Woods Hole Oceanographic Institution

1996 Annual Report

Director's Comments

If 1996 for the Woods Hole Oceanographic Institution were to be described in just two words, my choices would be "moving forward." This forward motion rides on the excellence and leadership of many people, from scientists to managers to support staff. To me, this year has been one of purposeful coordination, spirited team work, and determined focus—energy and synergy that together have moved the Institution forward in a variety of areas. In short, it has been a very good year.

The year's high points included the successful conclusion to our unprecedented $50 million Capital Campaign (happily exceeded by $4 million) and launch of the newest, state-of-the-art academic research vessel, R/V *Atlantis*. An Institution-wide strategic plan began to meld the needs and directions for research, education, access to the sea, and services with a focused approach to external activities in the private sector and with the federal government.

We were proud to bring Congressman Jerry Lewis (CA) and Neal Lane, Director of the National Science Foundation, together for a mile-deep dive in the submersible *Alvin* off the coast of California, and, at the same time, to name the Gratia Houghton Rinehart Coastal Research Center in honor of an extraordinary gift that will greatly enhance and seed WHOI's coastal programs. The juxtaposition of the deep ocean event with a coastal one, to me, exemplifies how the Institution is pushing several ocean frontiers.

The Capital Campaign has already affected the daily lives of WHOI researchers. Three additional Senior Scientist Chairs, six new Senior Technical Staff Awards, a second month of Institution support for Assistant Scientists, and increased cost-sharing and seed research funds were all initiated just in 1996—and we do not intend to stop there. The needs of science and engineering research and education, combined with a tightening federal research budget, demand that we continue to work hard to increase and broaden the sources of support for the bold and far-sighted research that is the soul and spirit of the Woods Hole Oceanographic Institution. Indeed, in 1996 alone, 18 WHOI scientists received significant, nationally competitive awards, ranging from medals to fellowships to other prestigious acknowledgments. It is imperative that we continue to improve the Institution's fertile research environment in order to foster the most creative research possible.

Shelley Lauzon

Director Robert Gagosian, second from left, is pictured with other ceremony dignitaries near Atlantis *following the ship's launch on February 1, 1996. From left, they are the ship's sponsor, Anne Bingaman, WHOI Associate Director for Marine Operations Richard Pittenger, and Assistant Secretary of the Navy for Research, Development, and Acquisition John Douglass, who was the principal speaker for the event.*

Even great scientific work, however, often needs to be brought forward, explained, and put into context. In 1996, our external strategies for both Washington and the private sector have been coordinated with mission-focused, internal strategies that mold services and resources. These strategies are centered around two major themes:

1) what is good for the ocean sciences community is good for WHOI, and

2) the ocean sciences community must continue to educate the public about the wise use of the oceans, not just their protection. Following these themes, we are making the case for ocean sciences research and education to our elected officials and to potential private donors. Our approach is focused, consistent, and deliberate. It does not change with the audience, nor will it.

Director's Comments

Jane Neumann

National Science Foundation Director Neal Lane, left, and Congressman Jerry Lewis, center, made an Alvin *dive with Dudley Foster, right, as pilot, in March 1996 off Catalina Island.*

Shelley Lauzon

At the dedication of the Gratia Houghton Rinehart Coastal Research Center in her name, Topsy Montgomery shakes hands with Center Director Rocky Geyer. Charley Hollister, Vice President of the Corporation, has just presented the bouquet.

Launch of *Atlantis* began a new era for deep-sea technology and exploration. Never before has a ship been built with a coordinated deep-sea purpose. With adequate research support, understanding of Earth's "inner space" may now be closer at hand. We expect *Atlantis* science to yield new insights into how the oceans function as the flywheel for the many complex systems of our "blue" planet. These systems range from natural ones such as weather and fisheries, to human ones that include national security and agriculture. *Atlantis* is not just another ship: It is unique. As the most advanced deep submergence support vessel in the world, it adds a whole new dimension to the term "access to the sea." It represents the future. And we are moving forward with it.

Internally, the Institution has also moved forward in several areas. WHOI's mission statement was the coordinating theme for strategic planning sessions involving many different groups representing vastly different backgrounds and job responsibilities. These meetings identified key areas needing either new or sustained focus. An unprecedented business development plan began to take form in 1996. A disciplined, coordinated plan for budgeting and spending unrestricted funds was designed to conserve our precious internal funds for enhancing our goals of broadening research and education support for scientists and students and continuing to educate Washington and the private sector about the importance of the ocean sciences to the survival of our society.

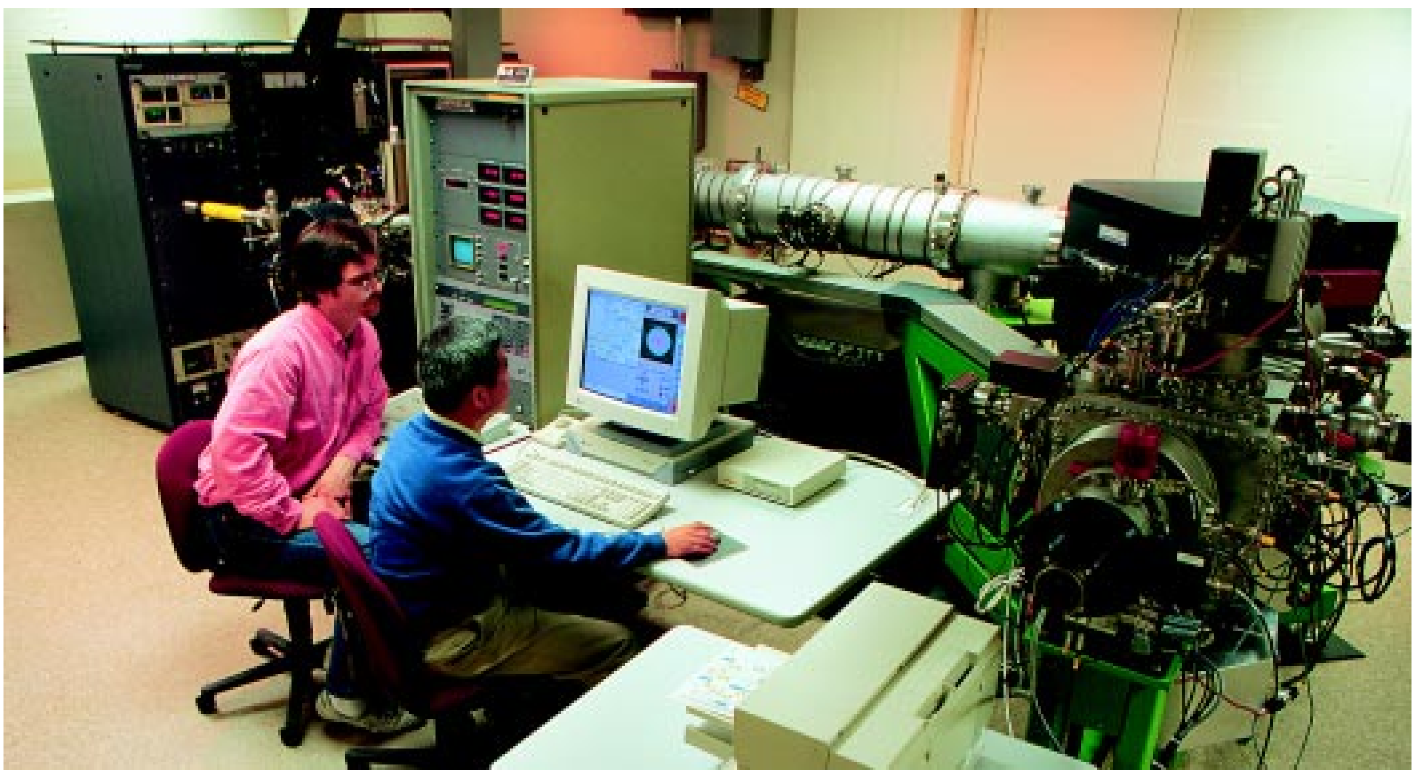
The tremendous support given by our Board of Trustees and Corporation to the careful but broad business oversight of the Institution and to the growth and diversification of support for research and education was the keystone to our progress in 1996. It will continue to be so in the future. The leadership of Board Chairman Frank Snyder and Corporation President James Clark, along with the devoted energies of Capital Campaign Committee Chair John Bockstoce, have created a sound foundation for continuing our capital endeavors.

In summary, as Director of this remarkable Institution, I am proud—and sometimes awed—at the talent and potential that is moving us toward the next millennium. Perhaps, therefore, it is not a great accomplishment to be "moving forward"—it is a necessity.

—Robert B. Gagosian, Director

Chris Griner

Many hands are ready for action aboard Oceanus *during one of five 1996 cruises that supported the Coastal Mixing and Optics Experiment. The researchers aboard deployed a synthetic aperture sonar array and then towed acoustic sensors through the array.*



Tom Kleindinst

This new ion microprobe, delivered early in 1996 and dedicated in April, is part of the Northeast Regional Ion Microprobe Facility. One of only four such instruments in the world, the microprobe extracts information from rock about geological events that occurred millions or even billions of years ago. Nobu Shimizu, right, is head of the laboratory and Graham Layne, left, oversees the instrument's daily operations.

Applied Ocean Physics and Engineering Department

The Applied Ocean Physics and Engineering (AOP&E) Department, with 141 staff members and 29 students, continued in 1996 to make significant advances spanning diverse areas in ocean science, technology, and engineering research. Forty-seven principal investigators led 184 projects.

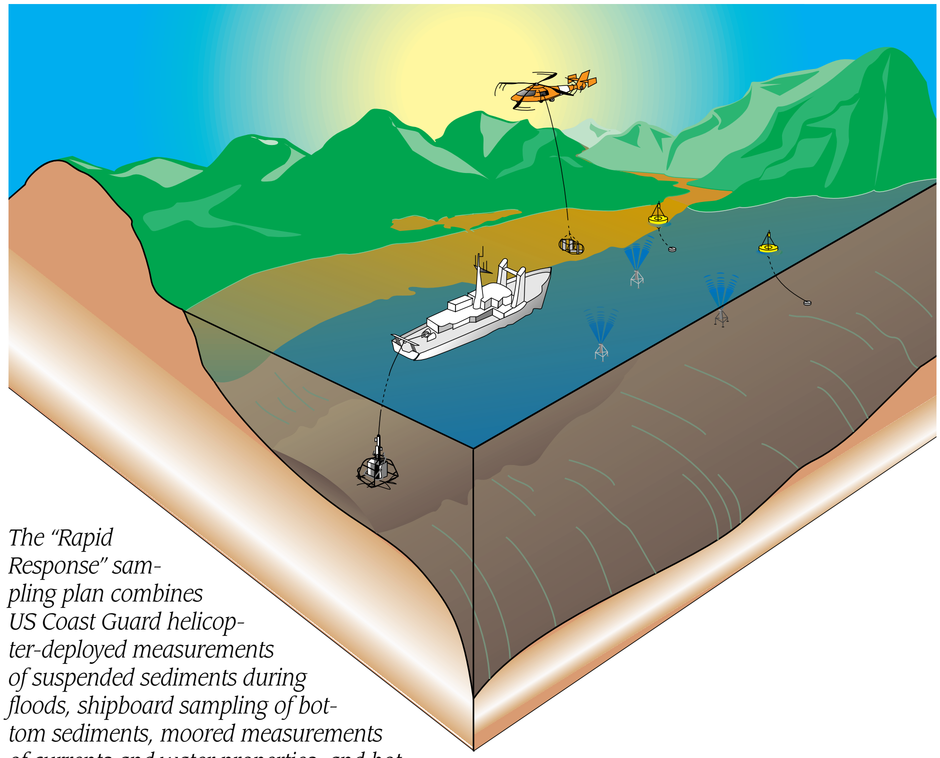
Ocean science research ranged from air-sea interaction and various mixing processes to sediment transport and benthic biology, and included acoustical oceanography, estuarine and coastal hydrodynamics, internal waves, and physical-biological interactions. In the technology category, AOP&E staff are developing a wide variety of ocean sensors, data acquisition systems, and telemetry systems. They continue to develop or enhance various sensor platforms including bottom-mounted systems and moorings as well as submersible, autonomous, and remotely operated underwater vehicles. Engineering research encompasses signal processing, underwater communication, autonomous vehicle control theory, image analysis, hydrodynamic modeling of vehicles and cables, dynamics of moorings, and fish propulsion.

George Frisk stepped down in late 1996 after more than four years as Department Chair, and Tim Stanton began his term as Chair. Three new Assistant Scientists joined the department. They are John Colosi, who studies the physics of acoustic propagation through internal waves; Wade McGillis, who is developing techniques for visualization and characterization of flow near boundaries; and Dennis McGillicuddy, whose work focuses on quantitative numerical methods to characterize physical–biological interaction. Rob Wheatcroft was promoted to Associate Scientist, Dan Frye to Senior Research Specialist, and Bob Eastwood and Alan Hinton to Research Engineer. Paul Boutin (Research Specialist) and Ann Martin (Information Systems Associate II) retired in 1996 after each had devoted more than 30 years to the Institution.

Rocky Geyer was named Director of the Institution's Gratia Houghton Rinehart Coastal Research Center, and other AOP&E staff were formally recognized through various honors and awards. Bob Ballard received the Lone Sailor Award from the US Navy Memorial Foundation and the National Geographic Society's Hubbard Medal. Three staff members were elected fellows of major scientific professional societies: Cheryl Ann Butman by the American Association for the Advancement of Science and Jim Lynch and Tim Stanton by the Acoustical Society of America. Al Bradley, Ken Doherty, and Ken Prada each received a WHOI Senior Technical Staff Award.

