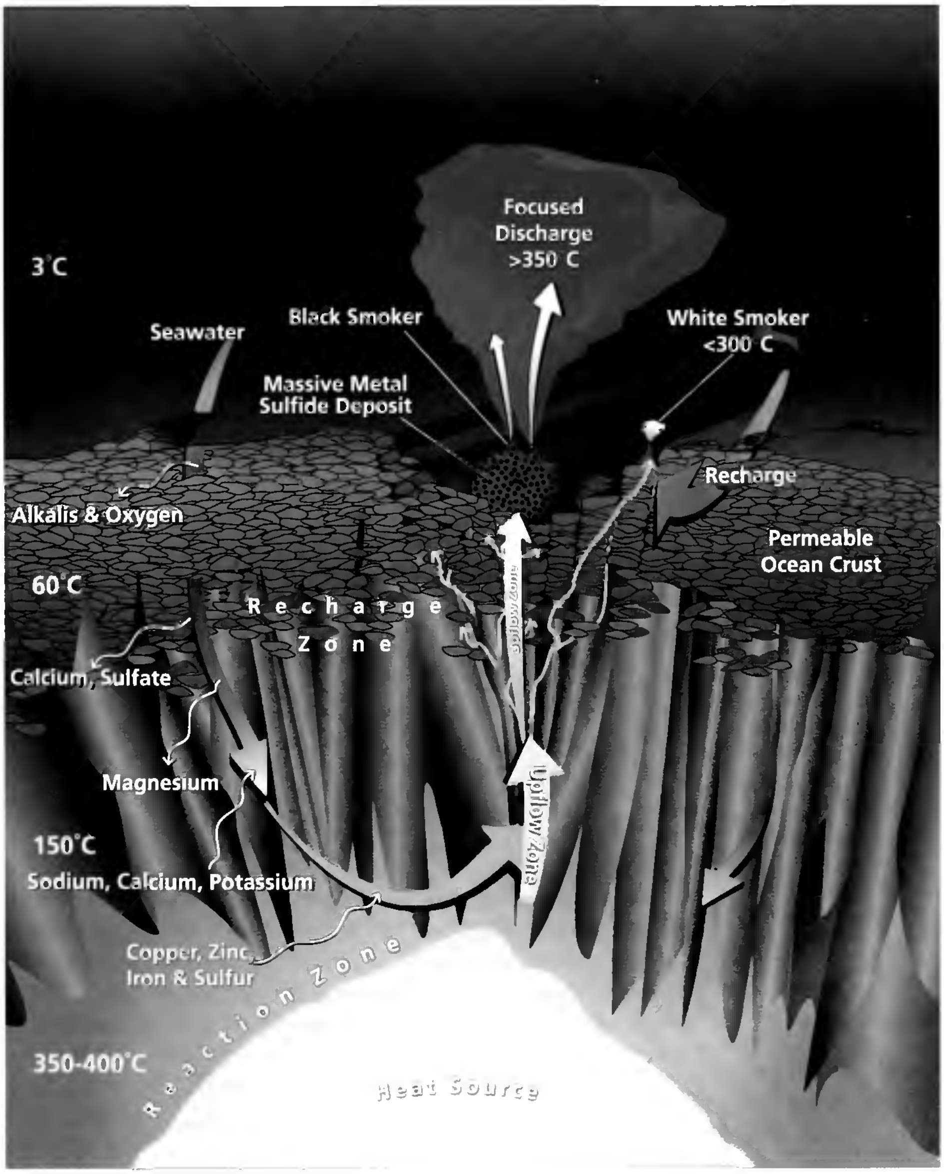
Gaining access to investigate the subsurface portion of a hydrothermal system is, of course, a difficult problem, and scientists must employ several different strategies. The most direct approach is to find techniques to collect and analyze altered rocks. One way is to drill a borehole through a seafloor hydrothermal mineral deposit and recover samples from the oceanic crust beneath. Over the past few years, the international Ocean Drilling Program (ODP) has conducted drilling operations in two hydrothermal areas—one on the Juan de Fuca Ridge off the northwestern US coast, and one on the Mid-Atlantic Ridge about halfway between Florida and West Africa. The drill cores recovered from these sites allow scientists to study the variability in rock-water reactions that occur under the different physical and chemical conditions found at different depths within the earth's crust. Ocean drilling operations, however, are extremely expensive and consequently have been carried out at only a few locations.

Scientists can also collect seafloor rock samples by using dredges and small submarines ("submersibles") in areas where faults and fractures have exposed rocks on the seafloor that were once in the deep subsurface. The disadvantage of this method is that the same processes that expose the rocks may also muddle the spatial and temporal relationships among individual samples. Nevertheless, much has been learned about the chemical effects of water-rock reactions from dredge and submersible samples. In many samples, the outer rim, which has been altered by exposure to circulating hydrothermal fluids, can be compared to the fresh, unaltered interior of the rock in order to learn how the rock has been changed by the fluid (see page 20).

While drilling, dredging, and submersibles can be used to collect rocks to study the shallower portion of the ocean crust, scientists have had to turn to rocks on land to investigate deeper sections of the hydrothermal system. In a few locations, including sites in the western US, Oman, Cyprus, and the west coast of Newfoundland, sequences of rocks exposed on land resemble what scientists believe to be the structure of the oceanic crust. Many geologists think that these rocks represent sections of oceanic crust that have been thrust onto the continents by tectonic movements. Within these so-called "ophiolite" sequences are ancient analogs of seafloor hydrothermal mineral deposits, and these sites provide another source of hydrothermally altered rocks for study. But this method, too, has pitfalls: In some cases, ophiolite rocks have been altered during the tectonic processes that uplifted and thrust the oceanic crust onto land. This subsequent alteration often obscures the original alteration that took place on the seafloor, making it difficult to use the rocks to study submarine hydrothermal processes.

Scientists also employ experimental strategies in laboratories to understand fluid-rock interactions, setting up reactions between rocks and seawater under conditions simulating those in a seafloor hydrothermal system. The earliest of these experiments actually pre-dated the discovery of seafloor hydrothermal systems. In the experiments, crushed rock samples and seawater in varying proportions are placed in a sealed reaction vessel (commonly referred to as a "bomb"!), which is then subjected to high temperatures and pressures. These "cook-and-look" experiments provide a way to explore how reactions change as physical and chemical conditions are varied, and they help scientists determine how the chemistry of the fluid and the rock evolves as the reactions proceed. Over the years, experimentation has progressed to include "flow-through" models that examine the changes in chemistry and physical state as fluids migrate through a system. While laboratory simulations often result in end-products that are somewhat different from those observed in rock samples from actual altered ocean crust, scientists have gained insights that have been critical in deciphering the complex set of water-rock reactions taking place in natural hydrothermal systems.

A third approach to understanding the chemistry of hydrothermal systems is geochemical modeling. Scientists have used models to investigate the sequence of minerals that dissolve and precipitate during fluid-rock reactions, as well as to examine how the fluid changes its composition as it circulates through the crust. These efforts depend on the



In a hydrothermal circulation system, cold seawater seeps through the permeable seafloor and deeper subsurface dikes. It undergoes a series of chemical reactions with subsurface rocks at various temperatures to create hot hydrothermal fluid that eventually vents at the seafloor.

E. Paul Oberlander

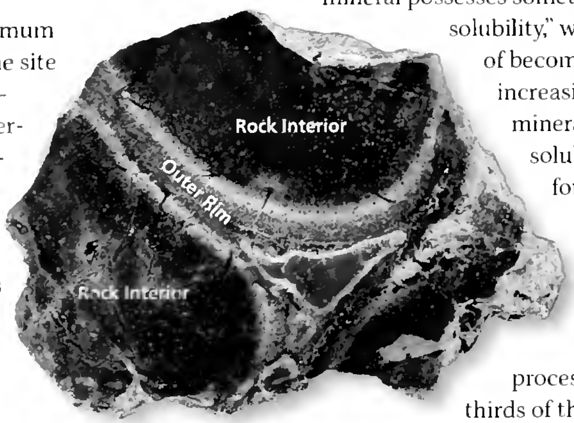

Margaret Sulanowska

WHOI Senior Scientist Susan Humphris (foreground) prepares to deploy the near-bottom *Argo II* optical and imaging system operated by WHOI's Deep Submergence Operations Group. Towed behind ships at 5 to 15 meters off the seafloor, *Argo II* collected video and still images of seafloor hydrothermal vent systems.

availability of good thermodynamic data at the temperatures and pressures that occur in hydrothermal vent systems, much of which has been generated only in the past few years. The models provide a framework for integrating the observations made from rock samples and experimental studies, and they have proven to be a powerful tool to relate the changes in fluid chemistry to the alteration mineralogy of the rocks.

By integrating results from these different investigative strategies, a model is beginning to emerge of how seawater chemistry changes in an active seafloor hydrothermal system, from the time it enters the oceanic crust until it is discharged as a vent fluid. Conceptually, the circulation of seawater through the oceanic crust can be divided into three parts (see page 19):

- *A recharge zone*, where seawater enters the crust and percolates downward;
- *A reaction zone* at the maximum depth of fluid penetration, the site of the high-temperature reactions that are thought to determine the final chemical characteristics of the hydrothermal fluid; and
- *An upflow zone*, where the buoyant hydrothermal fluids rise and are discharged at the seafloor.



A rock sample dredged from the Mid-Atlantic Ridge shows how seawater flowing between subsurface rocks alters them and cements them together. The rocks' outer rims (gray) have been chemically changed by interaction with hot seawater and can be easily distinguished from the relatively unaltered interior (brown). By comparing the geochemistry of the rim and the interior, researchers can determine the ways in which elements are exchanged between seawater and rock.

The Recharge Zone

Seawater percolates readily into the upper layer of the oceanic crust, which is constructed of highly porous and permeable volcanic rocks that are broken apart in many places by cooling cracks and tectonic fractures. As a consequence, reactions between seawater and the exposed rocks at relatively low temperatures up to about 60°C are pervasive. Although reactions are relatively slow at these low temperatures, they nevertheless begin to change the composition of the seawater through two processes. First, the seawater partially oxidizes the crust, resulting in the removal of oxygen from the seawater. Minerals containing iron in the rocks are replaced by iron oxides and hydroxides (a process analogous to the formation of rust), which also fill veins and pore spaces in the upper crust. Second, the reactions with seawater break down the original rock minerals, replacing them with alteration minerals such as mica and clay. In the process, potassium and other alkali elements, such as rubidium and cesium, are transferred from seawater into the rocks.

Beyond about 300 meters into the oceanic crust, penetration of seawater becomes more and more restricted as the rocks' permeability decreases. Larger fractures and fissures are more likely to become the main conduits for fluid flow. As the fluid (already oxygen- and alkali-depleted relative to seawater) continues to penetrate downward toward the heat sources, it becomes heated further, and other reactions occur. At temperatures above about 150°C, clay minerals and chlorite precipitate out of the fluid, essentially removing all of the magnesium originally present in the fluid. The formation of clay minerals and chlorite also removes hydroxyl ions from the fluid, resulting in an increase in acidity (that is, a lower pH). This increase in acidity, in conjunction with the breakdown of the original minerals in the rocks, causes calcium, sodium, potassium, and other elements to be leached from the rock into the fluid. Hence, the removal of potassium (and the other alkalis) from the fluid at lower temperatures is partially reversed at higher temperatures at greater depths!

Another important reaction results in the formation of the mineral anhydrite (calcium sulfate). This mineral possesses something called "retrograde solubility," which means that instead of becoming more soluble with increasing temperature as most minerals do, it becomes less soluble. At the pressures found at the bottom of the ocean, this results in anhydrite precipitating from seawater when temperatures rise above about 150°C. This process removes about two-thirds of the sulfate initially present in the seawater and also limits the calcium concentration of the fluid. At temperatures greater than 250°C, the remaining sulfate in the fluid reacts with iron in the crust to form metal sulfide minerals.

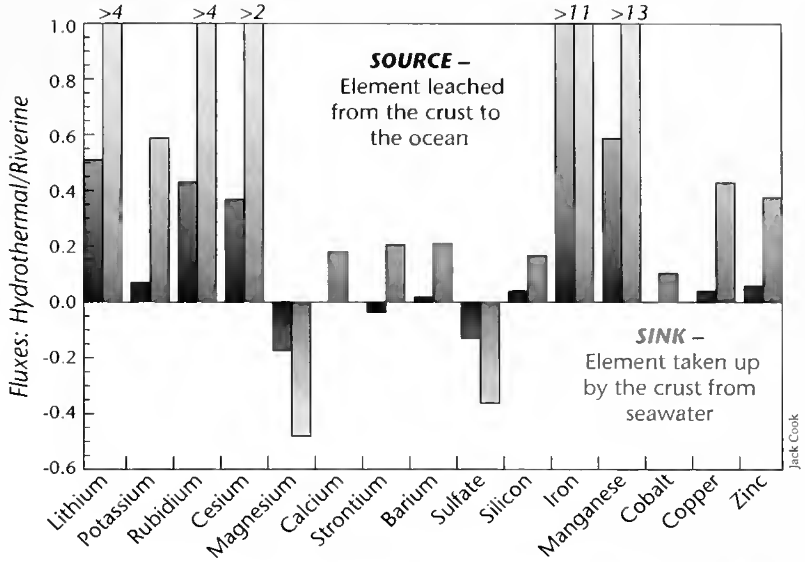
The Reaction Zone

The "reaction zone" designates the region where high-temperature, water-rock reactions occur. This zone is near the heat source that drives the circulation system. The depth of the reaction zone depends on the depth of the heat source and varies from one mid-ocean ridge to another. On the fast-spreading East Pacific Rise, the presence of a magma lens at a depth between 1.5 and 2.4 kilometers defines the lower limit of circulation, but seawater may penetrate deeper on slower-spreading ridges where no melt lens has been detected. Scientists think reactions in this zone determine the final chemical characteristics of the hydrothermal fluid. Reactions at such high temperatures (up to 350° to 400°C) produce a characteristic suite of alteration minerals (chlorite, sodium-rich feldspar, amphibole, epidote, and quartz), which, in turn, controls the fluid composition. Metals, such as copper, iron, and zinc, as well as sulfur, are leached from the rock by the acidic fluid. This provides the source of metals for the massive sulfide deposits observed at the seafloor, as well as the hydrogen sulfide to support the chemosynthetically based hydrothermal biological community.

The Upflow Zone

Buoyancy forces cause the hot fluids to rise rapidly toward the seafloor, much as hot air causes a balloon to rise in the atmosphere. Initially, the upflow is focused along a conduit of high permeability, such as a fault surface. As it reaches shallow depths, the flow may continue to be focused and may discharge through a chimney, or it may follow more tortuous pathways and be discharged as a more diffuse flow (like water flowing through a sponge). Continued high-temperature reactions between the rock and the upward-flowing, metal-rich, magnesium-depleted hydrothermal fluid produce an "alteration pipe" of highly altered rocks with an interconnected network of veins filled with sulfides, silica, and chlorites. As focused high-temperature (350° to 400°C) fluids discharge at the seafloor as black smokers, mixing with the surrounding seawater causes metal sulfides to precipitate and form massive sulfide deposits rich in iron, copper, and zinc (see article, page 22). However, at locations where the volcanic pile is especially permeable, the upflowing hydrothermal fluid will mix with colder seawater in the shallow subsurface, resulting in the metal sulfides being precipitated beneath, rather than at, the seafloor. The resulting lower-temperature fluids, depleted of metal sulfides, vent as "white smokers," rather than particulate-laden black smokers. Shallow subsurface mixing may also heat seawater to form anhydrite and cool hydrothermal fluids to precipitate silica, both of which cement the metal sulfides or seal fluid conduits.

Together, all the hydrothermal water-rock reactions that occur—from the time seawater enters the system to the time hydrothermal fluid leaves it—play a role in regulating the chemistry of seawater. But the relative importance of hydrothermal reactions must be balanced with other factors that influence ocean chemistry—particularly, rivers, which are the principal conduits by which most (but not all) chemical elements enter the ocean. River input provides a good measuring stick by which to compare the relative contribution of hydrothermal activity to the fluxes of elements in and out of the ocean. Hydrothermal vents are a source to the ocean of alkali elements that leach from the crust during hydrothermal alteration (although this process may be tempered somewhat by lower-temperature weathering of the shallow crust away from the ridges, which removes alkali elements from seawater).Vents also represent a significant source of manganese input to the ocean. Most of the metals present in hydrothermal fluids (iron, copper, zinc, etc.) are removed rapidly by precipitation, either at the seafloor or by mixing with seawater in the subsurface, so most of the metals do not enter the oceans. On the other hand, hydrothermal circulation removes magnesium and sulfate from seawater, so the crust acts as a sink for these elements. The magnesium loss is perhaps the most significant, and hydrothermal activity may be a major mechanism of balancing the magnesium budget in the ocean.



Jack Cook

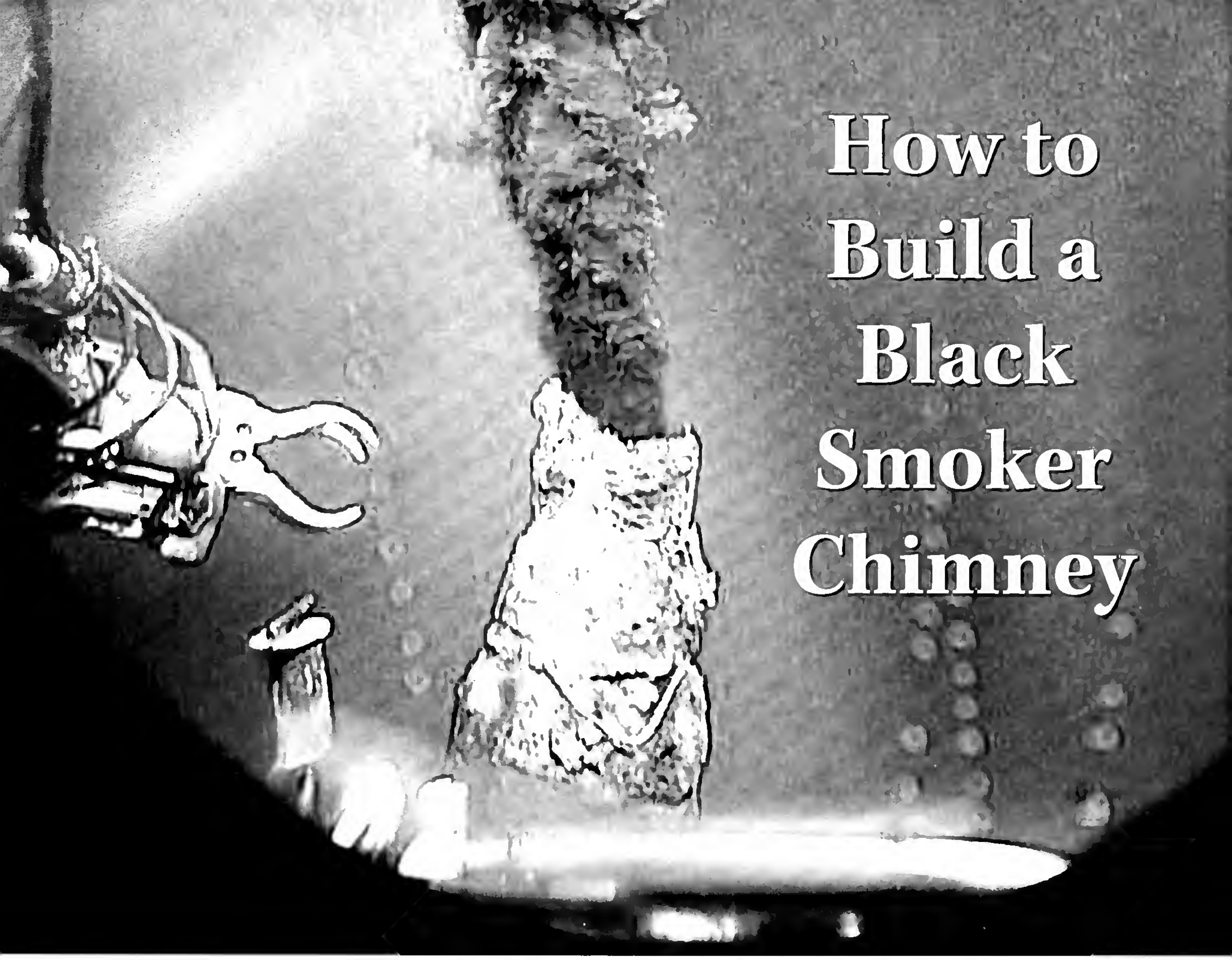
Chemical reactions in hydrothermal vent systems are a source of elements (positive values) leaching from the ocean crust to the ocean, and a sink (negative values) for elements removed from seawater and incorporated into the crust. In the chart above, fluxes of elements into and out of seawater caused by hydrothermal activity are compared to element fluxes caused by rivers. Green bars indicate minimum estimates of element fluxes: purple bars represent maximum estimated fluxes. (Adapted from *Global Impact of Submarine Hydrothermal Processes, The Final Report*, RIDGE/VENTS Workshop, 1994.)

Susan Humphris's research is supported by the National Science Foundation. Thomas McCollom is an NSF Earth Sciences Postdoctoral Fellow.

Susan Humphris first came to Woods Hole from England in 1972 to enter the MIT/WHOI Joint Program. For her Ph.D. thesis, she studied some rocks dredged from the ocean floor that had reacted with seawater and determined the reactions that must have occurred. Six months after she completed this work in 1976, the first hydrothermal vents were discovered. She has spent more than three years of her life on research vessels of various kinds, ranging from traditional sailing ships, when she worked at the Sea Education Association teaching oceanography to undergraduates, to drilling vessels as a participant in the Ocean Drilling Program. She has completed about 30 dives in submersibles and has used ROV Jason *to study new hydrothermal sites. In her spare time, Humphris and her husband tend a large vegetable garden and raise chickens and the occasional pig.*

Tom McCollom's interests are in the organobiogeochemistry of seafloor hydrothermal systems. He manages to squeeze in a little research now and then between running around on the soccer and ultimate fields, pedaling his bicycle, climbing up (or skiing down) hills, dancing to his favorite bands, and birdwatching with his wife, Ifer.

How to Build a Black Smoker Chimney



Alvin's manipulator reaches toward a black smoker chimney, seen through the sub's viewport, at 17°S on the East Pacific Rise. Hot hydrothermal fluids surge through the chimney at velocities of 1 to 5 meters per second. The "black smoke" consists of an abundance of dark, fine-grained, suspended particles that precipitate when the hot fluid mixes with cold seawater.

The Formation of Mineral Deposits At Mid-Ocean Ridges

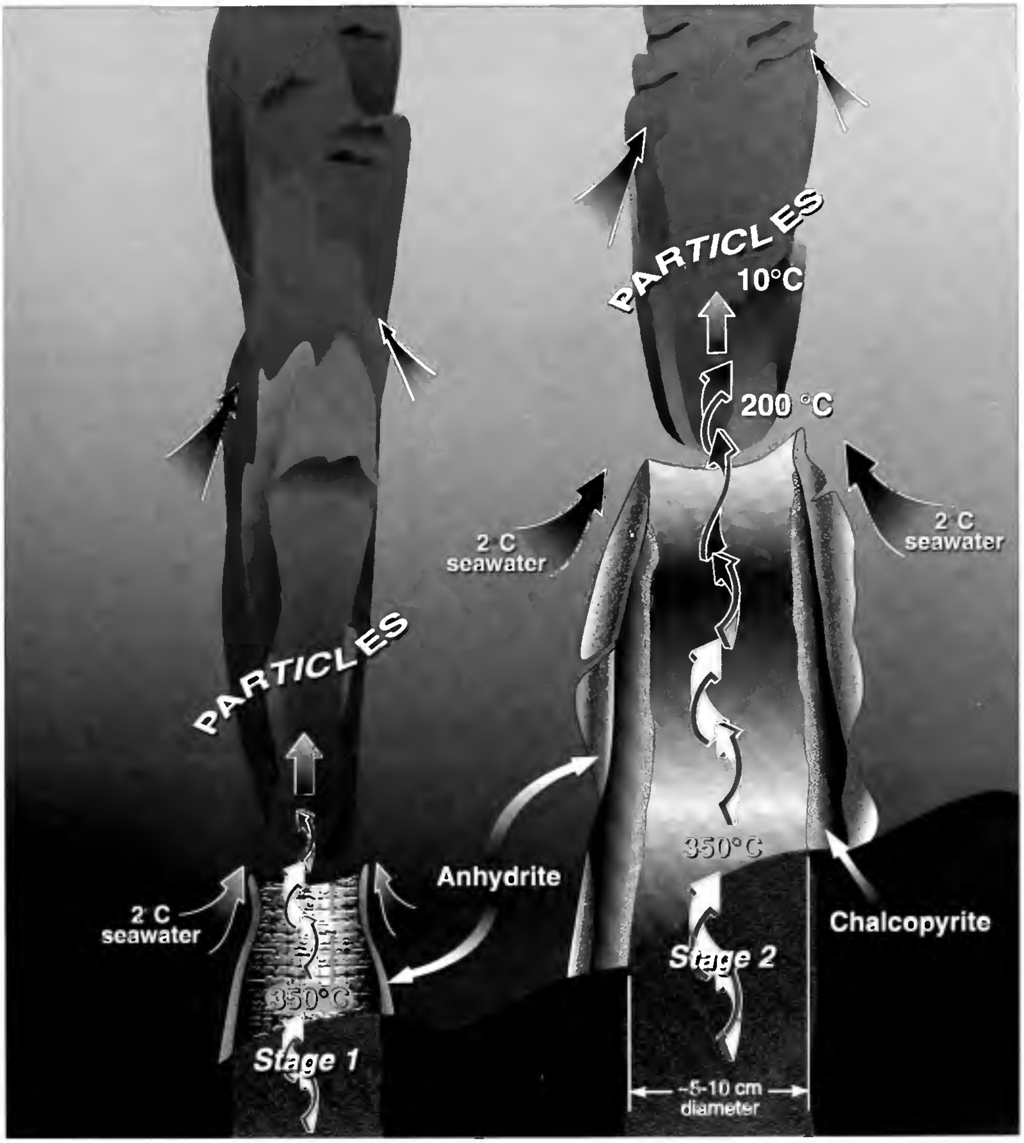
Margaret Kingston Tivey
Associate Scientist, Marine Chemistry & Geochemistry Department

iving along the mid-ocean ridge at 21°N on the East Pacific Rise, scientists within the deep submersible *Alvin* peered through their tiny portholes two decades ago to see an astonishing sight: Clouds of billowing black "smoke" rising rapidly from the tops of tall rocky "chimneys." The "smoke" consisted of dark, fine-grained particles suspended in plumes of hot fluid, and the "chimneys" were made of minerals that were rich in metals. Using specially designed fluid bottles and temperature probes, *Alvin* took samples of these black smoker chimneys, as well as the 350°C fluids venting from them. Since then, scientists have observed and sampled numerous active vent sites along portions of the mid-ocean ridge in the Atlantic and Pacific Oceans, and in back arc basins in the Pacific Ocean. It has become abundantly clear that these high-temperature seafloor hydrothermal systems are the analogs to systems that created some of the world's economically valuable mineral deposits, including some that have been mined on land. In Cyprus and Oman, for example, ore deposits of millions of tons are found in ophiolites, portions of ancient seafloor thrust onto land by tectonic forces.