"Rapid Response" Studies of Oceanic Flood Deposits

The geological record of continental margins reflects complex processes that occur over a range of time and space scales. To better understand continental margins, North American geoscientists are involved in the "Strataform" Program, sponsored by the Office of Naval Research. One goal of Strataform is to link processes that form strata (for example, waves and currents) with the products themselves (for example, sediment layers). Studying strata formation is challenging because the most prominent features of the geological record were formed during infrequent, extreme events. This is particularly true of sediment delivered from small, mountainous river systems, which may transport most of their annual sediment load within a single two- to three-day flood event. To catch these short-lived pulses of sediment,



E. Paul Oberlander

The "Rapid Response" sampling plan combines US Coast Guard helicopter-deployed measurements of suspended sediments during floods, shipboard sampling of bottom sediments, moored measurements of currents and water properties, and bottom tripod measurements of the time variation of seabed conditions.

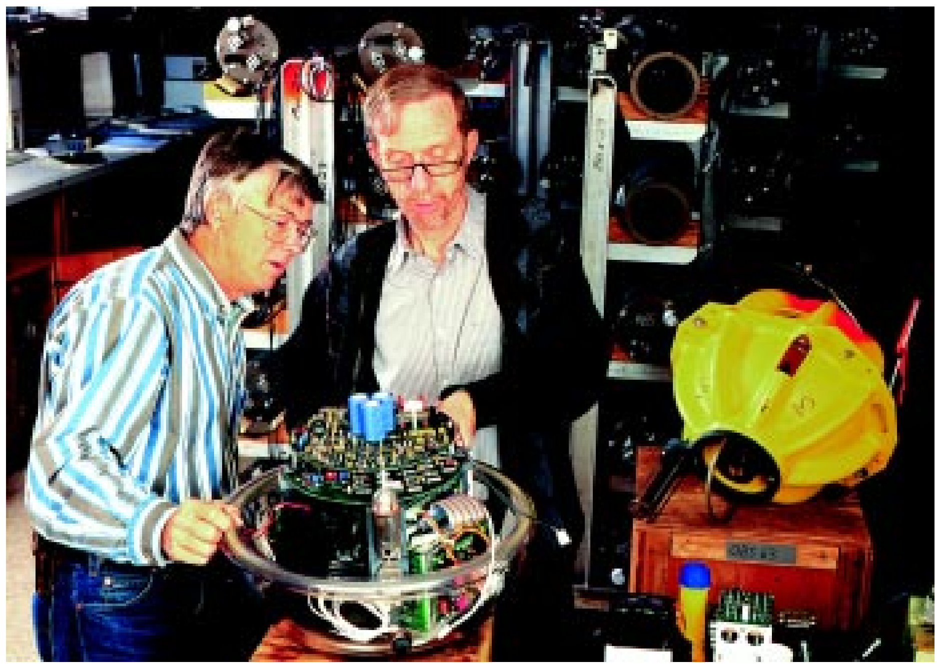
Rob Wheatcroft and Rocky Geyer have developed the "Rapid Response" sampling protocol, which requires a hair-trigger response to flood events on the Eel River in northern California.

For the study, Geyer enlisted the help of the US Coast Guard helicopter rescue unit in Arcata, California. Their task was to assist in surveying the flood waters from the Eel River—regardless of weather or sea conditions—within hours of the crest of a flood. The investigators set up a helicopter-deployed sampling sled to measure salinity and temperature, obtain water samples, and take in situ photographs of sediment particles.

With good fortune rarely encountered in studies of natural phenomena, the Eel River experienced one of the largest floods of the century on January 1, 1997, the first day of Rapid Response program funding. The helicopter sampling program provided an unprecedented look at conditions in a major flood of a small, high-relief river. Fifteen-foot seas and 40-knot winds drove the sediment-laden river plume hard against the coast, carrying the sediment northward at a brisk pace of 2 to 3 knots (100 to 150 kilometers/day). Based on the observed discharge of the river and the estimated sediment concentration, this three-day event delivered approximately 60 million tons of sediment to the ocean!

The second phase of Wheatcroft and Geyer's study was to document the signature of flood on the seabed. Wheatcroft had already documented the sediment distribution from a major 1995 flood that produced a thick layer of silt in a 300-square-kilometer patch north and offshore of the Eel River's mouth. Wheatcroft joined several other Strataform scientists aboard R/V *Wecoma* (Oregon State University) to map out the distribution of the 1997 flood deposit. He took X-radiographs of sediment cores to determine the thickness of the new flood deposit. Unlike the 1995 event, the sediment from the 1997 flood was dispersed over a much larger area and was observed on the slope. Surprisingly, investigators found no evidence of sediment nearshore where they had observed the plume during the helicopter surveys. They suspect that intense nearshore waves prevented the sediment from settling as it fell from the plume. Near-bottom currents driven by the northward winds probably carried the sediment out, where it settled offshore.

Wheatcroft and the other marine geologists will continue to monitor the evolution of the 1997 flood deposit as it is modified by subsequent storms and biological activity within the seabed. Geyer is performing numerical simulations of the 1997 flood to determine the key factors controlling the sediment delivery from the river. The ultimate goal of the modeling study is to reproduce the observed pattern of sediment deposits on the seabed by combining the effects of the river flow, waves, along-shore currents, and near-bottom turbulence on the sediment transport. Seabed geologists can then use the model to simulate the even more extreme events that are most conspicuously displayed in the sedimentary record.



Tom Kleindinst

Beecher Wooding, left, and Ken Peal set up an ocean bottom seismic recorder. Another recorder, fully rigged for deployment with yellow "hardhat" and spotting flag, is at right.

New Ocean Bottom Seismic Recorder

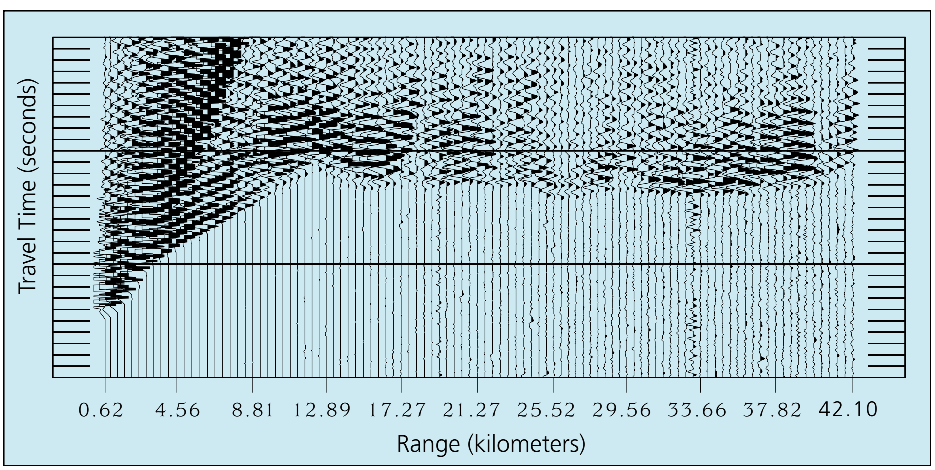
Marine seismologists study the earth's interior using sound generated by earthquakes or acoustic sources deployed from research ships. Sound travels at different speeds through various types of rocks, and seismologists can use these data to develop detailed images of the structure of the crust and upper mantle below the seafloor. Recent seismic studies have, for example, discovered evidence for massive volcanism along the US east coast when North America rifted from Africa, documented the existence of crustal magma bodies beneath some mid-ocean ridges, and monitored earthquakes in tectonically active areas of the oceans. These kinds of studies require seismic recorders that can be deployed on or near the seafloor for periods of a few days to a year. Although instruments of this kind have been used for more than 20 years, there is increasing demand for a new generation of ocean seismic instrumentation that is compact, inexpensive to build and operate, simple to use, and can be deployed in large numbers (25 to 50 or more for one experiment) in environments ranging from the coastal ocean to the deep sea.

With funding from several WHOI investigators, the Office of Naval Research, and a WHOI Vetlesen Award, a group of scientists and engineers, led by John Collins, Ken Peal, and Beecher Wooding, recently constructed and deployed a new generation of the WHOI ocean bottom hydrophone (OBH) to meet this need. Some of the electronics in the new system were purchased from Reftek Inc. (Dallas, Texas), giving the new instrument its name: Ocean Reftek in a Ball, or ORB. Peal and colleagues began work on the ORB system in July 1996. In October, four ORBs were used successfully on a cruise to the Mid-Atlantic Ridge. On a later cruise, several ORBs were adapted for use with a three-axis seismometer sensor as well as the hydrophone.

The acquisition and control electronics, a hard-disk recorder, acoustic-recovery electronics, and batteries are packaged inside a 17-inch-diameter glass ball. The ball not only provides flotation for recovery but also serves as the pressure case for the electronics. When ready to be deployed, the glass ball is placed in a yellow polyethylene housing (called a "hard hat"), equipped with the hydrophone sensor, a carrying bail, a spotting flag, and an anchor. The anchor is connected to the bail by a short tether and a mechanism that breaks apart when the system receives a sound signal from the surface ship. When it breaks, the mechanism drops the anchor, and the ball and hard hat float to the surface for recovery. Spotting flashers inside the glass ball aid nighttime recovery.

The Reftek electronics are based on a 24-bit digitizer (or analog-to-digital converter), a standard in land seismics. The digitizer changes the analog signal from the sensor into a digital value appropriate for the internal computer. The number of bits the digitizer uses to represent the signal determines how small a signal can be seen in the presence of larger, interfering signals. This criterion is important for seismologists because sensors often receive a mix of signals with widely varying amplitude. Commercially available hard disks store the data in the instrument. A wide range of freely available computer software running on standard computer workstations can retrieve and evaluate the data.

The new ORB system offers superior resolution and reduced noise in a physically small package, making deployment and recovery faster, safer, and easier. In addition, the Reftek components are widely known and used in the land seismology community; their incorporation into the ORB system ensures excellent support, including spare parts and hardware and software assistance. In the face of stiff competition from other investigators, development of the new ORB continues WHOI's strong position in the field of ocean bottom seismics.



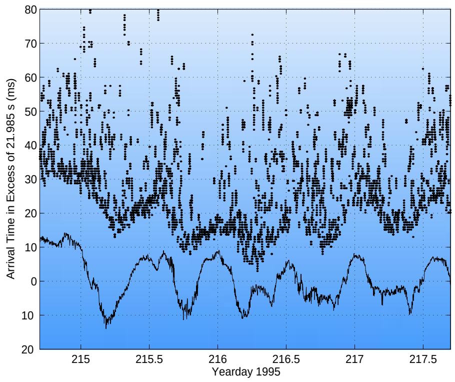
Hydrophone record section for ORB 1 acquired on a cruise to the Mid-Atlantic Ridge in October/November 1996. In this case, the ORB was deployed in ocean bottom hydrophone mode. The sound source for these data is the 20 airgun array of R/V Maurice Ewing *(Lamont-Doherty Geological Observatory). The data are from the non-transform offset between two spreading segments at 34°30'N. The very high velocities recorded at horizontal ranges as small as 13 kilometers imply anomalously thin crust in this region.*

Low-frequency Acoustic Transmissions through Coastal Internal Waves: The SWARM Experiment

Modern Navy antisubmarine warfare efforts require a thorough understanding of low-frequency (50 to 1,000 hertz) coastal acoustic transmissions. So, too, do coastal oceanographers developing new acoustic imaging systems. The complex physical characteristics and processes of coastal regions cause large fluctuations in acoustic transmissions from source to receiver. By learning about these fluctuations and what causes them, the Navy and coastal oceanographers can exploit or, at worst, compensate for them.

In 1992, investigators from WHOI and the Naval Postgraduate School (NPS) made simultaneous coastal oceanographic and acoustic measurements in the Barents Sea Polar Front experiment. Study results showed that internal waves and coastal fronts were probably two of the biggest influences on coastal acoustics. Internal waves are much like surface waves, but in the ocean's interior; they are perhaps most familiar as the oil-on-water wave toys sold commercially. Coastal fronts are the areas where warm and cold, or fresh and salty, water masses meet. Although the Barents Sea study indicated that coastal internal waves were important to acoustics, it did not measure them as well as was needed.

To address this need, Jim Lynch and Joint Program Student Bob Headrick collaborated in 1995 with Marshall Orr (Naval Research Laboratory), Ching-sang Chiu (Naval Postgraduate School), Mohsen Badiey (University of Delaware), and John Apel (Global Ocean Associates) on the Shallow Water Acoustic Random Medium, or SWARM, experiment. A battery of sound sources in 50 meters of water transmitted signals seaward to a pair of receivers 30 and 40 kilometers away. Internal waves, especially a particularly energetic form called a "soliton," propagated across the array, predominantly shoreward, and affected the acoustic transmissions. Many moored and shipboard instruments took continuous measurements along the propagation paths. Thermistor strings measured temperature structure. Acoustic Doppler current meters measured current profiles. Towed conductivity-temperature-depth (CTD) systems, moving up and down through the water column, measured temperature and salinity. Very high frequency (200 and 300 kilohertz) acoustic echo sounders measured density surfaces. Shipboard and satellite radars sensed surface disturbances that the waves produced.