Scientists can gain much insight into hydrothermal processes through detailed studies of these exposed areas of fossil systems, but only by investigating active systems can they simultaneously examine hydrothermal fluids and the corresponding mineral deposits created by them. By analyzing these fluids and deposits, we have been able to formulate models to explain how submarine mineral deposits, from seafloor chimneys to great subseafloor depths, are initiated and how they grow in their early stages.

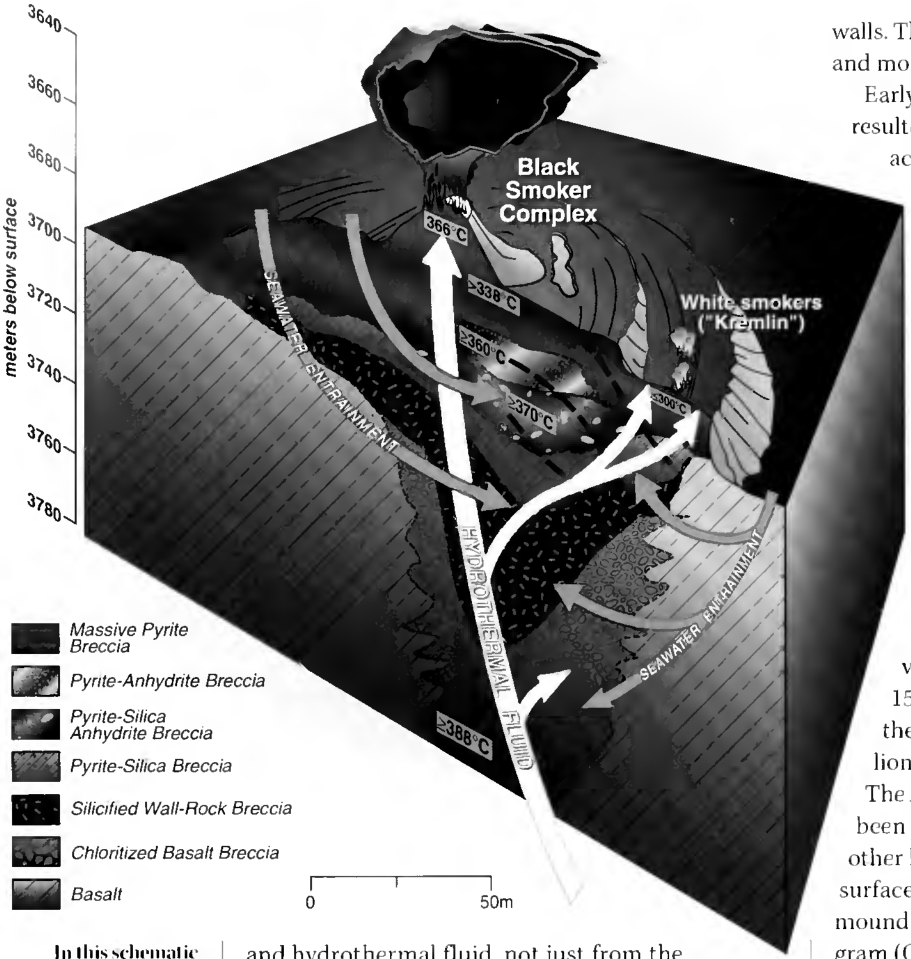
One of the most fascinating aspects of black smoker chimneys is how rapidly they form. They have been measured to grow (after upper parts of the chimneys are razed by sampling) as fast as 30 centimeters per day. Examination of young chimney samples, under the microscope and by X-ray diffraction, revealed that the earliest stage in the creation of a black smoker chimney wall involves precipitation of a ring of a mineral called anhydrite. The ring forms around a jet of 350°C fluid, which exits the seafloor at velocities of between 1 and 5 meters per second. Anhydrite, or calcium sulfate ($CaSO_4$), is an unusual mineral because it is more soluble in seawater at low temperatures than at high temperatures. Seawater contains both dissolved Ca^{2+} and SO_4^{2-} ions, and when it is heated to 150°C or greater, the ions combine and anhydrite precipitates. Hydrothermal fluids contain little or no sulfate, so the origin of the sulfate in the precipitated anhydrite is seawater. Calcium, however, is present in both seawater and hydrothermal fluid. That made it more difficult at first to determine whether the initial anhydrite chimney wall formed solely from seawater that was heated by hydrothermal fluids, or from the mixing of cold, sulfate-rich seawater with hot, calcium-rich hydrothermal fluid.

Strontium, which is present in seawater and hydrothermal fluid, was used to investigate this problem. Strontium has the same charge as calcium and a number of different, easily measurable isotopes. (Isotopes are elements having the same number of protons in their nuclei, but different numbers of neutrons. Thus they share chemical properties but have slightly different physical properties.) Strontium can readily take the place of calcium in the crystalline lattice that forms when anhydrite precipitates. The concentration of strontium, as well as the ratio of two of its isotopes, strontium 87 and strontium 86, were measured in both vent fluid and in seawater. Because the ratio of strontium 87 to strontium 86 is higher in seawater than in hydrothermal fluid, it is possible to determine whether the source of the strontium (substituting for calcium in newly formed anhydrite grains) is seawater or vent fluid. The answer is both: Anhydrite walls form from the turbulent mixing of seawater



Jayne Doucette

During Stage 1 of black smoker chimney growth, hot, calcium-rich vent fluid mixes turbulently with cold, sulfate- and calcium-rich seawater, resulting in precipitation of a ring of calcium sulfate (anhydrite). Metal sulfides and oxides carried in the hot fluid also precipitate rapidly during the mixing process, forming a plume of dark particles above the vent. During Stage 2 of chimney growth, the initial chimney wall of anhydrite forms a surface on which chalcopyrite (copper-iron sulfide) begins to precipitate and plate the inner chimney wall. Mixing of seawater and hydrothermal fluid components across the porous wall by advection and diffusion results in the deposition of zinc, copper-iron, and iron sulfides in the interstices of the wall, which gradually makes the chimney less porous and more metal-rich.



Jayne Doucette

In this schematic drawing of the TAG active hydrothermal mound, hydrothermal fluid rises rapidly and exits the mound at the Black Smoker Complex. Cold calcium- and sulfate-rich seawater is entrained into the mound, where it mixes with hydrothermal fluid. The mixing causes anhydrite, pyrite, and chalcopyrite to precipitate inside the mound. This precipitation increases the acidity of the hydrothermal fluid. Zinc and other elements, such as silver, gold, and cadmium, dissolve in this acidic fluid, allowing them to be carried by the white smoker fluid to the edges of the mound at the "Kremlin" area. Here the cooler temperatures within white smoker chimney walls cause the elements to precipitate.

and hydrothermal fluid, not just from the rapid heating of seawater.

During this mixing, other processes occur during early stages of chimney growth. Metal sulfides and oxides (zinc sulfide, iron sulfide, copper-iron sulfide, manganese oxide, and iron oxide) precipitate from the vent fluids as fine-grained particles, most of which form a plume of "smoke." Because bottom seawater is denser than the mix of seawater and hydrothermal fluid in the plume, the plume rises some 200 meters above the ridge to a level of neutral buoyancy. Some particles form close to the chimney and become trapped within and between grains of anhydrite within the nascent chimney walls. These particles give the anhydrite, which is white in its pure form, a gray to black color. Copper-iron sulfide (chalcopyrite, or $CuFeS_2$) begins to precipitate and plate the inner surface of the chimney. The evolving chimney walls are thin, ranging from less than a quarter of an inch to a few inches, but on either side of them are large gradients of pressure, temperature, and concentrations of elements. Aqueous ions, including copper, iron, hydrogen sulfide, zinc, sodium, chloride, and magnesium, are transported from areas of high to low concentrations (by diffusion). These elements also are carried by fluids flowing back and forth across the wall from areas of high to low pressure (by advection). As a result of these processes, zinc sulfide, iron sulfide, and copper-iron sulfide precipitate in the interstices of the chimney walls. The chimney walls thus become less porous and more metal-rich over time.

Early examinations of black smoker chimneys resulted in a model of chimney growth that is still accepted nearly 20 years later. But in terms of size and ore grade, black smoker chimneys are not important mineral deposits. Most of the metals are lost into the plume that rises into the water column above the vents and is dispersed. In the last decade, the focus of study has shifted to larger deposits present along mid-ocean ridges.

In 1985, scientists aboard Woods Hole Oceanographic Institution's *Atlantis II* discovered hydrothermal vents at the Trans-Atlantic Geotraverse (TAG) active mound, the single largest known active mineral deposit along the mid-ocean ridge. Roughly circular in plan view, the TAG site has a diameter of about 150 meters and rises some 50 meters above the seafloor, with an estimated mass of 3 million tons. TAG has been intensively sampled. The *Alvin*, *Mir*, and *Shinkai* submersibles have been used to recover vent fluids, chimneys, and other hydrothermal precipitates from the mound surface. And in 1994, 17 holes were drilled into the mound during Leg 158 of the Ocean Drilling Program (ODP). Drillcore was recovered from five mound areas to a maximum depth of 125 meters below the seafloor.

As in studies of black-smoker chimneys, the combination of vent fluid data and examinations of anhydrite played an important role in determining the processes involved in growth of the large TAG mineral deposit. In 1990, two distinct fluid compositions were observed to be exiting the TAG mound. From the so-called Black Smoker Complex in the northwest area of the mound, 366°C black smoker fluid billowed from an aggregation of chimneys in a huge black plume that shrouded nearly the entire complex. Approximately 70 meters southeast of this complex, however, clear fluid with temperatures of less than 300°C emanated from an area called the Kremlin, named for its 1- to 2-meter-high chimneys with their distinctive, onion-shaped Byzantine cupolas. The mineral composition of the black smoker chimneys was very similar to those of black smokers at other mid-ocean ridge vent sites. The chimneys forming from the cooler white smoker fluid, however, were quite different, containing significant amounts of zinc, as well as cadmium, silver, and gold. Analyses of the white smoker fluids indicated that they were more acidic and contained less copper, iron, calcium, and hydrogen sulfide, but 10 times more zinc, than the hotter black smoker fluids. However, concentrations of other elements, such as potassium, were identical, suggesting that the two fluids were related to one another.

A hypothetical series of steps was soon developed to explain these observations. The deficits of copper, iron, and hydrogen sulfide in the cooler white smoker fluid could best be explained by the precipitation of copper-iron sulfide and iron sulfide (that is, chalcopyrite and pyrite) *within* the mound. In addition, it was theorized that precipitation of anhydrite *within* the mound could explain the lower calcium concentrations in white smoker fluids. To trigger the deposition of sulfates and sulfides inside the mound, sulfate-rich seawater would have to percolate down into the mound and mix with the hotter hydrothermal fluid. The precipitation of sulfides would release hydrogen ions, making white smoker fluid more acidic. The increased acidity, in turn, would cause metals in the mound, such as zinc, cadmium, silver, and gold, to dissolve. Once dissolved in the fluid, these so-called "remobilized" elements could be transported toward the upper edge of the mound. This would explain the excess zinc observed in white smoker fluid. At the seafloor, the white smoker fluid, rich in remobilized metals, confronts 2°C seawater just outside the chimney wall. Crossing this thermal gradient, the fluid cools, and some metal-rich minerals precipitate. This process, known as "zone refinement," explains how some ore deposits are separated into large-scale zones containing different metals, with copper in the center of the deposits, for example, and zinc at the edges.

To determine whether the scenario described above was reasonable, we used geochemical modeling calculations, which take into account the thermodynamics of a range of different chemical reactions at high temperatures. The theoretical reactions had to reproduce the already-well-documented composition of the less-than-300°C fluid from combinations of the 366°C fluid and seawater. These calculations demonstrated that the composition of the cooler white smoker fluid we observed could theoretically result from mixing 86 percent black smoker fluid with 14 percent seawater, which would result in the precipitation of 19 parts anhydrite, 8 parts pyrite, and 1 part chalcopyrite within the mound, as well as the remobilization of zinc and other metals by the resultant acidic fluid.

These predictions were put to the test when the TAG mound was drilled in the fall of 1994. One of ODP Leg 158's major findings was that significant amounts of anhydrite are present throughout the mound. Anhydrite has not been seen in analogous ophiolite structures probably because it dissolves at lower temperatures and essentially has disappeared from land-based deposits. But anhydrite was recovered from three of the five sites drilled at TAG. It was present at the base of the deepest hole drilled at the TAG site, to a depth of 125 meters below the seafloor. The drilling revealed that the mound contained wide, complex, anhydrite-rich veins, ranging in size from 1 millimeter to 1 meter wide, which formed as anhydrite precipitated in cracks within the mound.

The discovery of anhydrite confirmed the prediction that seawater was entering and traveling through the mound. It also let us determine the proportions of seawater that were mixing with hydrothermal fluid within the mound. Analyses of strontium isotopes from anhydrite grains recovered from various depths in the mound demonstrated that anhydrite was forming from mixtures that ranged from 99.5 percent seawater and 0.5 percent hydrothermal fluid to 52 percent seawater and 48 percent hydrothermal fluid.

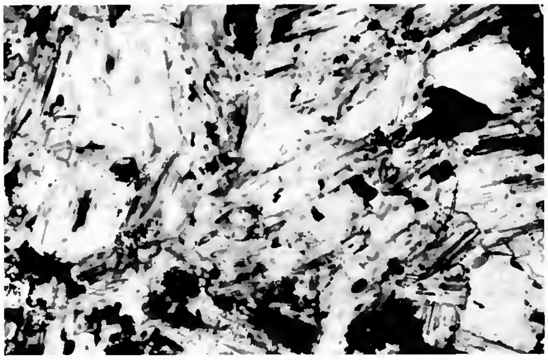
Samples of anhydrite grains recovered from drilled cores were also used to determine the temperature and salinity of fluids at various points within the mound. When mineral grains form, small amounts of the fluid from which they are forming can be trapped and enclosed within the precipitating grain. As a result, small cavities can form within the mineral,

Tom Kleindinst

Author Margaret Tivey examines the top of a spire of a black smoker chimney retrieved by *Alvin* from the East Pacific Rise at 17°S.

which may contain one or more phases (liquid, vapor, or solid). These are called fluid inclusions. The cavities can range in size from about 1 micron to greater than 1 millimeter, though 3- to 20-micron inclusions are most common. The anhydrite grains from the TAG mound all contained abundant fluid inclusions with two phases: liquid and a vapor bubble.

We analyzed fluid inclusions within mineral grains by using a heating-freezing stage attached to a high-magnification microscope. The salinity is determined by freezing the fluid within the inclusion at temperatures of less than -50°C and then slowly heating until the last ice melts. The temperature of final melting is a function of the salt content in the fluid. The temperature of the fluid when it was trapped within the mineral also can be determined by heating the fluid inclusion and measuring the temperature at which the vapor bubbles disappear. With adjustments for undersea pressures, measurements of fluid inclusion trapping temperatures from a number of different anhydrite grains recovered from within the TAG mound indicated very high temperatures (greater than 337°C) throughout most of the mound. At depths greater than 100 meters below the seafloor, trapping temperatures were in excess of 380°C.



Thin-section samples of chimney wall specimens, examined under a microscope, reveal metal sulfide particles (black) embedded in and around anhydrite crystals (clear).

Tom Kleindinst

The combination of strontium-isotope and fluid-inclusion analyses of TAG anhydrite grains not only demonstrated that large amounts of seawater are being entrained into the mound, they also showed that anhydrite (and chalcopyrite and pyrite) precipitated in the mound from seawater-hydrothermal fluid mixtures that are greater than 50 percent seawater. That led to a dilemma and to another discovery. The dilemma was that our geochemical modeling calculations predicted that if the mixing proportions were greater than 50 percent seawater, and if mixing alone determined the temperature of the fluids in the mound, the fluid temperatures in the mound should be relatively low (5° to 250°C). Our fluid inclusion measurements, however, indicated that the anhydrite grains were nearly all precipitating at much higher temperatures, 187°C to 388°C.

The logical conclusion is that the seawater and seawater-hydrothermal fluid mixtures that are entering and travelling through the mound are being heated by conduction. Hot black smoker fluids are flowing rapidly along a direct, highly focused route up through the mound to the Black Smoker Complex. Drilling within the mound revealed extensive accumulations of breccia—rocks made of sulfide-rich fragments that conduct heat well. So it is reasonable to conclude that cold seawater is being conductively heated as it flows through channels bounded by breccias. If enough seawater is being heated in this way, black smoker fluid may be cooled slightly as it rises through the mound to the Black Smoker Complex—from the 388°C temperatures found in the anhydrite grains near the base of the mound to the 366°C temperatures of the exiting black smoker fluids.

Results of drilling revealed other important information on the internal structure of the TAG active mound. By dating mound materials, it is possible to reconstruct a history of the mound, showing that it has undergone repeated episodes of high-temperature fluid flow, punctuated by quiescent periods, over a roughly 20,000-year interval. When the high-temperature fluid flow ceases, the anhydrite dissolves, and the chimneys that the anhydrite supports collapse, scattering fragments of rock. When high-temperature fluid flows resume and percolate through these fragments, anhydrite precipitates and serves as a matrix that cements together fragmented chimney pieces and mound materials into breccia deposits. Textures within the TAG breccias indicate that there have been multiple cycles of mound material reworking—a likely consequence of repeated episodes of anhydrite deposition and dissolution.

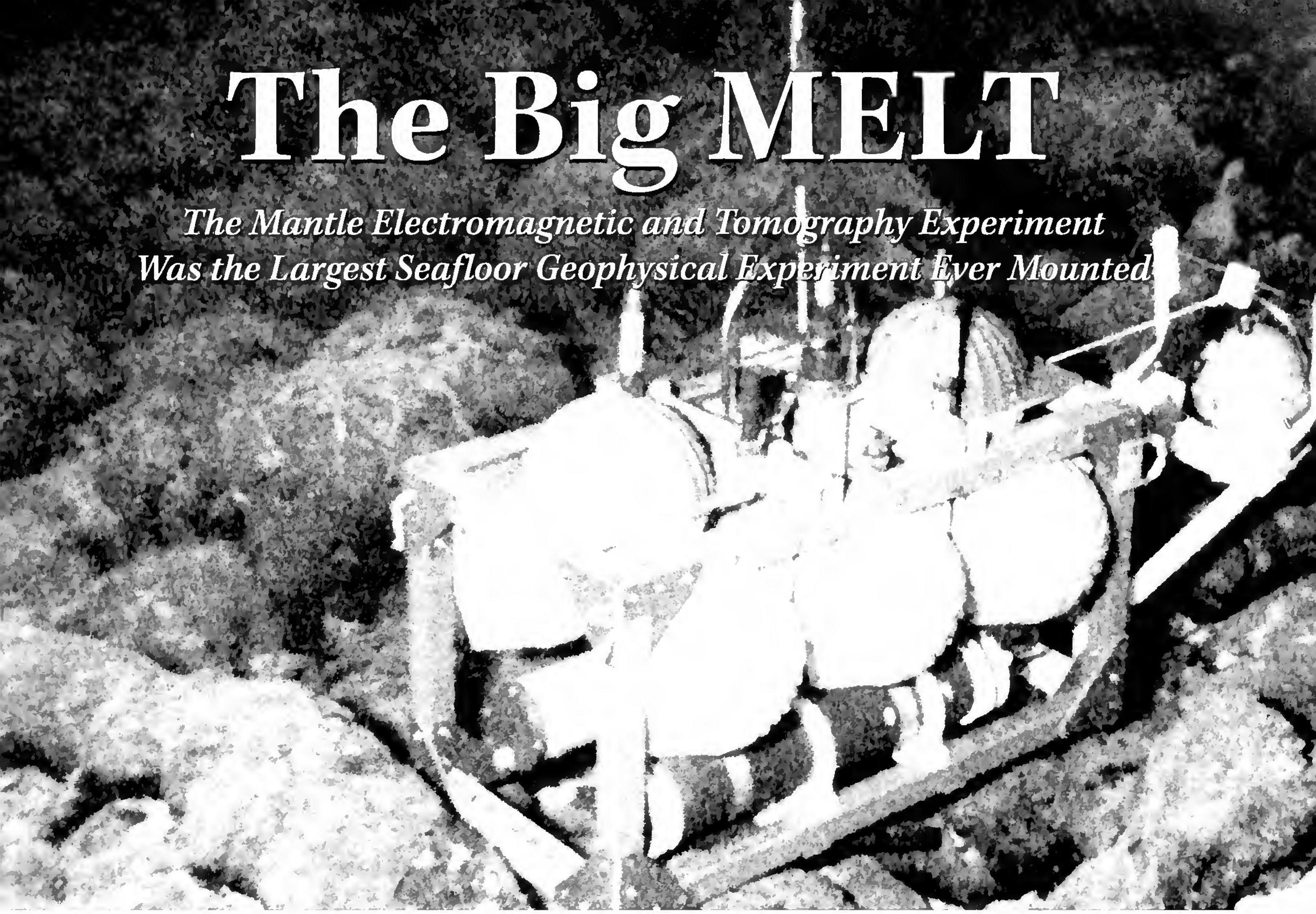
Information from the TAG mound shows how this kind of intermittent activity can, over long periods of time, result in the gradual formation of a large hydrothermal mineral deposit similar to the ore bodies preserved in Cyprus. Studying the large TAG active mound has greatly increased our understanding of how large mineral deposits like these can form.

Meg Tivey's research on hydrothermal deposits has been funded through the National Science Foundation and the Joint Oceanographic Institutions/US Science Advisory Committee. Her work on the TAG active mound has benefited from collaborations with many scientists, including Susan Humphris and Geoffrey Thompson (WHOI), Rachel Mills (University of Southampton), and Mark Hannington (Geological Survey of Canada).

Meg Tivey chose to major in geology after taking a course with five field trips to local beaches and fault zones. She then worked as a physical science technician at the US Geological Survey before deciding to pursue graduate studies in marine geology at the University of Washington. She now specializes in studies of active seafloor hydrothermal systems. Her current projects include examining the formation of polymetallic sulfide deposits, continuing work on linking measured vent fluid compositions to observed mineralogy of vent deposits, using X-ray computed tomography (CAT scans) to examine seafloor sulfide samples in three-dimensions, and working with engineers to build instruments capable of measuring temperatures and flow rates on the seafloor in high-temperature and low-pH fluids.

The Big MELT

The Mantle Electromagnetic and Tomography Experiment Was the Largest Seafloor Geophysical Experiment Ever Mounted



An ocean bottom seismometer on the Pacific Ocean floor measures the velocity of seismic waves traveling through the mantle and oceanic crust. These data allowed scientists to probe deep within the portion of the earth that generates new ocean floor.

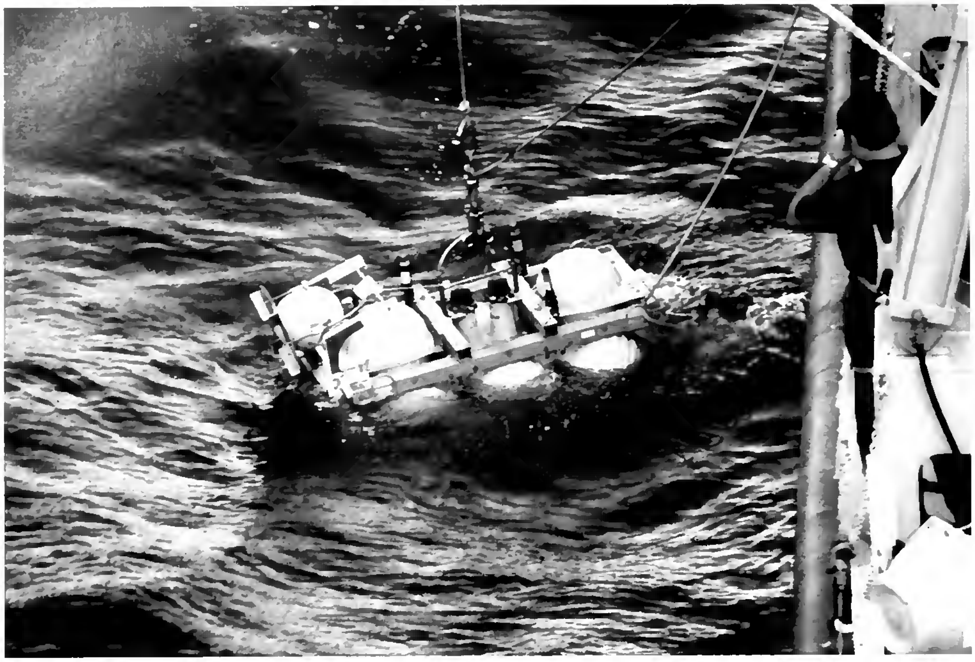
Donald W. Forsyth
Professor of Geological Sciences, Brown University

More than 95 percent of the earth's volcanic magma is generated beneath the seafloor at mid-ocean ridges. As the oceanic plates move apart at spreading ridges, hot mantle rock rises from deep in the earth's interior to replace material dragged away by the plates. This ascent releases pressure that had kept the hot mantle rocks solid. The mantle rock begins to melt and form basaltic magma, which then percolates up toward the surface through cracks and pores in the remaining solid, yet deforming, rock. At the ridge, the magma pools and solidifies to form a 6-to-7-kilometer-thick layer of new basaltic crust. This crustal layer underlies the seafloor throughout the ocean basins.

Most of what we know about this process of magma or melt production beneath ridges is inferred from the volume of melt indicated by the thickness of the crust and from the composition of basalts recovered at the seafloor by dredging, drilling, and submersible sampling. Much uncertainty remains about where and how the melt forms and is extracted from the mantle, because we have not had any means to directly probe into the melt production region tens to hundreds of kilometers beneath the earth's surface.

Geophysical measurements, however, can provide means to probe deep into the mantle to detect the presence of melt or hot rock. For example, studying seismic waves that travel through the mantle can tell us something about the structure of the earth along their paths, because these waves travel slower in hot rocks and slower still if there are melt-filled cracks or pores. In addition, the forces of flow and deformation within the mantle often cause crystals of olivine or pyroxene, the most common minerals in the mantle, to align in particular directions. This phenomenon, in turn, speeds up or slows down the propagation of seismic waves through the crystals, depending on the direction and vibration of the waves. We can also extract information by analyzing the propagation of electromagnetic waves through the mantle, because basaltic melt is a better electrical conductor than solid rock. If the melt pockets are connected together to form a conducting network, the wave propagation is strongly affected.