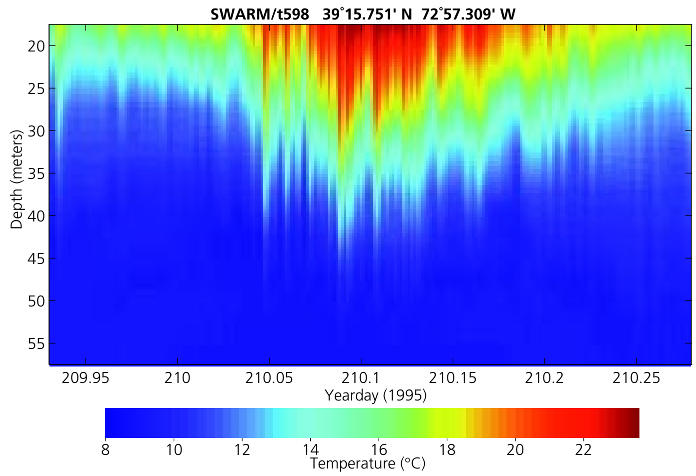


Acoustic record from a SWARM receiver, showing 400-hertz mode arrivals. The dots are the acoustic data; the solid line is the predicted wandering of the leading edge of the acoustic arrival. Temporal spreading can be seen in the contrast between, for example, data from day 215.9 and data from day 215.7. The former shows a tight, 10-millisecond pulse; the latter spans about 50 milliseconds.

The SWARM study, sponsored by the Office of Naval Research, helped investigators learn new things about coastal oceanography and the fluctuations seen in acoustic transmissions. For instance, the solitons, which greatly affect the acoustics, were associated with a more general phenomenon created at the shelf break, the seaward edge of the continental shelf where the continental slope abruptly begins its descent. A sudden before-and-after jump in temperature (and density) is called a "bore;" at the shelf break, a solibore internal tide is created. In the figure at right above (a temperature-time series), the solibore is the large blob of warm water near the surface. The spikes are the internal wave solitons. The blob, and the structure associated with it, propagate shoreward from the shelf break at roughly 0.6 meters/second every 12.42 hours.

The acoustics phenomena revealed by the SWARM experiment were as intriguing as the oceanographic ones. As the tides changed their phase and the solibores moved across the receiver toward the source, the acoustic pulses sent from source to receiver smeared or spread out in time. What was once a clean, 10-millisecond pulse of sound was stretched to 8 to 10 times that. The solitons apparently performed a trick on the sound, producing mode coupling. In shallow water, low-frequency sound travels as a group of normal modes, very much like the familiar modes of a string's vibration. Each one of those modes takes a certain amount of time to travel from the source to the receiver. In the SWARM experiment, the lowest mode traveled the fastest, and the higher modes traveled progressively slower. If there had been no internal waves or solitons, the modes would have arrived in sequence. The solitons, however, created an acoustic "wall" into which the sound crashed, scattering energy from one mode to the next. The receiver could not distinguish the paths of the modes; mode coupling distorted the receiver's perception of each mode.

The acoustic arrivals also wandered in time, a different effect from spreading. Changes in temperature along the path affect the time it takes for modes to arrive—they speed up in warm water and slow down in cold water. As the figure at left shows, the SWARM experiment produced good correspondence between what the temperature sensors had predicted for the acoustic travel-time fluctuations and what was actually measured, validating applications of acoustic tomography techniques in the coastal ocean.



Time series of a solibore internal tide crossing a thermistor string along the SWARM experimental track. The pale blue spiky features are the solitons and the warm, red-to-yellow "blob" they ride on is the internal tide.

Art Newhall

John Kemp, center, and Oceanus *crew members deploy a guard buoy for the SWARM experiment.*

Biology Department

Research in the Biology Department continues to span methodologies from molecular to mathematical, environments from coastal ponds to antarctic lakes, and organisms from viruses to whales. Altogether the department's scientific staff of 24, along with 6 postdoctoral scholars and investigators, 13 technical staff, 32 Joint Program students, and 30 other support staff, pursued about 130 separate research projects during the year and published over 64 scientific papers.

In these days of tight Federal support and intense competition in biology, WHOI researchers are finding increasingly diverse sources of support, and were successful in obtaining funding for at least 44 of the 95 proposals submitted to all government and private agencies in 1996. Participation in large national programs remained strong, including Joint Global Ocean Flux Study research by several scientists in the Atlantic Ocean, Arabian Sea, and the southern oceans, and research and leadership by Lauren Mullineaux in Ridge Inter-Disciplinary Global Experiments, cooperative international ridge studies, and Larvae at Ridge Vents programs for hydrothermal vents. Closer to home, the US Global Ocean Ecosystems Dynamics Northwest Atlantic Program on Georges Bank has its headquarters at WHOI, under the leadership of Peter Wiebe. This long-term effort involves 75 investigators from 20 institutions. Their 1996 ship time included four *Oceanus* cruises.

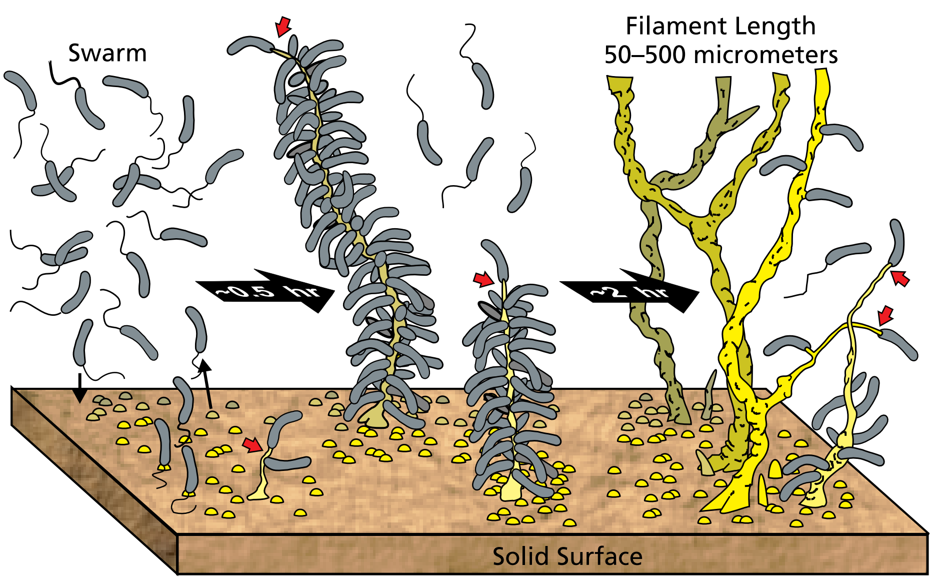
During 1996, Paul Dunlap and Steve Bollens departed to take other positions, and two Postdoctoral Scholars joined the staff as Assistant Scientists: Mike Neubert is a mathematical ecologist, and Carin Ashjian works on zooplankton ecology. As the result of a search in the area of marine mammal studies, Darlene Ketten of Harvard Medical School agreed to continue her studies on the hearing of whales and dolphins at WHOI as Associate Scientist beginning in early 1997.

Promotions during the year included Mark Hahn and Scott Gallager to Associate Scientist, Lauren Mullineaux to Associate Scientist with Tenure, and Larry Madin to Senior Scientist. Bill Watkins was named WHOI's first Oceanographer Emeritus. In November, Madin succeeded Joel Goldman as Department Chair.

Biology Department staff were honored with several awards, including an ONR Young Investigator award to Scott Gallager, and both a New Investigator and a Presidential Early Career Award to Heidi Sosik from the National Aeronautics and Space Administration. Peter Wiebe was the first recipient of the Adams Chair in recognition of his research and leadership in zooplankton ecology. A lifetime of achievement by Senior Scientist Holger Jannasch was recognized in the creation of the newly endowed Holger Jannasch Chair.

Microbe Produces a Novel Form of Elemental Sulfur

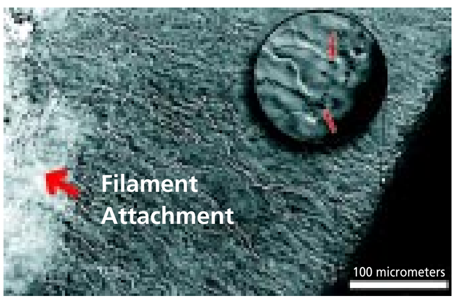
Microbes oxidize geothermally produced sulfur compounds (principally hydrogen sulfide) and thereby provide energy for dense communities of animals surrounding deep-sea hydrothermal vents. To better understand these chemosynthetic microbial processes, Craig Taylor and Carl Wirsen set up laboratory experiments in culture vessels containing hydrogen sulfide-enriched, flowing seawater. In that environment, a self-sustaining bacterial culture grew and produced large amounts of a white flocculent material. The material is composed of long filaments of a novel, previously undescribed form of elemental sulfur. Taylor and Wirsen's studies, funded by the National Science Foundation, show that these sulfur filaments are excreted by a motile hydrogen sulfide-oxidizing bacterium. Though initially produced by an individual bacterium, the newly formed filaments allow additional members of the species to attach. The community deposits more sulfur, a product of its energy metabolism, to form an entangling, funguslike matrix that resists turbulence.



Craig Taylor

In laboratory experiments, sulfur filaments radiate from the attachment substrate to form a funguslike structure that resists turbulence. Growth of filaments occurs primarily by excretion from individual cells (red arrows) and depostion by radially attached members of the population.

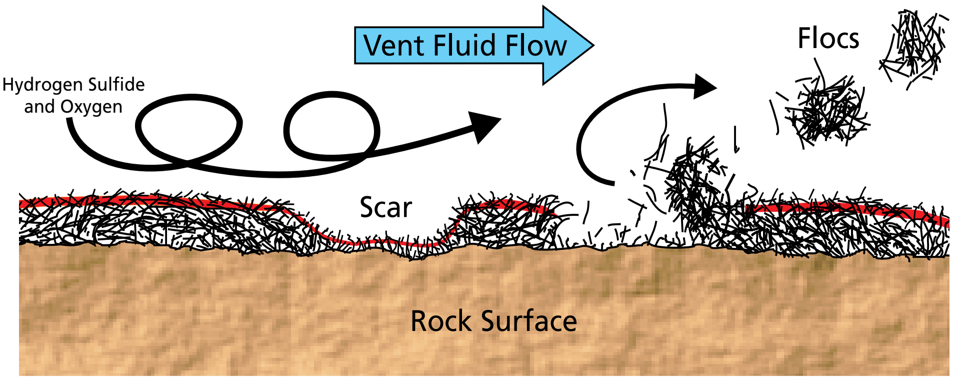
The filament-producing, hydrogen sulfide-oxidizing bacteria require the presence of both hydrogen sulfide and oxygen for growth and, therefore, grow only in the interface region where these chemicals coexist. The filament producers can swarm to these regions where chemical conditions are optimal. They can also remain there by attaching to (or later move by detaching from) solid surfaces. As the organisms oxidize hydrogen sulfide, they deposit a small droplet of sulfur on a surface or begin to excrete a filament. In about 30 minutes, they excrete an elongated filament, which quickly becomes a site of attachment by other members of the swarm. In time, filaments several hundred micrometers long form and are completely covered by sulfur-depositing bacteria, thickening the filament. When either hydrogen sulfide or oxygen starts to become limiting, the majority of attached



Bacteria produce sulfur filaments that allow a swarm to attach to a solid surface in a flowing environment. The community continues to deposit sulfur, increasing the length of filaments and thickening the mat.

microorganisms gradually abandon those filaments in search of more favorable conditions. Ultimately, only naked sulfur filaments remain.

Taylor and Wirsen have observed accumulations of filamentous sulfur in sulfidic-flowing environments, such as salt-marsh creeks. Recently, they examined the flocculent material that emanated in massive amounts from the "snowblower" hydrothermal vent at the 9° N vent field on the East Pacific Rise. It is composed largely of filamentous sulfur nearly identical to that produced in their laboratory experiments. Particulate material collected by Wirsen from other diffuse-flow warm vents also contained filamentous sulfur, suggesting that the phenomenon may be widespread in hydrothermal vent ecosystems. Taylor and Wirsen hypothesize that under certain circumstances filamentous sulfur-forming microbes may be dominant players in the subsurface microbiology of hydrothermal vents.



Flowing vent fluid eventually shears the thickened mat of microbe-containing sulfur filaments. Flocs break off, leaving scars that are recolonized.

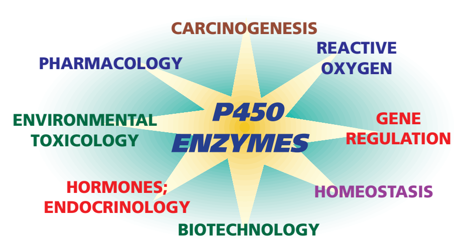
Filamentous sulfur deposition appears to be an ideal mechanism for growth of sulfur bacteria in warm-water hydrothermal vents where the hydrogen sulfide-containing vent fluid is continuously mixed with oxygenated seawater in the subsurface fissures. The filament-producing bacteria are able to stay in a favorable environment by building a flow-resistant "scaffolding" of metabolic sulfur. As the bacteria utilize the hydrogen sulfide and oxygen in the vent fluid, they produce new sulfur filaments on the outer surface of a gradually thickening mat. Eventually the mat thickens to a point where the flowing vent fluid shears flocks from the rock surface and carries them to the vent opening. The resulting "scar" in the sulfur-filament mat is recolonized by microorganisms left behind and by organisms carried in flocks that have dislodged upstream.

Taylor and Wirsen will visit a vent site in late 1997 with *Alvin* to investigate the physiology and phylogeny of collected samples for comparison with the microbe from their laboratory studies. They believe that their laboratory model system will help them understand the mechanism of filamentous sulfur excretion and its importance to the physiology and ecology of sulfur bacteria in high-flow, sulfidic environments such as in the subsurface zones of deep-sea hydrothermal vents.