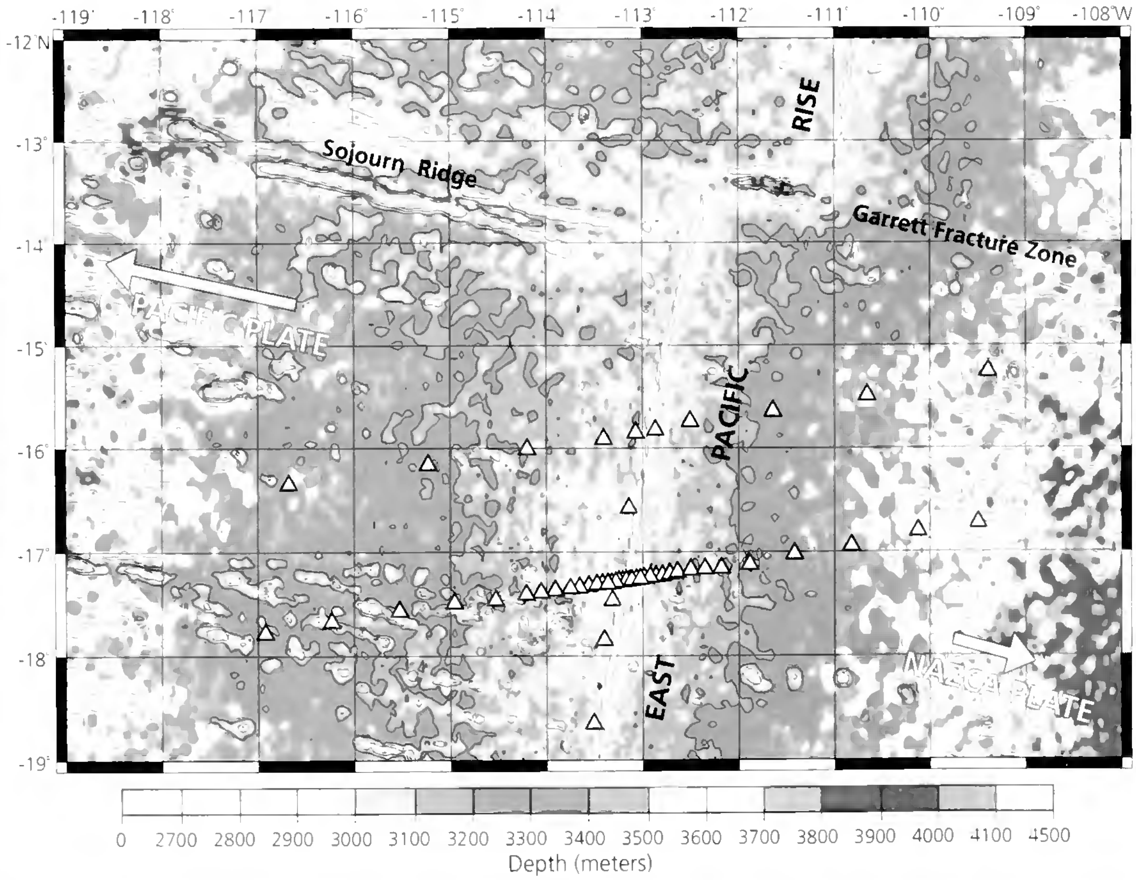
In previous studies, scientists examined velocities of seismic waves traveling from their earthquake sources through ridges and to land-based receivers. They mapped regions of slow wave propagation near ridges, but found the data lacked the


Don Forsyth

A WHOI ocean bottom seismometer (OBS) is deployed from R/V *Melville* (Scripps Institution of Oceanography) at the start of the MELT Experiment in November 1995. Seismometers within the yellow spheres record ground motion generated by seismic waves traveling through the mantle and the oceanic crust. In May 1996, an anchor on the OBS was released and the instrument floated to the surface, where it was recovered.

resolution to pinpoint the width or depth to which the region of melt production extends. That left room for two competing theories of how magma is generated beneath mid-ocean ridges: Some theoretical models predict that most of the upwelling and melting takes place in a narrow zone, perhaps less than 10 kilometers wide, directly beneath the ridge axis. In other models, melting extends over a broad region and the migrating melt is somehow forced back to the ridge axis to form new crust.

The Mantle ELectromagnetic and Tomography (MELT) Experiment was designed to distinguish between these competing theoretical models by investigating in detail the structure beneath a spreading center. In the largest deployment of geophysical instrumentation ever attempted on the seafloor, a total of nearly 100 ocean bottom seismometers (OBSs), electrometers, and magnetometers were placed in arrays across the East Pacific Rise (see map below). More than 50 scientists from 12 research institutions participated. The OBSs were supplied by groups from Woods Hole Oceanographic Institution and Scripps Institution of Oceanography (SIO), and electrometers and magnetometers by scientists from WHOI, Australia, France, and Japan. Beginning in November 1995, the seismometers recorded seismic waves generated by earthquakes around the world that propagated through the mantle beneath the ridge. In May 1996, the OBSs' anchors were released and the instruments were recovered along with their valuable recordings. The same cruise that retrieved the OBSs also deployed the electrometers and magnetometers to begin a one-year period of recording electromagnetic waves generated by ionospheric

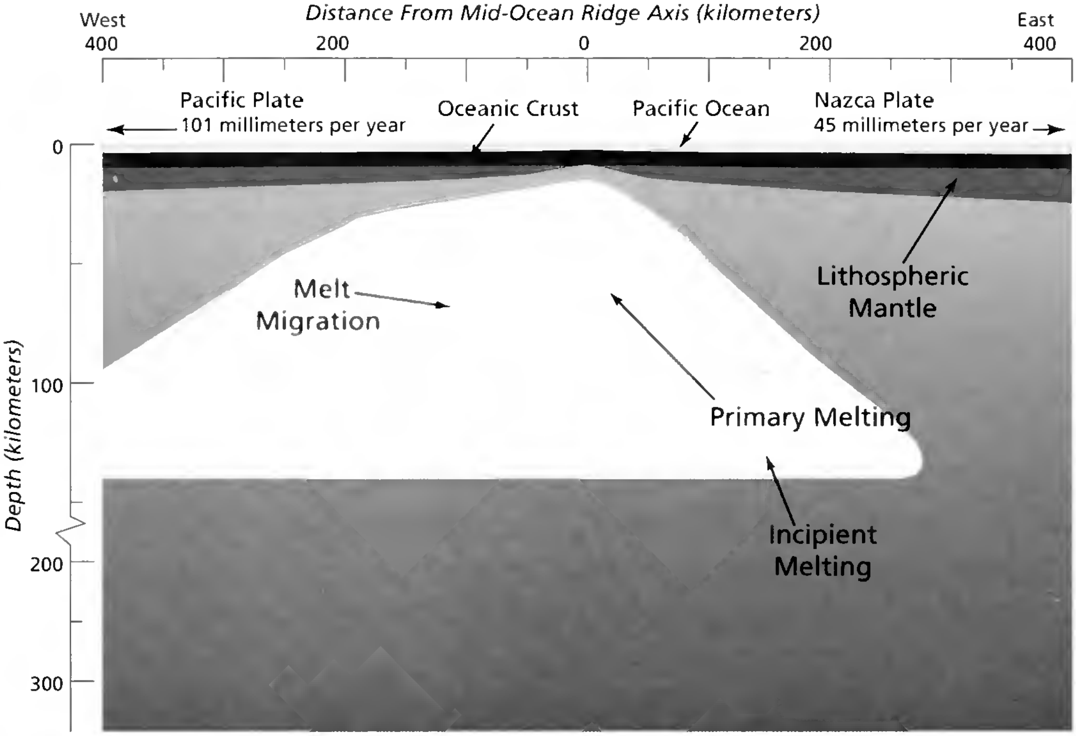


Don Forsyth

More than 50 ocean bottom seismometers (white triangles) were deployed across and along the East Pacific Rise off the west coast of Mexico during the MELT Experiment to probe the deep structure beneath the mid-ocean ridge. Arrows show the motions of the Pacific and Nazca plates, which are spreading in opposite directions from the ridge crest, shown by shallower depths (red).

currents that penetrate deep into the mantle (see article, page 32).

The East Pacific Rise at 17°S was chosen for the experiment because it is in the middle of one of the longest, straightest sections of the mid-ocean ridge system and is spreading at close to the fastest rate, about 14.5 centimeters per year. In addition, the subduction zones of the Pacific Rim provided an excellent surrounding source of seismic waves, since earthquakes frequently occur in these zones, where the seafloor created at the East Pacific Rise eventually sinks back into the mantle. We were lucky that our six-month recording period was seismically active; there were several earthquakes of magnitude 7 or larger, as well as some good, smaller events on other parts of the East Pacific Rise. One of the best sources was an earthquake 150 kilometers deep in the Tonga subduction zone. We also happened to record the last three underground tests of nuclear devices in French Polynesia, but the signals from these explosions were too small to be useful for our purposes. During the deployment cruise, a group led by Robert Detrick and Pablo Canales from WHOI and John Orcutt and Sara Bazin from SIO employed an array of airguns towed behind the ship as artificial sound sources to acquire data on the structure of the oceanic crust (see article on page 30). Differences in crustal thickness are caused by variations in the supply of magma to the spreading center and thus provide additional information about the process of melt production in the mantle.



Don Forsyth

Initial results from the MELT Experiment are shown in this schematic cross-section of the upper mantle beneath the East Pacific Rise. The melting region below the mid-ocean ridge extends over a broad area several hundred kilometers wide. The region is asymmetrical, with a wider zone west of the ridge than east of it. The melting region also extends far deeper than many scientists have previously theorized: to depths of 150 to 200 kilometers beneath the ridge, although the greatest concentration of melt occurs above 100 kilometers.

Seismic results from the MELT Experiment appear to have settled the long-standing debate about the form of the upwelling beneath the ridge. We found low seismic velocities through a zone several hundred kilometers wide, indicating the presence of melt at depths of 20 to more than 70 kilometers. This wide zone suggests that the separating plates provide the primary force that drives upward flow of the mantle beneath the East Pacific Rise. It contradicts the theory that melting occurs primarily in a narrow zone directly beneath the ridge and that upwelling of the solid mantle is driven and focused by buoyancy forces.

The seafloor begins to subside as it cools and moves farther from the ridge, but at the East Pacific Rise, it subsides more slowly on the western flank than on the eastern. This suggests that the mantle is hotter to the west. Nevertheless, we were surprised by the apparent asymmetry of the mantle structure, as evidenced by the seismic data. The low-velocity region extends as much as 250 kilometers west of the axis, but only about 100 kilometers to the east, and the lowest velocities may even be located west of the axis. Since there are also many more seamounts on the western, or Pacific Plate, side of the axis, the asymmetry may be related to melting and upwelling involved in the off-axis volcanism that builds seamounts. However, this volcanism is much less voluminous than that caused by the seafloor spreading process, producing only 1 or 2 percent of the oceanic crust in this area.

Another intriguing asymmetry was found by Cecily Wolfe (WHOI) and Sean Solomon (Carnegie Institution). One type of seismic wave, the shear wave, splits into two components that travel at different speeds in the upper mantle; shear waves go faster when vibrating in a direction parallel to the alignment of the crystals in the mantle—that is, when the waves' vibrations are aligned with, rather than against, the crystalline grain. Wolfe and Solomon found that shear-wave splitting is twice as large beneath the Pacific Plate as beneath the Nazca Plate on the eastern flank, indicating that crystals may be better-aligned beneath the Pacific Plate. This difference may be caused by the different rates of plate motion: relative to the deep mantle, the Pacific Plate is moving twice as fast to the west as the Nazca Plate is moving to the east.

We have determined that the melting region, the region of anomalously low-velocity seismic waves, extends to depths of 150 to 200 kilometers beneath the ridge, although the velocity begins to increase and melt concentration decreases below about 100 kilometers (see figure on page 29). This depth is confirmed by modeling of the electromagnetic signals by Alan Chave and Rob Evans (WHOI) and Pascal Tarits (Université de Bretagne Occidentale, France), which indicates that the mantle may be conductive at depths of about 180 kilometers. This is important because petrologists and geochemists have long debated the depth to which melting extends. Some argue that most of the melting occurs at depths shallower than about 60 kilometers. Others suggest that as much as 40 percent of the melting must take place at depths of 70 kilometers or more, where pressures make the mineral garnet a common and stable crystal. Our results indicate that a significant amount of melting does occur in the garnet region, but it is difficult to say exactly how much. Probably no more than 1 or 2 percent of the mantle exists as melt anywhere beneath the ridge, even though the maximum degree of melting may approach 20 percent. The degree of melting can be much larger than the amount of melt present because melt migrates effectively through cracks and tubes toward the surface, removing the melt

Using Seismic Waves to "See" A Slice of the Oceanic Crust

J. Pablo Canales
Postdoctoral Guest Investigator, Geology & Geophysics Department

The primary source of seismic data for the MELT Experiment came from natural earthquakes. But a secondary data set was obtained using a large array of airguns aboard R/V *Melville* and 15 ocean bottom seismometers (OBSs). The airguns release into the water a bubble of air compressed to 2,000 pounds per square inch. When these bubbles pop they create a sound pulse that travels through the water, penetrates the solid earth several kilometers down through the crust and upper mantle, and eventually returns to the seafloor, where it is recorded by the OBSs. The physics of this phenomenon is basically the same as that which changes a light beam's trajectory when it enters a different medium, such as a glass, or when it is reflected in a mirror. The velocity of the seismic waves through the earth's multi-layered interior reveals a lot of information about its structure and composition.