Unraveling the Biology of Chemical Insults: The P450 Story

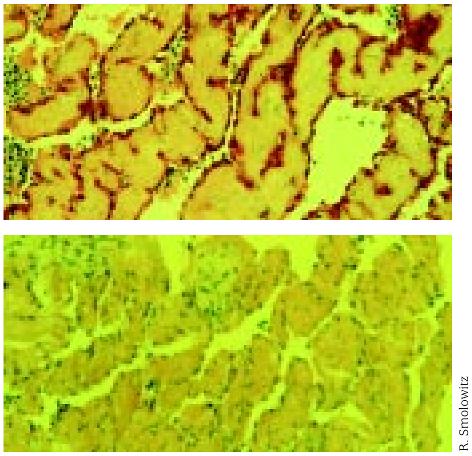
The sea is the ultimate sink for many natural and synthetic chemicals that occur as pollutants. These chemicals—drugs, agricultural and industrial chemicals, biocides, synthetic byproducts, fossil fuels, and others—may cause diseases such as cancers and cardiovascular problems in animals and humans. They also have been implicated in reproductive and developmental abnormalities and decreased immunity to pathogens. For 20 years, John Stegeman and colleagues have been investigating key processes by which such chemicals affect animals, particularly animals in the sea. Their research has focused on the proteins (enzymes) that metabolize foreign chemicals and, to a lesser extent, on the proteins (receptors) that help regulate the amounts of the enzymes.

Many enzymes that metabolize foreign chemicals are in a large family of proteins called "cytochrome P450," abbreviated P450 or CYP (pronounced "sip"). P450 enzymes can metabolize virtually all organic



P450 enzymes, named for their light absorbtion at the wavelength of 450 nanometers, catalyze reactions important in many biological processes. Diverse P450 enzymes make the pigments that color flowers, metabolize drugs and natural toxins, and make steroid hormones such as testosterone and estradiol.

chemicals that are pollutants or drugs, such as caffeine, morphine, antibiotics, antihistamines, barbiturates, petroleum hydrocarbons, and polychlorinated biphenyls (PCBs). To date, scientists have identified more than 500 of these enzymes, some of which may metabolize thousands of chemicals. A given species may have 100 different P450 enzymes. Members of the P450 family are important in many aspects of life. Stegeman's group is studying a number of different CYP genes.



The figure shows the strong induction of a P450 in endothelial cells such as those that line all blood vessels. The red color shows where specific antibodies have reacted with cytochrome P450 1A. The stained cells (top) are endothelial cells in the heart of a fish (scup) exposed to PCBs. The lower picture is heart tissue from a control fish. PCB, dioxin, or PAH exposure causes similar strong induction in blood vessels of fish, reptiles, birds, whales, and humans. In a practical application of this knowledge, Stegeman and colleagues are using the amount of CYP1A in blood vessels, for example in small skin biopsies of whales, to assess animals' exposure to pollutants.

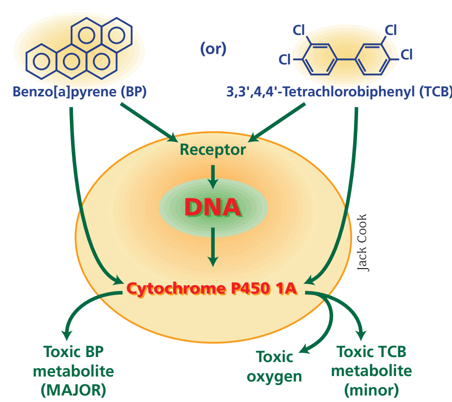
In a process called induction, chemical exposure causes the cell to make increased amounts of some CYP. Those enzymes and their induction are part of a defense mechanism that allows an animal (or a person) to remove a potentially harmful chemical more rapidly from the body. Inadvertently, that process sometimes creates a more dangerous chemical that can be toxic or cause mutations. A P450 studied extensively by Stegeman, termed CYP1A, is induced by PCBs, polynuclear aromatic hydrocarbons, and dioxins. Differences in the properties or amounts of this or other CYP can determine whether an individual, or a species, will be susceptible to the effects of a given chemical. Such differences may determine, for example, whether one person gets cancer while another does not. Much of Stegeman's study, with students and associates, has been devoted to learning how these enzymes are induced and work with different chemicals in different animal species, including fish, reptiles, birds, marine mammals, and even humans, often with cells in culture.

For example, using molecular biology, Stegeman and collaborators Hilary Morrison (Marine Biological Laboratory) and Johannes Doehmer (University of Munich) isolated a gene for fish CYP1A and inserted it into a cell that doesn't make any other P450s. Cultures of that cell then produce quantities of the fish P450, allowing it to be studied without interference from other enzymes. The researchers are defining which chemical shapes fit into the enzyme. This knowledge, in turn, may allow investigators to predict whether chemicals might become toxic as they bind to the enzyme. Some chemicals appear to fit in a way that causes the P450 to "malfunction," producing a toxic form of oxygen. (This may be one way that PCBs produce toxicity, a process still not understood.) Investigations also examine how natural hormones in the body are metabolized by the P450s, one way chemicals might affect reproduction. Similar studies are underway with new fish P450 genes identified by Joint Program Student Marjorie Oleksiak. This approach will greatly help investigators understand how chemicals exert various effects.

Knowledge of P450 induction and action may be used to test the success of remediation, to screen new chemicals for hazard, to assess exposure in the environment, and to determine how a chemical is toxic. For example, if a cell makes a particular P450, then that cell will be a target for chemicals that are acted on by that P450. The importance of that cell in the body may determine the outcome of the chemical exposure. By using antibodies to detect where CYP1A is induced in animal tissues, Stegeman and colleagues have identified many such target cells. A prominent target for induction is the single cell layer (endothelium) that lines all blood vessels. The cardiovascular system appears to be particularly susceptible to chemical effects during development. How CYP1A induction is involved in vascular dysfunction is under study. In part this is through analysis of other genes, such as those that make vascular signaling molecules (nitric oxide, arachidonic acid products) and genes that control endothelial cell growth and vascular development. Interaction of CYP1A and the induction machinery with oxygen also could be involved in chemical effects.

Stegeman's studies, supported by federal and private funding sources*, address the complex biochemistry and molecular biology of chemical-biological interactions. Results are used to evaluate the health of the oceans and to understand how different species respond to chemical insults. Such research also provides insights into the evolution of the molecular machinery that permits organisms to deal with the external chemical environment, and how that molecular machinery is linked to basic physiology of animals.

*Funding sources over the years have included: National Science Foundation, NOAA, Sea Grant, National Institute of Environmental Health Sciences, National Cancer Institute, Environmental Protection Agency, Air Force Office of Scientific Research, The Donaldson Trust, and the Jessie B. Cox Charitable Trust.



Chemicals such as the aromatic hydrocarbon benzo[a]pyrene (at left) and the polychlorinated biphenyl called 3,3',4,4'-tetrachlorobiphenyl (at right) enter a cell and interact with a receptor that cause the cell to make the P450 1A. The chemicals then interact with the P450, sometimes leading to formation of toxic products. Defining the shapes of chemicals that fit into the receptor and into the P450 may help predict the outcome of chemical exposure (or drug treatment in people).

Heidi Sosik and co-workers recover a free-fall spectral radiometer used for sea-truth observations of ocean color during an expedition in the Black Sea.

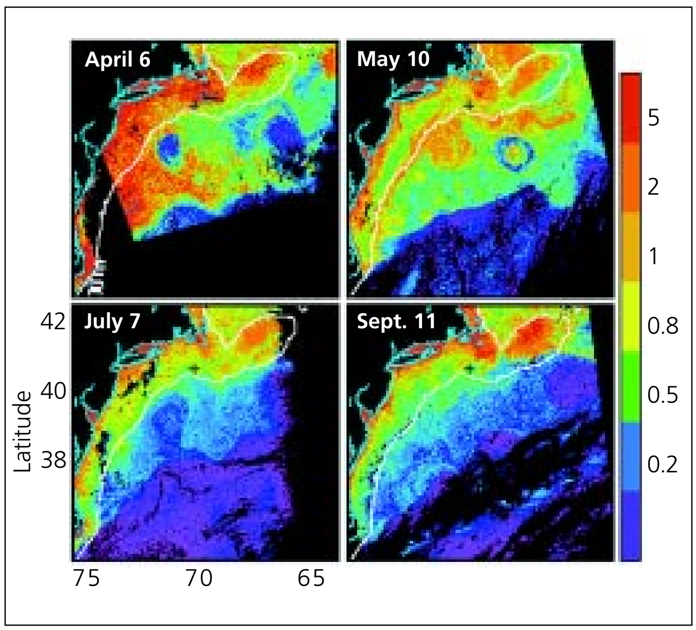
Bio-optical Oceanography: From Micrometers to Ocean Basins

Phytoplankton share a common role as primary producers in marine ecosystems. A typical phytoplankton community, however, includes many species that range in size from less than one micrometer to millimeters and exhibit a remarkable variety of physiological adaptations to life in the sea. This diversity presents a fascinating challenge to biological oceanographers trying to unravel relationships between phytoplankton growth and environmental factors. Heidi Sosik is using advanced optical instruments and techniques to characterize spatial and temporal distributions of phytoplankton and photosynthesis in the coastal ocean, taking advantage of phytoplankton's role in both absorbing and scattering light in the upper ocean.

All phytoplankton contain pigments (including chlorophyll) that collect the sun's energy for photosynthesis. Because these pigments have distinct light absorption and fluorescence properties, they affect not only the color and magnitude of light penetrating the water column, but also the light reflected from the upper ocean. Investigators can detect optical "signatures" by taking in situ measurements of spectral light absorption and by remotely sensing ocean color. These approaches promise unprecedented information about scales of variability in phytoplankton, but many biological, chemical, and physical processes influence optical properties and thereby complicate interpretation, especially in coastal waters.

Sosik, Rob Olson, and researchers from other universities and institutions are collaborating in an Accelerated Research Initiative on Coastal Mixing and Optics (CMO). The program, sponsored by the Office of Naval Research, includes a 10-month field study on the continental shelf south of Woods Hole, using moored instruments and two multi-ship investigations. Sosik and Olson's work focuses on the response of phytoplankton and other particles to mixing processes and the effects of the particles on ocean color. They are using state-of-the-art underwater spectral radiometry to describe the underwater light field, and laser-based flow cytometry to measure light scattering and fluorescence properties of individual particles. In the first stages of the CMO experiment, this approach proved highly successful. Differential responses of picophytoplankton and larger phytoplankton cells were easily detectable when Hurricane Edouard—an extreme mixing event—passed through the study site in September 1996. These changes were accompanied by changes in the attenuation and reflectance of light. Sosik and Olson will collaborate with physical and optical oceanographers to fully describe the relationships.

Detailed investigations into the connections between optical and physical variability in coastal waters will improve interpretation of remotely sensed ocean-color imagery and its application to ecosystems studies. With additional support from a New Investigator Program award from the National Aeronautics and Space Administration, Sosik has extended the original concept of the CMO program to measure primary production rates and to characterize the photosynthetic physiology of the phytoplankton. Working with other researchers, she is using shipboard, moored, and satellite-based measurements to develop a bio-optical model for primary production on the continental shelf. For the first time in over a decade, there are new global ocean-color missions in space, and, with insights from programs such as CMO, researchers will be able to use new large-scale views of the upper ocean to study some of the smallest organisms living there.



Satellite images of ocean color can be used to estimate spatial and temporal variability in phytoplankton pigment distributions. WHOI researchers are developing improved methods for interpreting these images using satellite oceanography combined with ship- and mooring-based work. The + symbol indicates the location of the Coastal Mixing and Optics study site south of Woods Hole.

Geology & Geophysics Department

At year's end, the Department of Geology and Geophysics consisted of 29 scientific staff, 21 technical staff, 28 support staff, 30 graduate students, and 8 postdoctoral scholars and investigators. Although the size of the scientific staff remains the same, there were several changes in department personnel. Postdoctoral Scholar Yang Shen, who studies the structure and composition of the ocean lithosphere using a variety of seismological techniques, was named Assistant Scientist. A new Senior Scientist, John Hayes, formerly of Indiana University, also joined the department. A highly respected organic geochemist and mass spectroscopist, Hayes is serving as the Director of the National Ocean Sciences Accelerator Mass Spectrometer Facility.

Several members of the department received awards in 1996. Senior Scientist Bob Detrick was awarded the 1996 A. G. Huntsman Medal from the Bedford Institute of Oceanography. Senior Scientist Henry Dick was elected Fellow of the Geological Society of America, and Senior Scientist Nobu Shimizu was elected Fellow of the American Geophysical Union. Senior Scientists Stan Hart and John Hayes were elected geochemistry fellows of the Geochemical Society/European Association of Geochemistry.

In 1996 department research interests included the structure and evolution of oceanic crust, the chemical evolution of the mantle, the ocean's role in the history of Earth's climate, and the processes affecting the nearshore and coastal environments. The staff was responsible for 114 scientific publications in 1996 while submitting 137 research proposals to various funding agencies and beginning 43 new research projects. Department members participated in 22 research cruises and continued participation in several large, interdisciplinary research programs, notably Ridge Interdisciplinary Global Experiments, a large marine geology research program to understand the structure and evolution of mid-ocean ridges. Department members also participated in the Southern Ocean Process Study of the Joint Global Ocean Flux Study.