The MELT Experiment was designed to determine the thickness of the ocean crust in the research area and its velocity structure (that is, how fast the seismic waves propagate through the crust at different depths). There were several important reasons to focus on the crustal structure:
1) Seismic waves originating at remote earthquakes travel through the earth and arrive at the OBSs after passing through the crust immediately beneath the instruments. Before seismologists can use seismic wave measurements to deduce the distribution of melt in the mantle, they must be sure that variations in oceanic crustal structure are not affecting their data.
2) Since the distribution of melt in the mantle affects its density, it also affects the local gravity field, so gravity measurements provide additional information with which to deduce how melt is distributed deep beneath the seafloor. But the gravity field is also affected by variations in the density and thickness of the oceanic crust. Once again, we must quantify and account for the crustal contribution to the gravity field before using gravity data to interpret the mantle.
3) In the area of the MELT Experiment, the Pacific Plate, west of the East Pacific Rise ridge, has far more abundant seamounts than the Nazca Plate, east of the ridge. Seismic measurements can help us to determine if the more abundant volcanism in the Pacific Plate is, as expected, associated with the formation of a thicker crust.

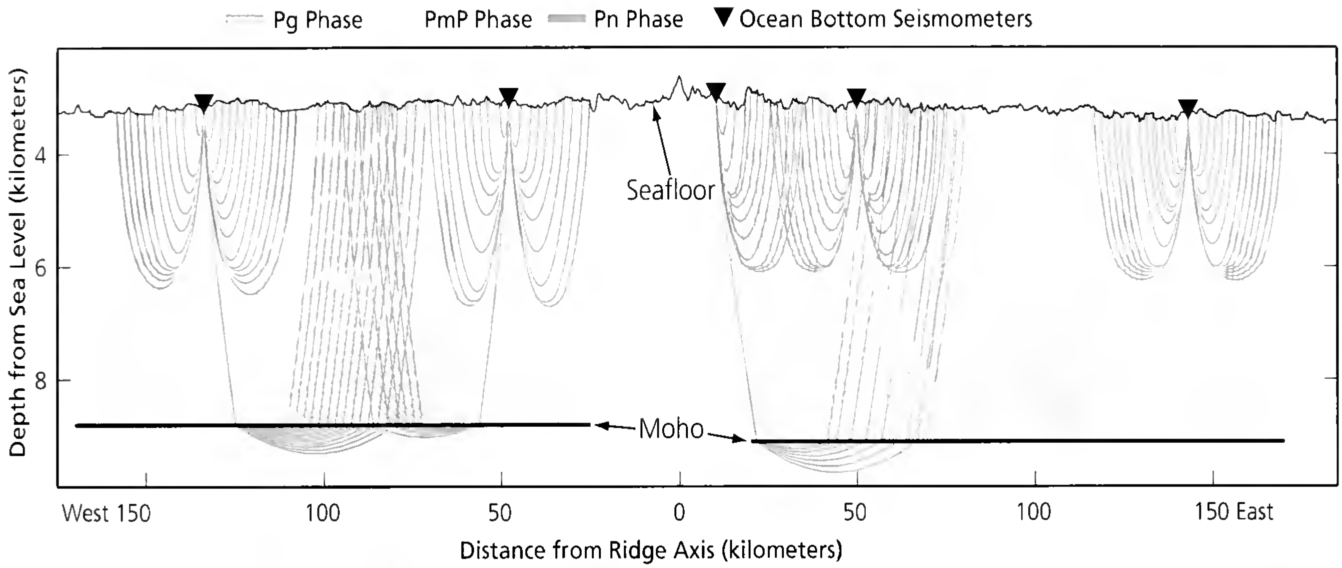
In our study we analyzed the travel times of three types of seismic phases. A single seismic wave generated from a single airgun shot consists of several phases, depending on the number of rock layers that it travels through. Pg rays are refracted within the crust; PmP rays reflect off the Moho (the mantle-crust transition); and Pn rays are refracted in the upper mantle (see figure opposite). Respectively, these waves provide information on the speed of waves traveling through the crust, the thickness of the crust, and the speed of waves traveling through the mantle. We first obtained the crustal velocity structure using the Pg phase. Then, we obtained the average crustal thickness in four regions (at the center and end of a ridge segment in both the Pacific and Nazca plates) by matching the observed PmP and Pn travel times with travel times predicted by various models of crustal thickness. We tested a variety of models, changing the crustal thickness from 4 to 7 kilometers, and selected those that best fit the data.

Overall we did not find a resolvable difference in crustal thickness between the Pacific and Nazca plates. This implies that the asymmetries in depth and gravity measurements observed on each side of the ridge axis must be caused by almost as fast as it is generated and leaving only a small concentration behind in the mantle matrix at any one time.

The MELT Experiment created a huge archive of geophysical data. It will probably take several years to complete analyses of this unique experiment and to create a new generation of models of mantle flow and melt production that will satisfy the many powerful constraints provided by these observations. Even the preliminary results described here, however, have significantly altered our understanding of seafloor spreading and the formation of the oceanic crust.

The MELT Experiment was funded by the National Science Foundation through the RIDGE Program.

Don Forsyth is a marine geophysicist and earthquake seismologist who concentrates on problems of plate tectonics: How thick are the plates? What drives plate motion? How do new plates form at mid-ocean ridges? Don graduated from the WHOI/MIT Joint Program in 1974 and has maintained connections with WHOI scientists ever since. He currently is chair of the Department of Geological Sciences at Brown University. His first research cruise was on R/V Chain *out of Woods Hole. His latest was in the Indian Ocean studying interactions of hotspots and mid-ocean ridges. On shore, he loves playing squash and basketball.*



To measure the thickness of oceanic crust near the East Pacific Rise, WHOI scientists measured the velocity of airgun-generated seismic waves that travel through the crust, refract off rock layers, and are recorded by ocean bottom seismometers. A single seisimic wave from a single airgun shot consists of several phases, or rays, depending on the number of layers it penetrates. Pg rays (blue) are refracted within the crust and provide information on the speed of waves traveling through it. PmP rays (orange) reflect off the Moho (the mantle-crust transition boundary) and provide data on crustal thickness. Pn rays (green) are refracted in the upper mantle and offer data on the speed of waves traveling through the mantle. Only one of every 10 rays is plotted.

density variations in the mantle, not the crust. Evidence for the asymmetry in mantle structure was observed in the teleseismic (waves from distant sources) data recorded on the same OBSs (see article on page 27). The crustal thicknesses measured along a primary array of OBSs were 4.8 to 5.6 kilometers on the Pacific Plate and 5.1 to 5.7 kilometers on the Nazca Plate. Along a secondary array, crustal thicknesses measured 5.4 to 6.2 kilometers on the Pacific Plate and 5.8 to 6.3 kilometers on the Nazca Plate. So the more abundant volcanism in the Pacific Plate is not creating a thicker ocean crust.

We did observe some smaller-scale, local differences in crustal thicknesses. The most noticeable and surprising one is in the Nazca Plate, where we found thinner crust along a line that crossed an inflated section of the ridge over a "melt lens reflector"—an image of the roof of a chamber, where magma has accumulated, and an indication of a robust magma supply. We found thicker crust along a line that crossed near the end of a ridge segment, where there is no magma lens or other indications of a large magma supply. The crusts in both areas are of similar age (0.5 million to 1.5 million years), but their thicknesses differ. Along with subsequent tectonic studies, this suggests that the configuration of the ridge has changed since those crusts were formed, moving crust from a volcanically active to an inactive location, and vice versa.

WHOI participants in the the MELT experiment were funded by the National Science Foundation. J. Pablo Canales was also supported by the Ministerio de Educación (Spain)/Fulbright Program.

Pablo Canales conducted his Ph.D. thesis at the Institute of Earth Sciences of Barcelona (Spain), studying the structure of the oceanic lithosphere affected by hotspots in "exotic" areas, such as the Canary Islands, Tahiti, and the Galápagos Islands. He first came to WHOI in 1996 as a guest graduate student and since April 1997 has been a postdoctoral guest investigator, funded by a grant from the Commission for Educational Exchange between the US and Spain (Fulbright Program) and the Department of Education of Spain. His research has focused on seismic studies of mid-ocean ridges, including the East Pacific Rise and the Mid-Atlantic Ridge.

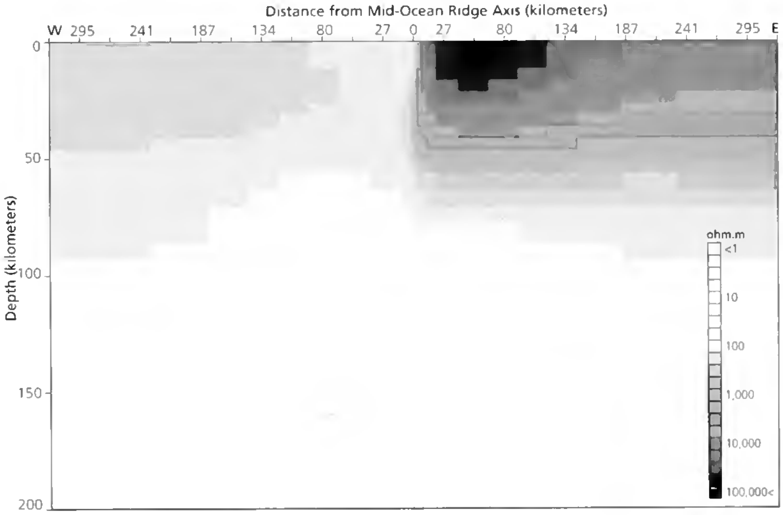
A Current Affair

A New Seafloor Technique Measures Electrical Conductivity Deep Within the Earth

Robert Evans
Associate Scientist, Geology & Geophysics Department

The MELT Experiment was the largest seafloor geophysical experiment ever attempted, and one of its major components was MT, the magnetotelluric technique. MT offers a valuable tool toward the MELT Experiment's goal of probing the earth's inaccessible deep interior. But the technique remains something of a mystery even to many marine scientists. It has been used widely on land, particularly for regional-scale surveys, but only a few full-scale MT surveys have been carried out on the seafloor.

The primary data collected by marine MT experiments are measurements of changes in the earth's electrical and magnetic fields at the seafloor. These fields are affected by electromagnetic currents within the earth, and here's where MT's apparent complexity starts—because the source of these currents is not within the earth, but rather in the ionosphere.



Hiroaki Toh, University of Tokyo

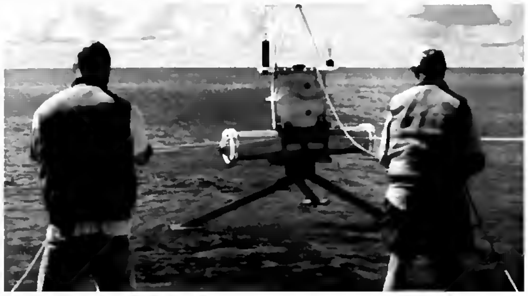
The conductivity of the mantle beneath the East Pacific Rise is depicted in this example of an inversion result from magnetotelluric technique (MT) data collected during the MELT Experiment. Warm colors (white, yellow, orange, and red) represent increased conductivity (lower resistivity). Cold colors (green, blue, black) represent lower conductivity (higher resistivity). The upper 50 kilometers of the mantle appear to be more conductive beneath the Pacific Plate, west of the ridge, than on the Nazca Plate, east of the ridge. The region of high conductivity, extending about 80 kilometers west of the ridge crest and 140 to 190 kilometers deep, suggests deep melting processes affected by the presence of water, or it may simply reflect the effect of water on the mantle resistivity itself.

Charged particles, emitted from the sun as a solar wind, become trapped in the ionosphere by the earth's magnetic field. These moving charges essentially create a variety of electric currents encircling the earth. If the earth were a perfect insulator, like space, that would be the end of the story. But the earth can conduct electricity. As these ionospheric currents flow around the earth, they generate a response within the planet itself. More specifically, the pattern of ionospheric currents induces almost a mirror-image pattern of currents within the earth.

These so-called "induced image currents" cause changes in the earth's electric and magnetic fields. These changes depend on the conductivity of the earth's interior, which, in turn, is determined by the composition and structure of the materials that constitute our planet's interior. Thus, by measuring changes in Earth's electric and magnetic fields at the surface, we can effectively deduce its electrical conductivity and reveal its interior structure. As CAT scans reveal images and frameworks that enable us to learn about the workings of the human body, MT experiments similarly provide essential cutaway views that allow us to learn about processes taking place within our planet.

Like standard alternating currents in most households, which have a frequency of 60 Hertz, or one cycle per 1/60 of a second, induced image currents also alternate—though they do so over a wide range of frequencies. The variations, or frequencies, we use in seafloor MT range from periods of about 100 seconds to several hours. These variations are caused by the chaotic nature of the events that entrap ions from the solar wind, as well as by more regular events, such as the earth's daily orbit around the sun. The important point is that different frequencies penetrate the earth to different depths. If induced image currents came in only one flavor, we would be able to image the earth's interior at only one depth. As it is, higher-frequency currents (with one cycle per 100 seconds, for example) don't penetrate deeply and can tell us about structure 10 to 15 kilometers deep; the lowest-frequency currents (with one cycle per several hours) can tell us about depths of several hundred kilometers.