In October the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) office charged with Ocean Drilling Program planning began a rotation at WHOI. Research Specialist Susan Humphris heads this office and will chair the JOIDES Science Committee for the next two years during a crucial period for renewing the Ocean Drilling Program.

Exploring the Distribution of Hot Springs along the Mid-Ocean Ridge System

The creation of new crust along the globe-encircling, mid-ocean ridge system has intrigued geologists since the advent of plate tectonics and seafloor spreading over 30 years ago. It was not until the late 1970s, however, that scientists discovered spectacular hot springs on the seafloor—the equivalent of Yellowstone National Park's geysers. At these hydrothermal sites, seawater circulates through young oceanic crust; deposits rich in metals such as iron, copper, and zinc form; and highly productive and exotic biological communities thrive. Geologists and geophysicists quickly realized that this phenomenon has important consequences for transferring heat from the earth's interior and for regulating the chemical composition of seawater.

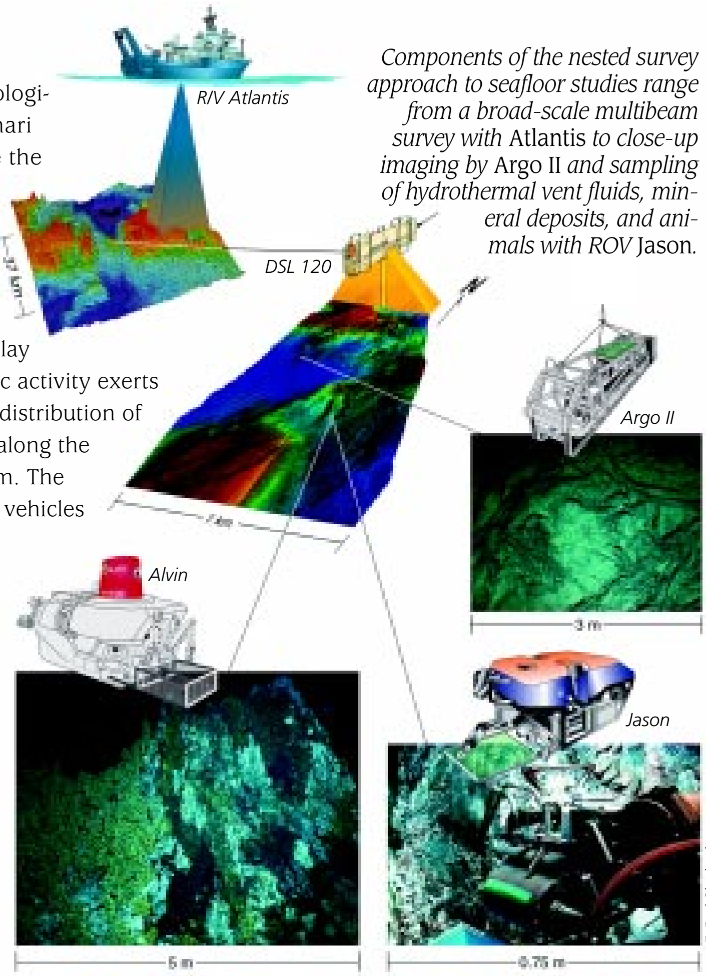
To assess the importance of hydrothermal circulation for global heat and chemical budgets, investigators need to understand where and how much hydrothermal activity occurs along the mid-ocean ridges. Dan Fornari and colleagues have spent the last few years monitoring the evolution of hydrothermal activity following a 1991 volcanic eruption near 9° 50'N on the East Pacific Rise crest, a part of the fast-spreading (110 millimeters per year) Mid-Ocean Ridge about 400 miles south of Acapulco, Mexico. These geophysical and geochemical studies, together with more regional surveys along fast- and intermediate-spreading ridges in the eastern Pacific, have documented many sites of hydrothermal activity and their relation to volcanic and tectonic phenomena, and have begun to allow investigators to better understand the processes involved in generating the earth's crust at mid-ocean ridges.

Locating hydrothermal sites along the much slower-spreading (20 to 30 millimeters per year) Mid-Atlantic Ridge, however, has been serendipitous because the ridge has considerably rougher topography. Only six hydrothermal sites have been verified by seafloor studies, although hydrothermal plumes have been detected with chemical sensors at a number of other locations. Using a combination of geophysical surveys, drilling, and submersible work, Susan Humphris and colleagues have been studying the Trans-Atlantic Geotraverse (TAG) hydrothermal field at about 26° N on the Mid-Atlantic Ridge, one of the largest known sites of mineral deposition on the seafloor. Here, tectonic activity and the resulting faults and fissures play an important role in controlling the distribution of hydrothermal activity.

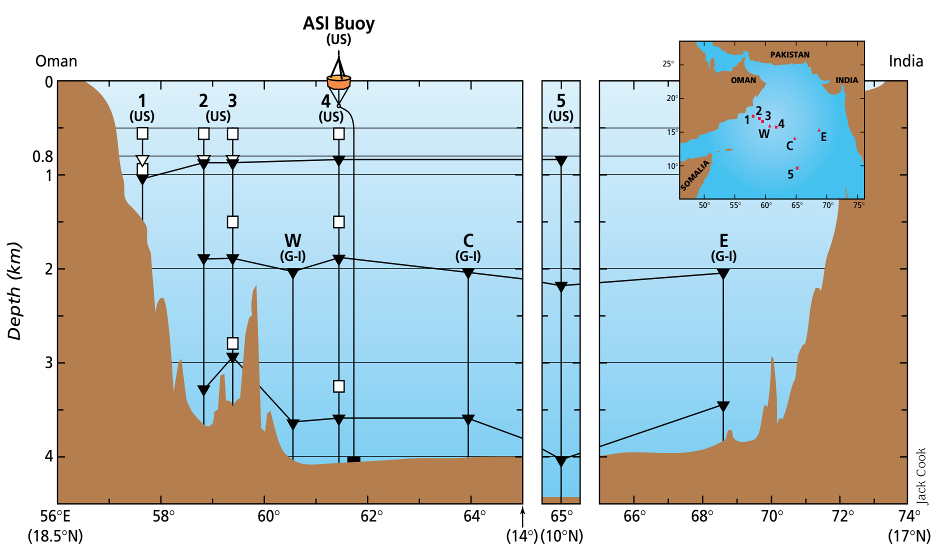
In summer 1996, Dan Fornari and Susan Humphris jointly investigated a site of hydrothermal activity about 300 miles southwest of the Azores Islands. The site, unlike any other Mid-Atlantic Ridge hydrothermal site, is located on the summit of a seamount in the Mid-Atlantic Ridge rift valley. During a six-week cruise funded by the National Science Foundation, Fornari and Humphris employed three different towed, near-bottom vehicles, all operated by WHOI's Deep Submergence Operations Group, in a "nested survey" approach. First, they conducted an acoustic and bathymetric survey of a 200-square-kilometer area within the rift valley using the *DSL-120* sidescan sonar system. Next, they used the *Argo II* imaging and mapping vehicle to take detailed photographs of the one-square-kilometer hydrothermal field on the seamount's summit. Finally, they used Remotely Operated Vehicle (ROV) *Jason* to take detailed photographs and samples at individual hydrothermal vents.

Although there has been sufficient volcanic activity to build a seamount, preliminary results from this survey indicate that the region is presently undergoing considerable tectonic extension. Faults from a few to tens of meters high cut through the seamount's summit. The hydrothermal sites are located in a depression on the summit. The larger, older mineral deposits are associated with the faults, but numerous smaller, active vents are found around the edges of a very fresh, recently erupted lava flow in the center of the depression. Such lava lakes are common on the faster-spreading East Pacific Rise, but have not been observed on the slower-spreading Mid-Atlantic Ridge. Based on the morphology of the deposits, the chemistry of the fluids, and the lack of associated hydrothermal vent biological communities, Fornari and Humphris believe the recent eruption of lava may have reactivated hydrothermal venting on the seamount's summit.

The complex interplay of volcanic and tectonic activity exerts strong controls on the distribution of hydrothermal venting along the mid-ocean ridge system. The suite of new surveying vehicles (recently made part of WHOI's National Deep Submergence Facility) and their use in sequential operations from a large research vessel, such as R/V *Knorr*, permit investigators to map and delineate relations between volcanic, tectonic, and hydrothermal features more clearly over larger areas than was previously possible. As Fornari and Humphris continue to expand their studies to previously unexplored parts of the mid-ocean ridge system, this type of survey approach eventually may allow them to predict the distribution of hydrothermal activity and its impact on the ocean's thermal and chemical budget.



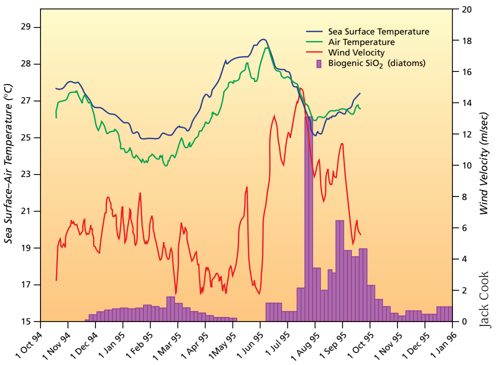
Components of the nested survey approach to seafloor studies range from a broad-scale multibeam survey with Atlantis *to close-up imaging by* Argo II *and sampling of hydrothermal vent fluids, mineral deposits, and animals with ROV* Jason.



The western Arabian Sea is the heart of area affected by the monsoon. A network of sediment trap moorings was set across this sea from Oman to India (see insert) to catch particles settling from the upper ocean downward through the ocean interior to the seafloor.

Biological Pumps, Ocean Sediments, and Global Climate Change: The Arabian Sea Experiment

Phytoplankton in the open ocean grows as photosynthesis fixes carbon dioxide (CO_2) from the atmosphere in the upper ocean layers. A large portion of the phytoplankton is then consumed and oxidized by zooplankton, which returns CO_2 to the atmosphere in a short time. A smaller portion of photosynthetic carbon, however, escapes from oxidation and settles through the water column. Carbon particles in plant cell material mixed with other ocean particles (calcareous and siliceous tests and shells, dust particles, and

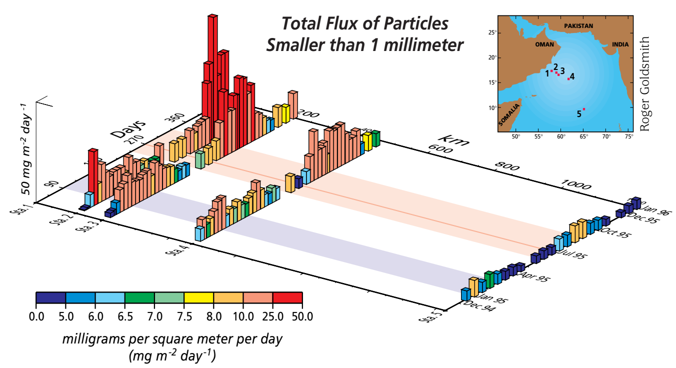


Sea surface temperature (SST), air temperature (ATM), and wind velocity during the winter (January to April) and summer (July to September) monsoons as measured by Bob Weller's air/sea interaction buoy at Station 4 (see lower figure on page 13). The figure above compares buoy data with the biogenic silicon oxide found in diatom frustules 1.8 kilometers deep at Station 5.

other matter) produce "marine snow," relatively large, amorphous aggregations of particles that accumulate on the ocean floor and become sediment through chemical and biochemical processes. The particles take only a few weeks to travel from the ocean surface to the deep bottom—the "sink"—where carbon cannot return to the atmosphere for several hundred years. The processes that remove and transport biogenic material, particularly carbon, from the atmosphere and upper ocean to the sink are called the "biological pump." The rate of removal of CO_2 carbon (the "export production") is one of the most important criteria for understanding and forecasting global climate change caused by the greenhouse effect, the runaway buildup of CO_2 in the atmosphere.

To understand the processes that support the biological pump and deep-ocean sedimentation, investigators can use a sediment trap that intercepts ocean particles at a certain depth as they settle to the bottom. The sediment trap, a large funnel with a cod-end, can be set vertically along a mooring tethered to the deep ocean floor. Knowing how long the trap is open, scientists can estimate the export fluxes of ocean particles, that is, the rate of sedimentation of particles in a particular area over a period of time in the deep-ocean layer where the trap is moored. Computer-controlled sampling can be repeated at specified intervals (typically two weeks) during a one- or two-year study of seasonal sedimentation.

Under the auspices of the US Joint Global Ocean Flux Study, supported by the National Science Foundation, Sus Honjo and an interdepartmental team of WHOI scientists have measured the export flux of ocean particles at critical locations for the last few decades. They have found that a distributed sediment-trap array collecting samples at specified time intervals is the most effective tool for understanding the evolution of the open ocean's biological pump throughout a year. In 1996, their research focused on the Arabian Sea, whose productivity is among the largest in the world. Strong, one-directional monsoon winds (southwest in summer, northeast in winter) move deep-ocean nutrients to the surface. Honjo and colleagues are studying how much and by which processes atmospheric CO_2 carbon is removed to the sink in the interior of the Arabian Sea by the extraordinarily powerful biological pump.



One year's organic carbon particle flux in the ocean's interior at western Arabian Sea stations. Blue and pink bands on the flat plane indicate the maximum winter and summer monsoon periods. In the zone several hundred meters from the Oman shoreline during the few weeks after the maximum summer monsoon period (thin red line), a powerful "biological pump" removes carbon dioxide from the surface water as organic carbon particles in quantities as large as 50 milligrams per day within one cubic meter (tall red columns).

From late November 1994 to early 1996, a team of WHOI, Oregon State University, and Brown University scientists deployed 19 time-series traps across the Arabian Sea, spanning the region from the coast of Oman halfway to India. Scientists from the University of Hamburg, who have long studied the Arabian Sea and have collaborated closely with WHOI, filled the other half of the sea with their array. The US and German arrays were identical, so the investigators were able to bridge the Arabian Sea with one giant sediment-trap array on a single open-close schedule. All the sediment traps and other technological instrumentation used in the Arabian Sea Export Flux Experiment worked flawlessly for one year. The researchers recovered all 528 samples, each of which represents 4.2 to 17 days of ocean sedimentation; these samples were strictly synchronized at each designated location, depth, and time. In addition, all time-series traps operating in southeast Asian oceans were synchronized under one timetable for this experiment.

The successful export-flux measurements and the use of other advanced WHOI technology allowed scientists, for the first time, to understand the highly intricate interrelationships in the Arabian Sea. For example, in collaboration with the Air-Sea Interaction Experiment led by Bob Weller (Physical Oceanography), Honjo and colleagues have found that particle sedimentation is clearly coupled with the direction and strength of the monsoon. The upwelling of the nutrient-rich water, which results from the cooling of the ocean surface and the overlying atmosphere, is controlled by the summer and winter monsoons. In addition, study results indicate that the highly efficient removal of atmospheric CO_2 carbon is achieved by a succession of explosive diatom blooms carried by coastal plumes all the way from the Omani coast. Data from the 1995 WHOI SeaSoar towing experiment led by Ken Brink (Physical Oceanography) also aided Honjo and colleagues in understanding in detail the operation of the biological pump in the Arabian Sea.

The high-quality, highly interactive data from the Arabian Sea Export Flux Experiment will mean success for scientists constructing biogeochemical models of the ocean. These models, in turn, will help researchers predict future global climate change.

Melt Extraction from the Mantle beneath Mid-Ocean Ridges

Feedback between chemical and physical processes during reactive flow of fluids through rocks is important in a wide variety of Earth systems, ranging from melt transport in the mantle, to migration of water and oil in sedimentary basins, to formation of landforms. Advances in geophysical fluid dynamics, computer modeling, and analytical geochemistry permit new insight into reactive flow. At WHOI, a multidisciplinary research group has concentrated on reactive melt transport in the mantle.

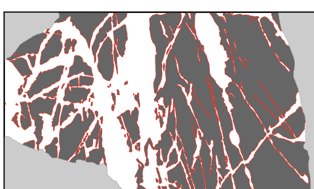
Magma rises from Earth's mantle to form new crust at oceanic spreading ridges. Melt is generated at depths of 100 to about 10 kilometers by decompression of the mantle as it is pulled upward by the separation of the plates. Although geologists understand the cycle of melting, crust creation, and seafloor spreading, they are uncertain about the processes of melt transport in the mantle. An obvious explanation, that melt ascends in cracks, is questionable because the hot, viscous mantle, like peanut butter or corn starch, may be too weak to crack. In 1995, Peter Kelemen, Jack Whitehead (Physical Oceanography), and MIT/WHOI Joint Program student Einat Aharonov proposed an alternative idea: that melt is extracted in porous "dissolution channels." As magmas rise, they become capable of dissolving minerals (pyroxenes) that comprise 10 to 40 percent of most mantle rocks. Another mantle mineral, olivine, is relatively insoluble. Initially, as diffusely distributed melt migrating by porous flow dissolves pyroxene, it may locally create high porosity channels. Because of their high permeability, these channels then become conduits carrying 99 percent of the melt flow. After all the pyroxene in the conduits is dissolved, only insoluble olivine remains. Thus, instead of rising passively in cracks, melt may actively eat its way out of the mantle, leaving olivine conduits in its wake.

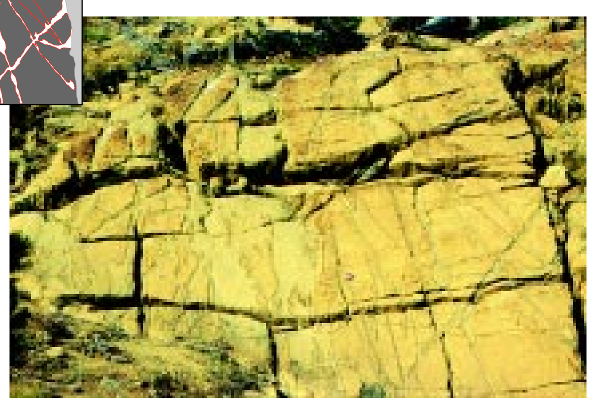
To test this idea, Kelemen, Nobu Shimizu, and MIT student Vincent Salters used the ion microprobe at WHOI to analyze samples from an exposed section of oceanic crust and mantle (an ophiolite) thrust upward to form mountains along the coast of Oman. This is one of the largest ophiolites in the world, up to 30 kilometers thick and covering an area larger than Massachusetts. Submarine lavas underlain by a continuous layer of dikes (lava conduits) indicate that the ophiolite formed as new igneous crust at a spreading ridge and that it preserves structures typical of oceanic lower crust and upper mantle. Rocks composed only of olivine (dunites) comprise about 10 percent of the mantle in the Oman ophiolite. These dunites might represent the dissolution channels predicted by theory. Ion probe analyses of trace elements reveal that dunites chemically record the passage of large volumes of ascending melt, while surrounding peridotites do not. Dunites also have geometrical relationships that indicate they formed by replacement of peridotite; for example, they do not displace preexisting layering in the peridotites, as they would if they were intrusive dikes. Thus, Oman dunites satisfy geochemical and geological requirements for porous conduits that transport melts through the mantle into the growing oceanic crust.

Mike Braun

With photographs taken from a camera mounted on this 24-foot blimp, scientists are constructing photo mosaic maps of rock outcrops in the North Cascades Range of Washington state.

These results fueled a vigorous debate. Some scientists believe that cracks play a more important role than porous flow in mantle melt extraction. In this view, dunites form as porous reaction zones around cracks. Dissolution channels and reaction zones around cracks should have distinctively different spatial distributions. To quantify the relative importance of cracks versus porous flow in dunite genesis, Kelemen and Greg Hirth collected data on the distribution of dunites in a mantle outcrop in the Washington Cascades. Inspired by the JASON Project, they wished to construct a photomosaic of the outcrop, recording features down to one square millimeter over an area of 300,000 square meters. Their prior research was supported by the National Science Foundation; however, in 1996, after a brief attempt involving a huge, steel tripod, Kelemen and Hirth received a WHOI Mellon Independent Study Award to buy a small blimp. The investigators navigated the "Blimp for On Land Oceanography" (BOLO) by tethers from the ground. BOLO carried a 35-millimeter camera, from which Kelemen and Hirth obtained the photomosaic in fall 1996. Size/frequency data from this mosaic can be used to discriminate between the effects of focused porous flow and reaction around cracks. The results of these studies will shed light on melt extraction and the general nature of reactive fluid transport structures.





Peter Kelemen

"Dunites" or dissolution channels, which show as smooth, light orange in the photo and white in the inset, were formed by lava migrating in a porous flow through mantle rocks (rough, darker orange in photo; black in inset) exposed in the Washington Cascades. This photo is one of several hundred that will be used to construct a highly detailed map of dunite channels for statistical analysis of their size and spacing.

Marine Chemistry & Geochemistry Department

Research interests in the Department of Marine Chemistry and Geochemistry (MC&G) cover a broad spectrum of topics related to global change, present and past ocean circulation, biogeochemical cycles, satellite remote sensing of the ocean, environmental quality, trace elements, radioactive contamination, organic geochemistry, photochemistry, sediment diagenesis, and the geochemistry of seafloor hydrothermal systems. Many of the research projects are parts of large national and international programs such as the Joint Global Ocean Flux Study (JGOFS), the World Ocean Circulation Experiment, Earth Observing System, Ridge Inter-Disclipinary Global Experiments, and the Ocean Drilling Program.

At the end of 1996 the department consisted of 18 scientific staff, 19 technical staff, 21 graded and administrative staff, and 7 individuals with postdoctoral appointments working on a total of 158 research projects. In addition there were 16 Joint Program students, 8 of them in residence at Woods Hole.

A number of important personnel changes occurred during the year. Associate Scientists Ken Buesseler and Jim Moffett were both awarded tenure; Mark Kurz was promoted to Senior Scientist; and Bernhard Peucker-Ehrenbrink, a recipient of one of the Institution's postdoctoral awards in 1994, was appointed to the scientific staff as Assistant Scientist. The department gathered on separate occasions to celebrate the retirement of Werner Deuser, after a 30-year career on the scientific staff, and Susan Kadar, also after nearly 30 years' service to the department as a technician, administrator, and, most recently, as the JGOFS Field Coordinator. Senior Research Specialist Nelson Frew received one of the Institution's new Senior Technical Staff Awards, Research Associate Judy Fenwick received the Linda Morse-Porteous Award, and Senior Scientist Bill Jenkins was named the twelfth recipient of the Bigelow Award in Oceanography, the Institution's highest honor. Ken Buesseler took a leave of absence to begin a two-year appointment as Associate Program Director of the Chemical Oceanography Program at the National Science Foundation.

Of the department's many diverse research projects, three have been selected for presentation here.

Untangling the Oceanic Productivity Knot

The oceans play a crucial role not only in the planetary food web, but also in the regulation of atmospheric carbon dioxide, and hence the global climate. Phytoplankton, the green plants of the ocean, fix carbon in a process that is particularly important to understand, quantify, and predict in response to our ever-changing environment. Yet consider the factors that influence the life of a phytoplankter. Physical forces, gravity, light, and fluid motion all play a role in its survival. Chemical processes, including the availability of micro- and macro-nutrients also must be considered. And biological factors, such as grazing by zooplankton, must be explored because they control phytoplankton population. These processes make it difficult to understand and predict—or even measure—ocean productivity; the often-chaotic interplay between the biological, chemical, and physical forces result in enormous spatial and temporal variability. Oceanographers may be able to determine the rate of carbon fixation (a measure of primary production) for a sample of water containing phytoplankton, but how can they estimate the average flux of carbon through the food web based on individual, point measurements in space and time?

One approach used effectively by chemical oceanographers is to infer the rates of biological productivity from tracers. Tracers are substances that exist in (or are put into) the environment in such minute quantities that they don't really affect the way things work; by tracing their pathways, however, one can learn about the way things move in the environment. Here is a simple analogy: In a department store, one can estimate the rate at which an escalator is moving by observing how long it takes a child in a brightly colored coat to move from the bottom to the top. The child's bright coat—an effective tracer—doesn't make the escalator move any faster, but it helps in tracking the progress of the escalator. Combining this observation with the average number of people on the escalator allows one to estimate the flux of people moving between floors. Using tracers in the ocean is a similarly powerful technique for looking at large-scale, long-term average rates of biological productivity.

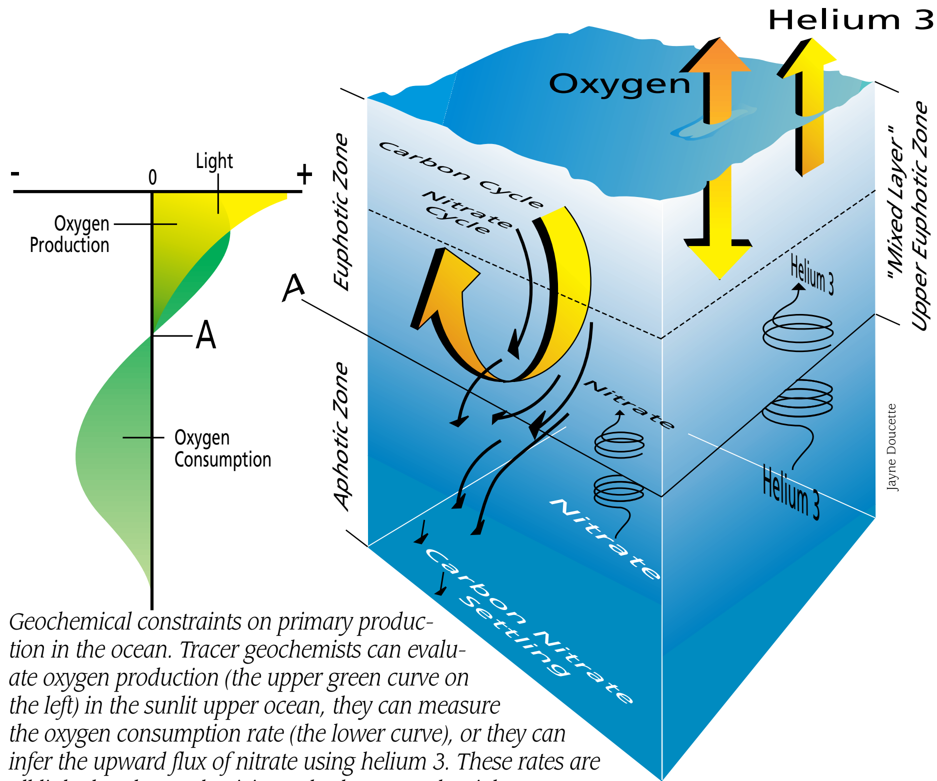
In studies funded by the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration, Bill Jenkins and MIT/WHOI Joint Program Student Maria Hood use tracers to study the biological cycling of carbon and nutrients in the upper ocean. Biological production (the fixing of carbon by phytoplankton) is fueled in the upper, lighted part of the water column (the euphotic zone) by the flux of nutrients from deeper layers. Although much of the fixed carbon is recycled within this zone as zooplankton graze the phytoplankton, some portion of the fixed carbon (called the "export production") escapes the euphotic zone either by sinking out as particles or mixing out as dissolved organic carbon. Once out of the sunlit upper layers, bacteria act upon the material and break it down to produce the nutrients that eventually mix upwards to fuel the cycle all over again.