The goal of the MELT Experiment was to map basaltic melt, from its source within the mantle to the base of the oceanic crust at the mid-ocean ridge crest. While the earth can conduct electrical currents, most rocks, including those comprising the mantle, do not conduct particularly well. This situation changes considerably when melt is present: Pure basaltic melt is several orders of magnitude more conductive than olivine, a common mantle mineral. In the mantle melting column, we do not expect to see pure melt, nor anything like it, but rather some distribution of streams and pools of liquid melt within a matrix of solid mantle rocks. In this case, how the melt is distributed is important. It is possible to think of the melt as a network of wires that connect parts of the mantle. If the melt forms a well-connected network through the rock, electric currents can flow and the mantle will be electrically conductive. Of course, reality is more complicated and other factors, such as water dissolved in the mantle rock, can affect conductivity. These other factors are also important for understanding the whole process of melt production.


John Bailey

Rob Evans (left) and Helmut Moeller of Scripps deploy a WHOI magnetometer from R/V *Thompson* (*University of Washington*).

The MT component of the MELT Experiment was a truly multinational effort involving more than a dozen scientists from Woods Hole Oceanographic Institution and Scripps Institution of Oceanography in the US, and from France, Japan, and Australia. Each group contributed instruments to the array and played a role in the data analysis. From June 1996 to June 1997, 47 instruments were deployed at 32 seafloor sites to measure the time variations of the electric and magnetic fields. Two lines were set out. The main southern line had 19 sites and crossed a magma-rich segment of the East Pacific Rise ridge crest, extending 200 kilometers on either side of the crest. The second line of 13 sites crossed the ridge to the north on a magma-starved ridge segment, extending 100 kilometers on either side of the axis.

Each group's instruments essentially did the same thing: measure changes in the electric and magnetic fields at the seafloor. But each group accomplished this in slightly different ways, deploying very different-looking instruments. As in all marine experiments, the environment makes seafloor MT measurements more difficult to make, but in one way nature helps us. The ocean is electrically very conductive and acts as a screen against electromagnetic noise—extraneous signals from other sources that would confuse interpretation of the data. On land, power lines, for example, can be a nuisance. The seafloor, however, is electrically quiet, making it possible to measure very small electric field variations. The other part of the MT signal is the seafloor magnetic field—not the steady field trapped in lavas and used to identify magnetic reversals, but the magnetic field variations linked to ionospheric currents.

To a first order, the ratio of the electric to the magnetic field at the earth's surface is a direct measure of the earth's electrical conductivity. We calculate this ratio for a range of current frequencies using modern processing techniques. To produce a model of the earth, data from all instruments have to be examined through a process of numerical inversion. The interaction of induced currents in the earth with the conductive bodies we hope to image (such as the melt column) affects the electric and magnetic fields over a wide region of seafloor. Generally, it is not possible to look at data from a single instrument and interpret the underlying structure. Instead, we have to use computer modeling to predict the fields that the mantle would create and compare these answers to data from all the instruments. The model is updated to improve the agreement and the process is repeated until a satisfactory model is found. There are many pitfalls involved in this process, as well as different ways of carrying it out. The groups involved in the MELT Experiment have been using a variety of methods over the past few months, and we are in the process of comparing results and discussing their implications.

The MT analyses are still in their early stages, but some first-order results are beginning to come through. The MT data show an asymmetrical distribution of melt between the areas west and east of the ridge crest, with a more extensive region to the west. The melt column also appears to be a broader feature, with a low percentage of melt in it, rather than a narrow vertical column of melt directly beneath the ridge. This indicates a more passive flow of mantle toward the ridge crest. Deeper, we see some evidence for a conductive mantle at depths greater than 150 kilometers. If this proves to be true, it could be evidence for deeper melting—deeper than the part of the mantle generally believed to be responsible for most melt generation. However, in the final analysis, water dissolved in the mantle rock may prove an important factor in mantle conductivity at this depth.

Funding for the MELT Experiment was provided by the National Science Foundation through the RIDGE Program. The many people involved in the MT component of MELT include: Alan Chave, Bob Petitt and John Bailey (WHOI), Jean Filloux and Helmut Moeller (SIO), Pascal Tarits (Université de Bretagne Occidentale), Martyn Unsworth and John Booker (University of Washington), Graham Heinson and Anthony White (Flinders University, South Australia), and Hiroaki Toh, Nobukazu Seama and Hissashi Utada (University of Tokyo).

Rob Evans was an undergraduate in the Physics Department at Bristol University in the UK when he saw an advertisement for a Ph.D. project that involved a cruise to the East Pacific Rise. Not letting the fact stand in his way that he knew next to nothing about what a mid-ocean ridge was, he applied for the studentship at Cambridge University, and the cruise to a sunny location. Since then, Rob has worked with most of the groups worldwide that carry out seafloor electromagnetic work. He did a postdoc in Toronto, Canada, before coming to WHOI as an Assistant Scientist. His lack of hair comes from the stress of doing marine science and has no relationship to his heavy use of EM fields.

A hotspot created the island of Iceland and its characteristic volcanic landscape. Hotspots are relatively small regions on the earth where unusually hot rocks rise from deep inside the mantle layer.

Hitting the Hotspots

New Studies Reveal Critical Interactions Between Hotspots and Mid-Ocean Ridges

Jian Lin
Associate Scientist, Geology & Geophysics Department

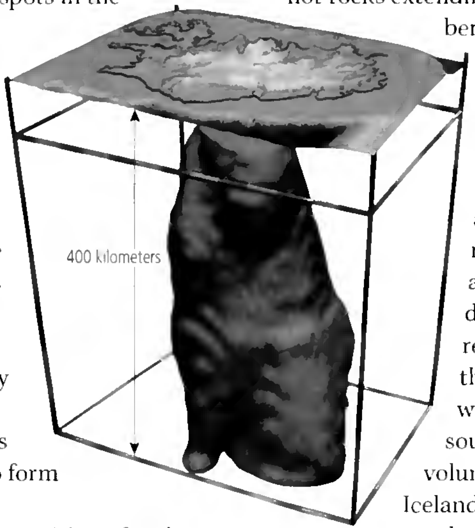
The great volcanic mid-ocean ridge system stretches continuously around the globe for 60,000 kilometers, nearly all of it hidden beneath the world's oceans. In some places, however, mid-ocean ridge volcanoes are so massive that they emerge above sea level to create some of the most spectacular islands on our planet. Iceland, the Azores, and the Galápagos are examples of these "hotspot" islands—so named because they are believed to form above small regions scattered around the earth where unusually hot rocks rise from deep inside the mantle layer.

But hotspots may not be such isolated phenomena. Exciting advances in satellite oceanography, seismology, geochemistry, and geodynamics, along with a treasure trove of new declassified data, are revealing that hotspots appear to have important and far-reaching impacts on a surprisingly large percentage of the global ridge system. Some 44 hotspots have been identified around the globe, and a large number of them are integrally connected to the ridge system (see map at right). Indeed, these hotspots may play a critical role in shaping the seafloor—acting in some cases as strategically positioned supply stations that fuel the lengthy mid-ocean ridges with magma.

Studies of ridge-hotspot interactions received a major boost in 1995 when the US Navy declassified gravity data from its Geosat satellite, which flew from 1985 to 1990. The satellite recorded in unprecedented detail the height of the ocean surface. With accuracy within 5 centimeters, it revealed small bumps and dips created by the gravitational pull of dense underwater mountains and valleys. Researchers often use precise gravity measurements to probe unseen materials below the ocean floor. In places where the seafloor contour has been well-charted by ship surveys, we can employ modeling to remove the gravitational effects of seawater and the seafloor. The leftover signal, called the Bouguer anomaly, reveals information about the rocks beneath the ridges and hotspots. Using this technique, we have detected unusually thick, hot crust and mantle rocks beneath virtually all major hotspots located near ridges, including Iceland and the Azores in the northern Atlantic Ocean, Tristan de Cunha in the southern Atlantic Ocean, the Galápagos and Easter Islands in the Pacific Ocean, and the Marion and Bouvet hotspots in the southwest Indian Ocean.

Beneath the earth's thin outer skin (called the lithosphere), mantle rocks creep plastically in a layer known as the asthenosphere, where temperatures stay near the rocks' melting point. Below the mid-ocean ridges, mantle rocks rise to fill the gap between two separating plates. As they ascend, some mantle rocks liquefy to form basaltic magmas, or melts, and the buoyant magmas float to the top of the mantle to form oceanic crust.

By studying the chemical composition of rocks dredged from the ocean floor, researchers have determined that most melts are probably produced at depths of 20 to 80 kilometers and at temperatures of 1,150° to 1,400°C. Below a hotspot, however, geochemical evidence shows that mantle rocks may start melting at greater depths and higher temperatures, giving rise to voluminous lavas and melts that solidify to form shallow ridges such as the Reykjanes Ridge near Iceland, underwater volcanic plateaus such as the vast Kerguelen Plateau in the southern ocean, hotspot islands such as Hawaii, and smaller submerged volcanoes called seamounts.



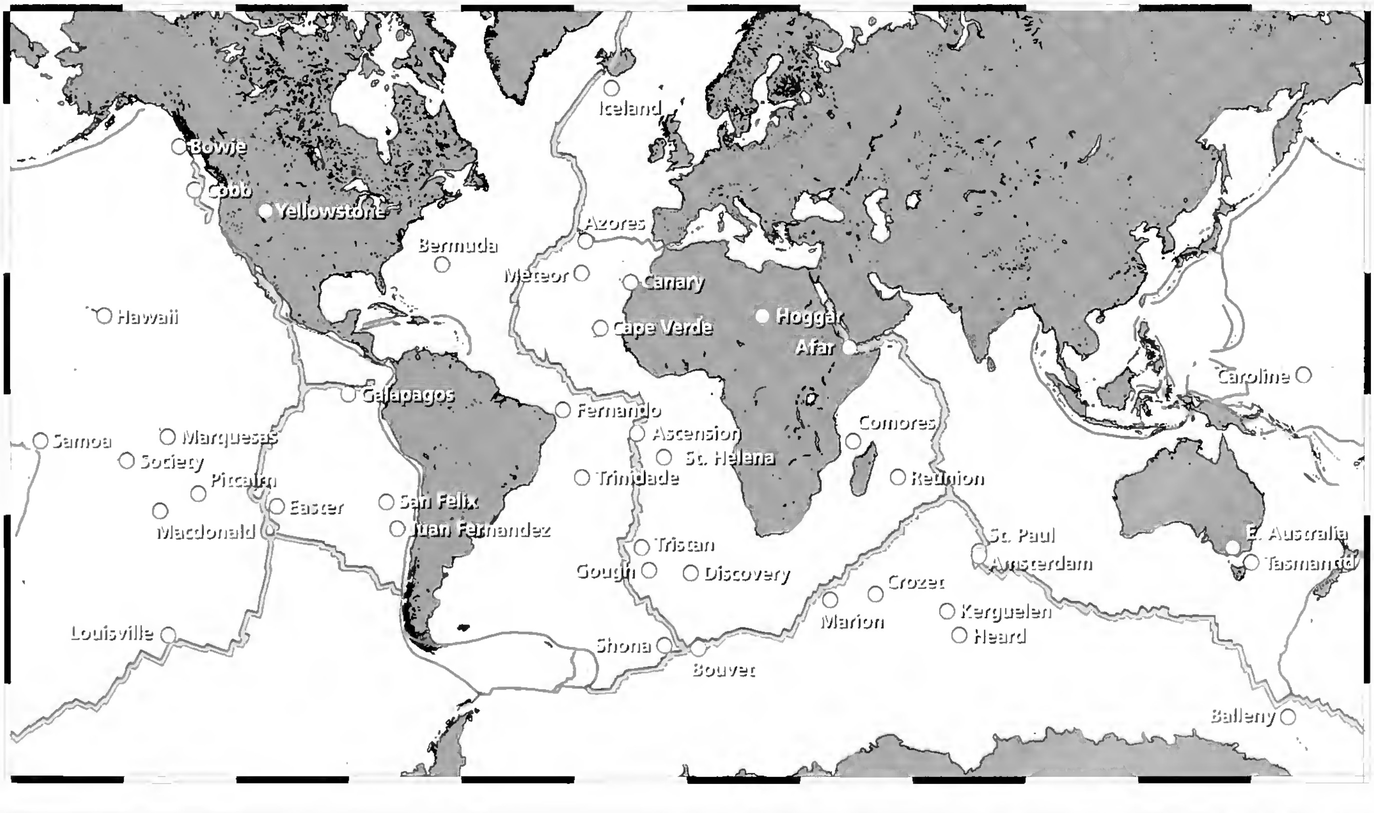
By measuring precise travel times of seismic waves passing through mantle rocks beneath Iceland, scientists have recently identified a surprisingly narrow and deep cylindrical "root" of anomalously hot rocks, extending to a depth of at least 400 kilometers, and probably farther.

From Wolfe, Bjarnason, VanDecar, and Solomon, 1996

By measuring the precise travel time of seismic waves passing through the mantle rocks under Iceland, researchers have recently identified a surprisingly narrow cylindrical "root" of anomalously hot rocks extending to at least 400 kilometers beneath Iceland (see figure at left). Below 400 kilometers, seismic data cannot be easily gleaned, but more indirect seismic evidence suggests that this narrow root, which is about the width of Iceland, may be underlain by a region of anomalously hot mantle as deep as 660 kilometers. Theoretical geodynamic models show that such a narrow hotspot root would generate a vigorous source of heat, providing a huge volume of lava to build and feed Iceland's volcanic landscape. Even more dramatically, this heat source would also cause mantle rocks to migrate laterally in the asthenosphere hundreds of kilometers out from Iceland (see figure on page 36).