Jenkins uses various substances riding this "wheel of life" to trace how fast the cycle spins. One such substance is dissolved oxygen, which is produced in the euphotic zone by photosynthesis. By watching the oceans "breathe" dissolved oxygen out, Jenkins can infer the rate of carbon fixation. Determining how fast the oceans breathe oxygen involves accounting for seasonal changes and the complexities of air-sea gas exchange. To accomplish this difficult task, Jenkins studies the behavior and variations of other, less complicated gases, particularly the noble gases, along with oxygen to estimate seasonal to annual averaged primary production.

These investigations use oxygen in yet another way. In the deeper layers, the oxidation of carbon and the breakdown of nutrients is accompanied by a requisite consumption of oxygen. Thus the deeper layers of the ocean are generally less saturated in oxygen than they would be if they were directly in contact with the atmosphere. The dissolved oxygen concentration in these layers is fairly steady and not zero—a result of a delicate balance between the rate at which the oxygen is consumed and the rate at which it is resupplied by the process of ventilation (by mixing and flow of oxygen-recharged water from the ocean surface). If scientists can measure the rate at which this ventilation occurs, they can then deduce the rate at which it is being consumed, since the two must balance. Jenkins uses various radiometric techniques, the most useful of which is "tritium-helium" dating. Knowing the net oxygen demand in the water column below, he and his colleagues estimate the flux of carbon that must support the demand. The resulting production estimates are very long-term averages, since the deep oxygen distributions are governed by balances that span years or decades.

In additional studies, Jenkins uses tracers to infer the rate at which nutrients rise upward to fuel production. Helium 3, produced by the decay of tritium (a product of radioactive bomb fallout), moves upward through the water column, accumulating in the surface waters before it escapes to the atmosphere. By knowing how rapidly helium 3 is produced in the waters below and by knowing the rate at which it can escape to the atmosphere, Jenkins uses the tracer to estimate the flux of nutrients.

The three techniques just discussed are linked by the common thread of biological production, yet they are uniquely different from one another. They yield estimates that tend to agree quite closely, allowing Jenkins and colleagues to believe they are beginning to converge on a firm, quantitative understanding of the large-scale, long-term average biological productivity in the world ocean. These studies have started to unravel the complex knot of causality in biogeochemical cycling in the oceans.



Geochemical constraints on primary production in the ocean. Tracer geochemists can evaluate oxygen production (the upper green curve on the left) in the sunlit upper ocean, they can measure the oxygen consumption rate (the lower curve), or they can infer the upward flux of nitrate using helium 3. These rates are all linked to the productivity cycle shown on the right.

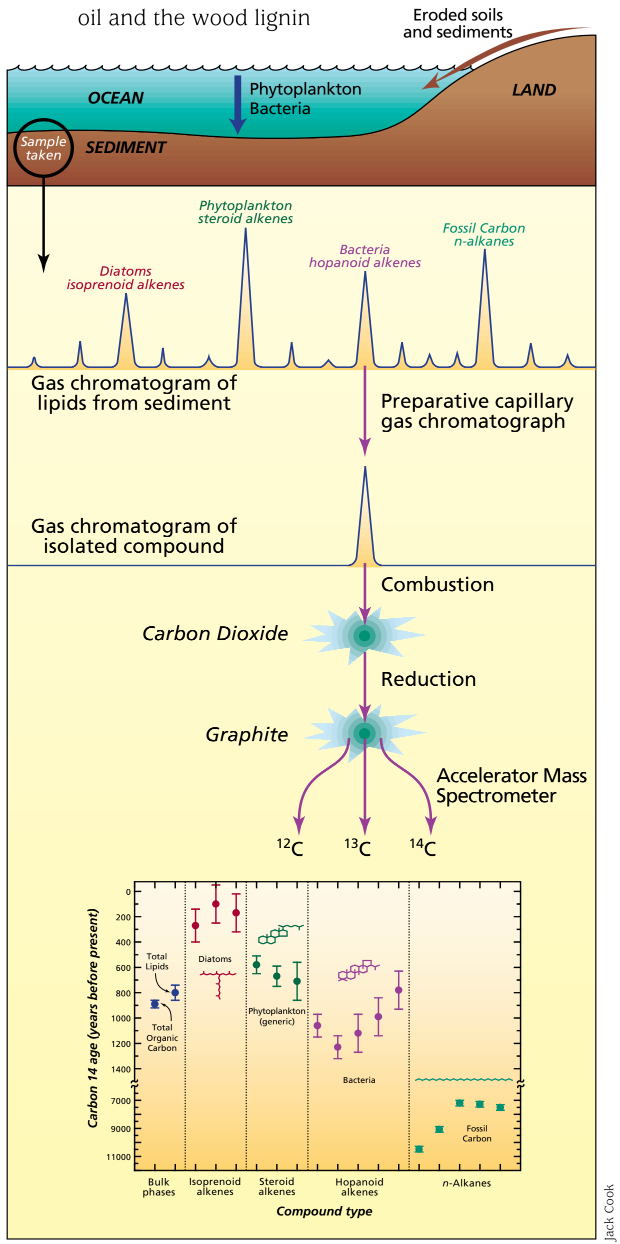
Molecular Radiocarbon Dating of Archaeological Artifacts and Marine Muds

Many areas of scientific research use radiocarbon (^{14}C) dating to determine the age of organic materials. In archaeology, researchers must establish when artifacts such as bones, paintings, and furniture were made or used, the information that constrains the chronology of civilization at specific locations. In oceanography, researchers use the age of organic and inorganic carbon to calculate the movement of water masses and to establish sediment chronologies in paleoceanographic studies. Radiocarbon's 5,700-year half-life provides information on processes that occur from decades to millennia. State-of-the-art accelerator mass spectrometer (AMS) systems, such as the National Ocean Sciences AMS Facility located at WHOI, have extended the applicability of radiocarbon dating because they require much smaller samples than previous techniques.

Most radiocarbon studies of organic matter use measurements of total organic carbon (TOC). Complications arise, however, when interpreting ^{14}C data of TOC because extraneous organic matter can contaminate the material being studied. In archaeology, for example, age estimates can be compromised if carbon from surrounding soil impregnates bone. In marine sediment geochemistry, where investigators establish chronologies on the premise that most organic carbon comes from phytoplankton in the overlying water column, nonindigenous organic matter can interfere. In particular, coastal sediments may gain organic matter from land via runoff and wind. This material, which includes fresh plant debris, soil organic matter, and organic carbon from eroded sedimentary rocks exposed at the land surface, may vary dramatically in age. When mixed with marine (phytoplankton) debris, it will influence radiocarbon ages of TOC.

To avoid these complications, Tim Eglinton, WHOI/MIT Joint Program students Bryan Benitez-Nelson and Ann Pearson, and Ann McNichol (from the AMS facility) have developed a method to radiocarbon date individual organic compounds. This molecular-level isotopic approach allows researchers to select a specific molecule or "biomarker compound" characteristic of a single material. The key to their approach, funded by the National Science Foundation and a WHOI Independent Study Award, has been the use of a preparative capillary gas chromatography (PCGC) system to isolate pure individual compounds in sufficient quantity (greater than 20 micrograms of carbon) for AMS measurement.

Eglinton and coworkers tested their approach on a suite of materials that, by virtue of their origin, were expected to yield similar ages between the TOC and individual compounds. Among these test materials were two samples of archaeological interest. The first sample was amber oil composed of plant fatty acids, from an alabaster pot archaeologists had found in an Egyptian tomb dating from dynastic records to 1498 B.C. The second sample was juniper wood shavings from a crafted object archaeologists found in the 2,700-year-old Turkish tomb of King Midas. The radiocarbon ages for both the individual fatty acids from the Egyptian oil and the wood lignin from the King Midas furniture were identical to the bulk material, indicating that the PCGC and AMS systems can be combined successfully to determine ^{14}C ages for individual compounds.



Carbon 14 results for individual hydrocarbons isolated from an Arabian Sea sediment were found to vary according to the origin of each biomarker class. The sequence of analytical steps outlined above the data illustrates the progression from a bulk sample to analysis of a single compound.

Interestingly, neither the calculated calendar age from ^{14}C measurements on the bulk oil nor those on the individual fatty acids matched the dynastic age of the Egyptian tomb, but rather showed it to be about 300 years younger! This result forces the investigators to consider that either there is an error in the calibration for conversion of radiocarbon ages to calendar ages, or the dynastic age is incorrect. The discrepancy warrants further study by geochemists and archaeologists.

The researchers recently reported the first measurements on individual compounds from sediment cores. These data (see figure) indicate that radiocarbon ages of different compounds from the same depth horizon vary considerably. Radiocarbon measurements of hydrocarbons isolated from a two-centimeter interval (spanning about 150 years) of an Arabian Sea sediment core revealed compounds with ^{14}C ages ranging from 100 to 10,000 years ago. These data provide a completely new perspective on the factors controlling ^{14}C ages of TOC and on the sources and ages of specific input materials.

Eglinton and coworkers are now applying their approach to study contaminants in the marine environment. Polycyclic aromatic hydrocarbons (PAH), one of the largest and most potent classes of carcinogenic compounds, are produced during combustion of organic materials. Their chronic accumulation in the environment over the past century has been attributed to fossil-fuel utilization. The investigators are using molecular-level radiocarbon measurements to distinguish contributions of specific PAH from the combustion of fossil fuels (coal, gas, oil) versus that from the combustion of modern biomass (residential wood burning, forest or grass fires). These studies will more accurately apportion PAH sources and provide valuable information to aid in the development of emission-control regulations for this important group of contaminants.

Fire, Ice, and Climate in Antarctica

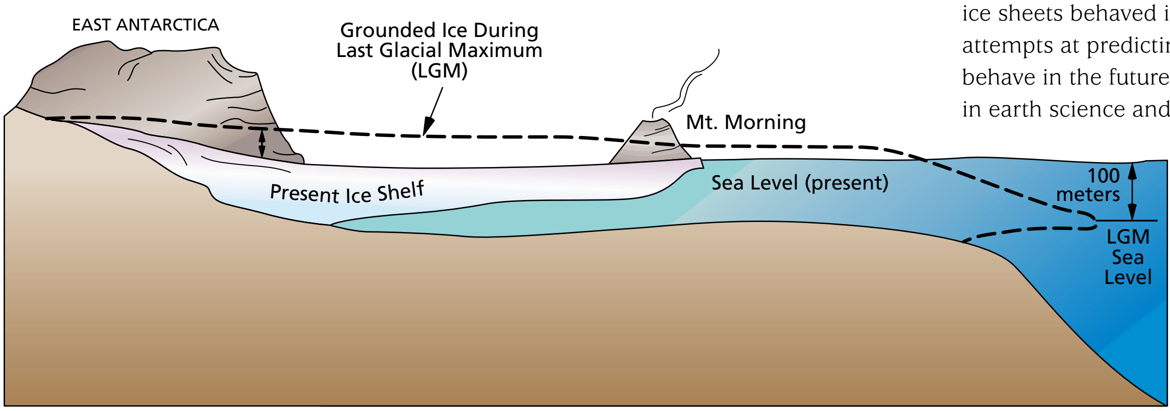
Mark Kurz

The northern flank of Mount Morning with Mount Discovery in the background. The large flat area in the center is one of the ancient lava lakes that mark the position of the ice sheet during the penultimate ice age. The two Scott tents barely visible in the left foreground housed Kurz and Ackert.

How do volcanoes in the Ross Sea of Antarctica relate to climate and oceanography? Recent studies of Mount Morning, a young volcano in McMurdo Sound, provide a link between global sea level and ice thickness in the Ross Sea during the ice ages, and provide important clues to how the antarctic ice sheets and their fringing ice shelves have changed in the past. Ice shelves form when ice sheets flow into the sea and begin to float. During Earth's ice ages, thick continental ice sheets (including the one that covered much of North America) lowered sea level by approximately 100 meters because they took up so much water. The response of the antarctic ice sheets to lower sea levels and colder climate is poorly understood. One model assumes that, as sea level lowered, the Ross Ice Shelf grounded on the continental shelf, allowing the ice sheet to expand and thicken (see figure below).

To test this idea, Mark Kurz and Joint Program student Robert Ackert have been studying the glacial deposits and lava flows on the northern flank of Mount Morning in the Ross Sea. They have been using a new method, developed at WHOI, for dating lava flows and glacially deposited boulders; the method involves measuring helium 3 (the rare isotope of helium) produced by cosmic rays. By measuring the amount of helium 3 in the lava flows, it is possible to calculate how long a particular surface was exposed to cosmic rays (the "exposure age"). This method makes it possible to obtain the ages of glacial deposits and lava flows that were previously impossible to date. The field and laboratory studies are funded by the Office of Polar Programs at the National Science Foundation.