The Geosat data show that in the cases of Iceland and the Azores, a bulge of unusually thick and elevated crust extends from the two hotspots in both directions along the Mid-Atlantic Ridge. This region of thick, hot crust and mantle extends 1,300 kilometers north and south of the Iceland hotspot and some 1,000 kilometers north and south of the Azores hotspot. Together, the two hotspots appear to be feeding a huge supply of magma to nearly the

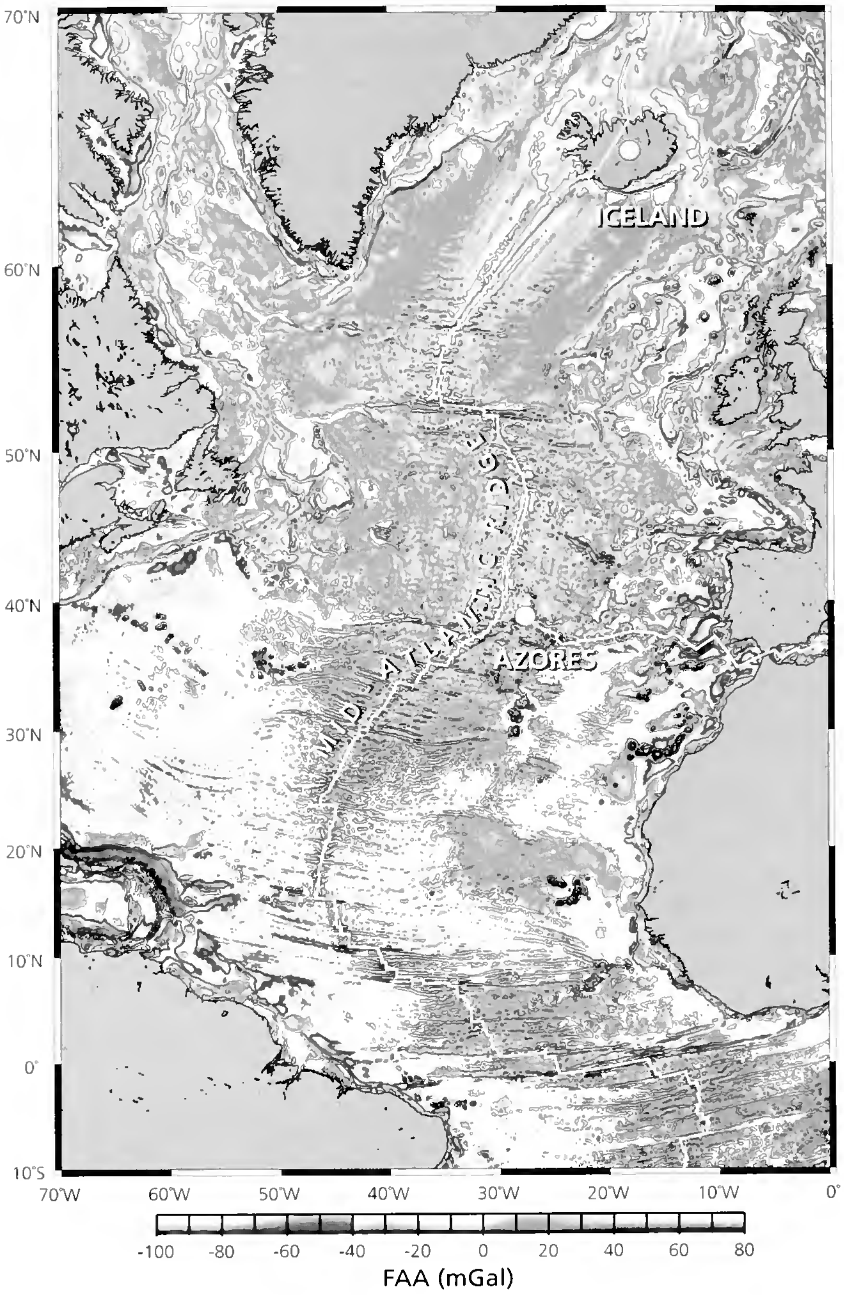
A map of the world's major hotspots shows that many of them are integrally connected to the global mid-ocean ridge system (red lines). Green lines indicate subduction zones, where plates plunge back into the mantle. Not shown is the Jan Mayen hotspot north of Iceland.



Jennifer Georgen, MIT/WHOI Joint Program

Recently declassified satellite gravity data reveal bulges of unusually thick and elevated oceanic crust (red, yellow and green on the map) extending hundreds of kilometers from the Iceland and Azores hotspots. The two hotspots may be feeding huge supplies of magma to nearly the entire northern segment of the Mid-Atlantic Ridge.

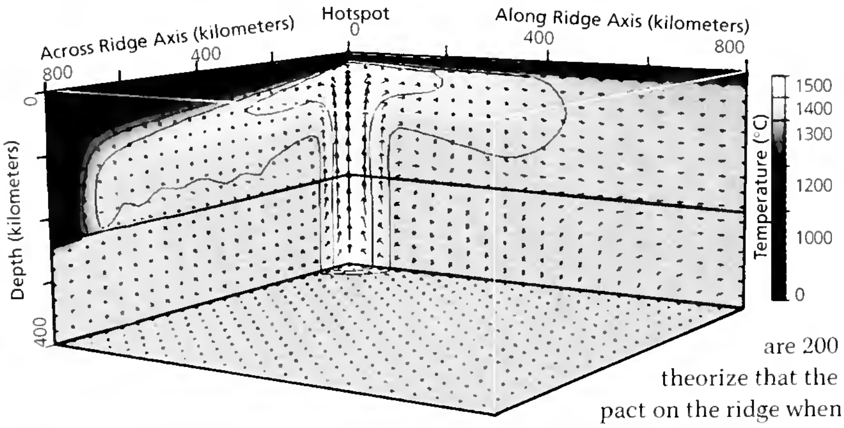
Map produced by Jennifer Georgen, MIT/WHOI Joint Program, with data from of David Sandwell, Scripps Institution of Oceanography, and Walter Smith, NOAA.



entire northern segment of the Mid-Atlantic Ridge. These hotspots, like others, don't seem to provide a steady supply of magma, but rather periodic surges. What regulates this episodicity is an intriguing question currently under investigation.

In the far southern Atlantic, a string of hotspots—Tristan, Gough, Discovery and Shona—align with the southern Mid-Atlantic Ridge, and may be contributing magma supplies that maintain the ridge (see map opposite). Just to the east of the Shona hotspot lies the Bouvet hotspot, whose geological importance may go far beyond creation of the tiny, remote island of Bouvet. Researchers speculate that the hotspot may play a critical role in maintaining the triple junction, where the mid-ocean ridge branches that define the boundaries of the South American, African, and Antarctic plates all intersect. Farther east, the prominence of the Kerguelen, Crozet, and Marion hotspots suggests that ridge-hotspot interactions have helped shape the seafloor of the southern ocean.

In the western Pacific, our studies show a complex pattern of interaction between the Galápagos hotspot and the Cocos-Nazca Ridge, the boundary between the Cocos and Nazca plates. About 8 million years ago, the ridge and hotspot collided and the hotspot-induced melt flux was estimated to be very robust. But comparisons of older and younger crust in the region reveal that the intensity of the ridge-hotspot interaction has been diminishing as the Cocos-Nazca Ridge gradually moved away from the Galápagos hotspot. Today the two are 200 kilometers apart, and we theorize that the hotspot will lose its impact on the ridge when the two reach a distance



A theoretical geodynamic model shows that a narrow hotspot "root," such as the one recently discovered beneath Iceland, would generate a vigorous source of heat (light colors) and produce a huge volume of magma that would migrate laterally along and across the ridge axes hundreds of kilometers away from the hotspot source.

of about 500 kilometers apart.

Emerging geophysical and geochemical data indicate significant dissimilarities among hotspots and tell us that the interactions between individual hotspots and ridges have their own peculiar dynamics. While hotspots such as Iceland and Hawaii may have their origin deep in the mantle, others may simply reflect large concentrations of unusual chemical properties in the earth's shallow mantle. While Iceland's impact on the ridge extends up to 1,300 kilometers north and south, the Marion hotspot's effect on the Southwest Indian Ridge diminishes after only 300 kilometers. Magma eruption rates vary among different hotspots, and each hotspot has its own distinguishable geochemical signature, which provides clues to understand how melting occurs at each hotspot. Iceland and the Azores, for example, both show an elevated ratio of stronium 87/stronium 86 isotopes in the basaltic rocks they produce, compared with basalts produced in Mid-Atlantic Ridge regions farther south. However, basalts generated by the Azones hotspot do not exhibit the same elevated helium 3/helium 4 isotopic ratios that the Icelandic basalts do.

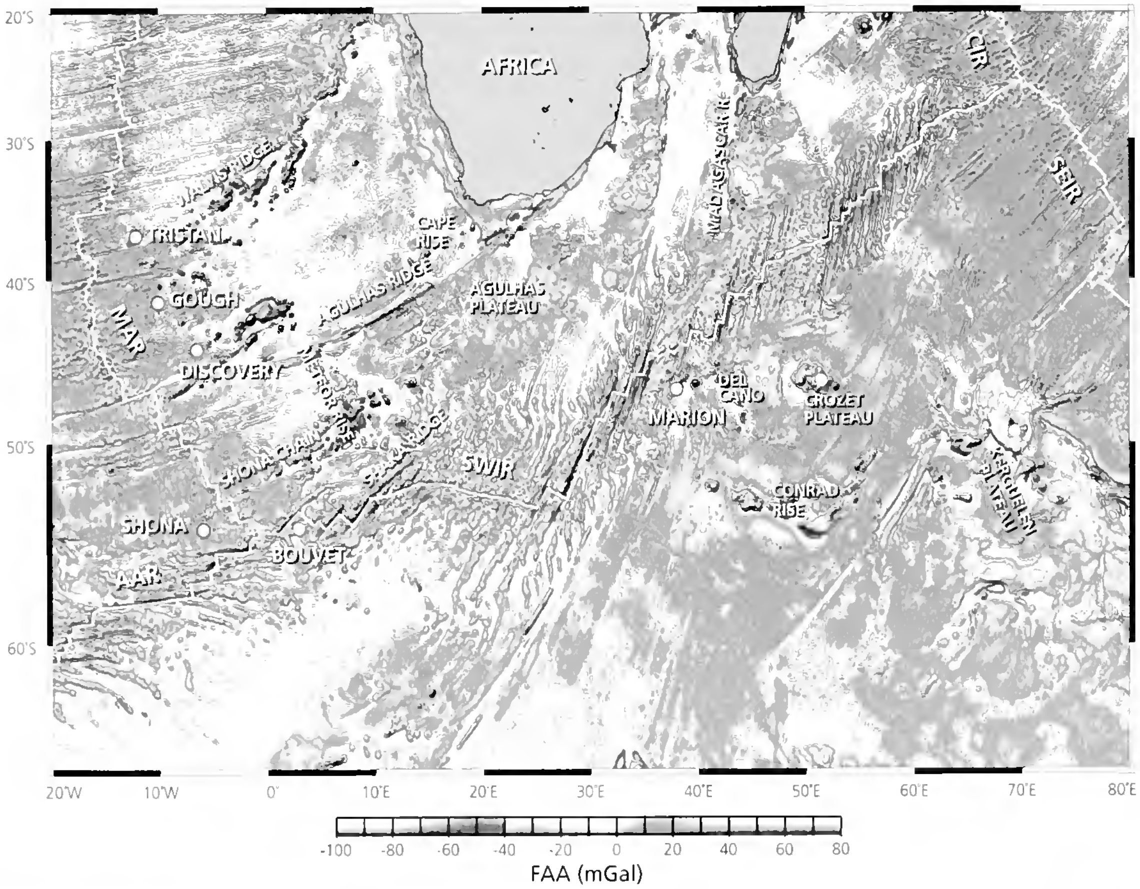
Rapidly progressing techniques in geochemistry, as well as in broadband seismology, autonomous underwater geophysics, and geodynamic modeling—combined with the new global geophysical data coverage—should make the coming decade a most exciting time to study the fascinating geological phenomenon of ridge-hotspot interactions.

Jian Lin

Author Jian Lin captured this image of Iceland's volcanic landscape during a research expedition.

The National Science Foundation supported the research described. The author is indebted to MIT/WHOI Joint Program graduates Garrett Ito (now at University of Hawaii), Javier Escartin (now at CNRS, Paris, France), and current student Jennifer Georgen for sharing exciting time at sea and ashore in studying mid-ocean ridges and oceanic hotspots.

Jian Lin joined WHOI in 1988 after graduate study at Brown University and research on earthquakes at the US Geological Survey in Menlo Park, California. He divides his travel time between going to sea and investigating quakes in California. His latest expedition was on board the French ship L'Atalante *to the Mid-Atlantic Ridge south of the Azores hotspot, where spectacular new underwater volcanoes were discovered.*



Satellite gravity map of the western Indian and southern Atlantic Ocean basins, as revealed by satellite gravity data. A string of hotspots (Tristan, Gough, Discovery, and Shona) aligned with the southern Mid-Atlantic Ridge (MAR) may be contributing magma supplies that maintain the ridge. The Bouvet hotspot may play a critical role in maintaining the triple junction, where three mid-ocean ridge branches and the three boundaries (white lines) separating the South American, Antarctic, and African plates all intersect. Farther east, the Kerguelen, Crozet, and Marion hotspots may have extensively shaped the seafloor of the southern ocean. SEIR is the Southeast Indian Ridge. CIR is the Central Indian Ridge, and SWIR is the Southwest Indian Ridge.

Map produced by Jennifer Georgen, MIT/WHOI Joint Program, with data from David Sandwell, Scripps Institution of Oceanography, and Walter Smith, NOAA