The results from Kurz and Ackert's studies of Mount Morning show that this volcano has erupted a number of times in the last 300,000 years, and that the lava flows can be used to tell how thick the ice was in the Ross Sea. During an ice age approximately 170,000 years ago, several eruptions caused lava to flow down the flank. Where the lava reached the edge of the ice sheet, it formed a lava lake that was preserved after the ice retreated (photo above). By determining the ages of these flows (and the boulders left behind by the glaciers) and combining that information with their elevations, Kurz and Ackert can show that the ice was much thicker during the ice ages, a conclusion that supports the ice-age picture of the Ross Sea. The results also show that the ice was thicker during the penultimate ice age (170,000 years ago) than the most recent one (18,000 years ago). Possible explanations include differences in sea level or different durations of the ice ages. If one ice age was longer than the other, it may have allowed more time for the ice to pile up, resulting in a thicker ice sheet in the Ross Sea. Understanding how these huge ice sheets behaved in the past is critical to attempts at predicting how they might behave in the future. As is often the case in earth science and oceanography, answers to these important questions come from unexpected sources; in this case, the lava flows from Mount Morning show that ice was thicker in the Ross Sea during periods of low sea level.



Jayne Doucette

The relative thickness of the Ross Ice Shelf during the last glacial maximum and the present. During glacial times, sea level is lower, leading to thicker ice in the Ross Sea.

Physical Oceanography Department

Scientific research interests in the Physical Oceanography Department range in scale from the broad, general circulation in ocean basins over years and centuries to mixing and dissipative processes that occur on scales of millimeters and seconds. Department staff members both conduct individual research programs and participate in large, cooperative interinstitutional and international field programs such as the World Ocean Circulation Experiment, Global Ocean Ecosystems Dynamics, Ridge Interdisciplinary Global Experiments, Tropical Ocean Global Atmosphere-Coupled Ocean Atmosphere Response Experiment, Joint Global Ocean Flux Study, a coastal mixing and optics experiment, and the Arabian Sea Experiment. Specific research efforts include theoretical and field work, analysis of observations, remote sensing, laboratory experiments, and analytical and numerical modeling. Three of the department's many research projects are highlighted here.

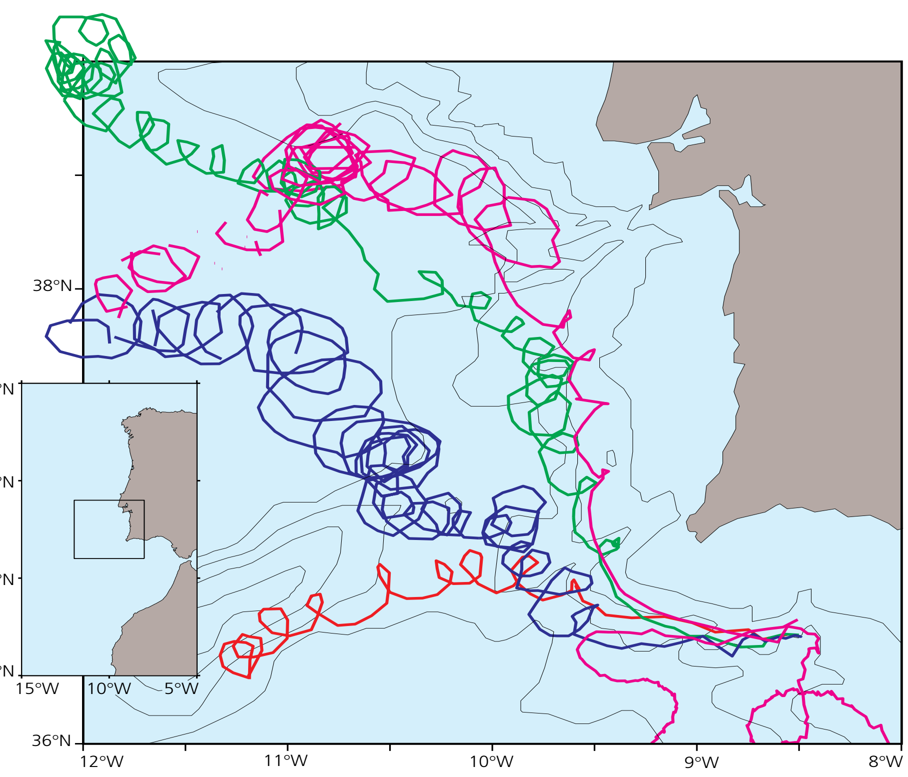
The Department of Physical Oceanography consists of 32 scientific staff, 24 technical staff, 38 graded and administrative staff, 7 postdocs, and 28 Joint Program students. There are 44 principal investigators working on about 200 research projects. During 1996, 101 new research proposals were submitted and 64 proposals were funded.

Assistant Scientist Kurt Polzin, who joined the department in 1996, is working on the role of mixing in the deep and abyssal ocean. Assistant Scientist Julio Candela was promoted to Associate Scientist, Associate Scientist Al Plueddemann received tenure, and John Toole was promoted to Senior Scientist. Two scientists were on leave from Woods Hole for visits to other institutions: Julio Candela visited the Centro de Investigación de Educación Superior de Ensenada, and Al Plueddemann served in Washington, DC, as a Program Manager at the National Science Foundation. Bill Schmitz, a 30-year department member, retired at the end of 1996 but continues his collaboration with WHOI colleagues as Scientist Emeritus.

Several department members received awards in 1996. Ken Brink was the Scripps Institution of Oceanography Cody Award recipient, and he was also elected President of the Oceanography Society and appointed Chair of the Ocean Studies Board. Joe Pedlosky was elected to the American Academy of Arts and Sciences. He also published a new book entitled *Ocean Circulation Theory*. Bill Schmitz was awarded the Navy's Meritorious Public Service Citation and the Superior Public Service Award. Bob Beardsley received the first appointment to the Institution's new Walter A. and Hope Noyes Smith Senior Scientist Chair.

An AMUSE-ing Discovery: Meddy Formation off the Iberian Peninsula

Warm, saline water from the Mediterranean Sea flows through the Strait of Gibraltar into the North Atlantic Ocean, forming a well-known hydrographic feature at mid-depth: the Mediterranean salt "tongue." Traditionally, oceanographers interpreted this tongue to be the result of advection or eddy mixing of Mediterranean water from its source. The discovery of meddies—coherent vortices containing cores of warm, salty Mediterranean water about 100 kilometers in diameter and 1,000 meters thick—challenges that view. In the past two decades, researchers have found and documented the structure of many meddies in the eastern North Atlantic. Meddies can persist for several years and transport their cargo of Mediterranean water far into the North Atlantic.



Tracks of four RAFOS floats that revealed four different meddy formation events at Cape St. Vincent, at the southwestern corner of the Iberian Peninsula. The small map shows the eastern North Atlantic, Portugal, Spain, the Strait of Gibraltar, and northwestern Africa.

Meddies may be responsible for 25 to 50 percent of the western flux of Mediterranean water, indicating that they play a significant role in distributing heat, salt, and other tracers in the North Atlantic.

Fundamental questions about where, how often, and by what mechanism meddies form have remained unanswered, largely due to the lack of observations of meddy formation. With funding from the National Science Foundation, Amy Bower, Larry Armi (Scripps Institution of Oceanography), and Isabel Ambar (University of Lisbon) have conducted a major field program, called "A Mediterranean Undercurrent Seeding Experiment" (AMUSE). The program's goals are to identify the most important meddy formation sites, to directly estimate the rate of meddy formation and the time required for meddies to form, and to observe the spreading pathways of Mediterranean water into the North Atlantic via meddies and other processes.

Between May 1993 and March 1994, Bower and colleagues sequentially deployed 49 RAFOS floats at about 1,000 meters in the Mediterranean undercurrent south of Portugal. RAFOS floats "listen" for sound signals from moored sound sources, record positions internally through a process of triangulation as they travel along with an eddy or current, and then rise to the surface at the end of their mission to transmit the data via satellites. Bower and colleagues acoustically tracked the floats for up to 11 months and obtained a total of 44 float trajectories, representing over 20 float-years of data.

Ten of the floats were caught in nine separate meddy formation events, six near Cape St. Vincent, at the southwestern corner of the Iberian Peninsula (see figure opposite). The floats took three to five days to make complete loops. While they were looping, they measured the warm temperatures characteristic of meddies. In all cases, meddy formation seemed to be tied to specific locations along the slope where the coastline turns sharply to the right (facing downstream)—strong evidence that topography may dictate where meddies form. Calculations of the dynamical properties of the meddies and their source water suggest that meddies form when the Mediterranean water flowing along the slope south of Portugal separates from the boundary and spins up into eddies. These results have also provided insight into the circumstances under which meddies form, contributing to an understanding of the role of meddies in transporting heat and salt into the North Atlantic.

David Fisichella

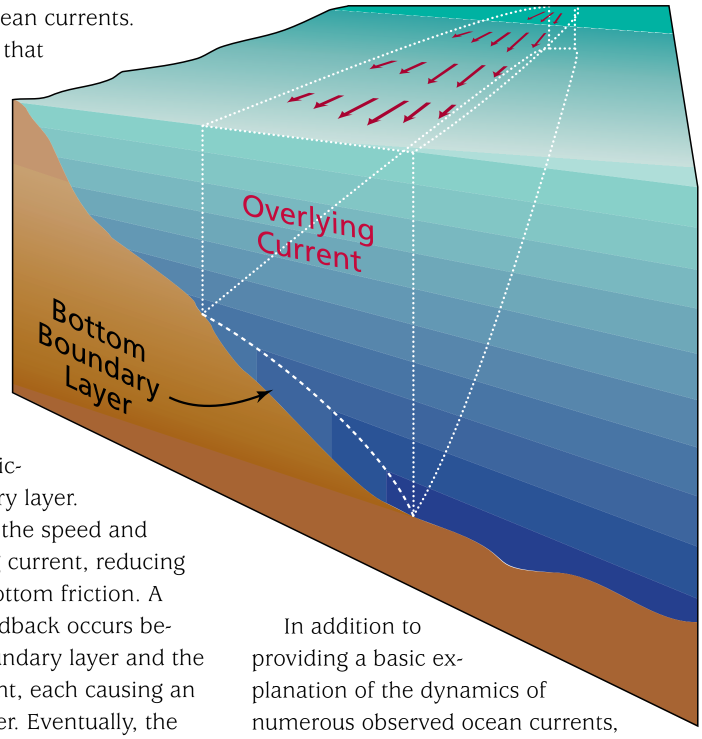
Amy Bower and Fred Grosse of Susquehanna University launch a RAFOS float from R/V Oceanus.

Can We Explain Long, Narrow, Persistent Ocean Currents?

Many ocean currents flow hundreds or even thousands of kilometers as narrow streams along the ocean bottom. For example, deep western boundary currents carry cold water from polar regions to midlatitudes, winding their way along the continental slope and rise. Boundary currents, such as the East Greenland and Labrador currents, flow along the upper slope, transporting large quantities of fresh water. Coastal currents make their way along narrow continental shelves, effectively connecting stretches of coastline along entire continents. Even in the deep ocean, energetic currents flow long distances along deep-ocean ridges.

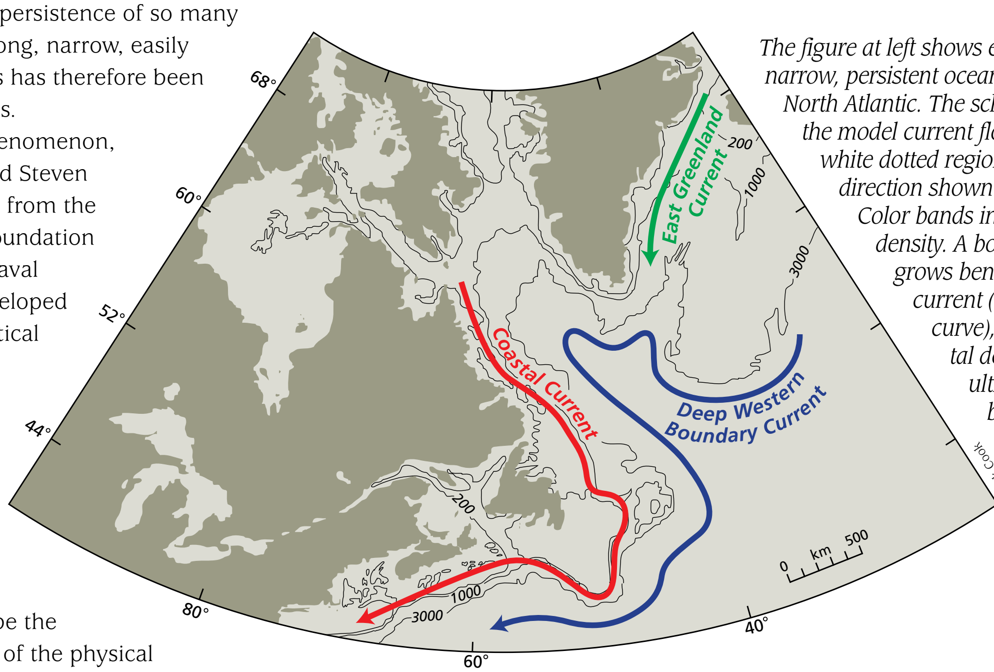
What makes these currents remarkable is that they persist as long, narrow streams despite being in contact with a frictional bottom. Usually, the roughness of the bottom generates a thin boundary layer adjacent to the bottom beneath an ocean current. The boundary layer retards the current, much as large stones slow the flow in a stream. As the ocean current slows, it must spread out to maintain its total flow. Eventually, the identity of the current is lost. The persistence of so many ocean currents as long, narrow, easily identifiable streams has therefore been a puzzle for decades.

To study this phenomenon, David Chapman and Steven Lentz, with support from the National Science Foundation and the Office of Naval Research, have developed an idealized theoretical model of an ocean current flowing over a sloping, frictional bottom. The model consists of a set of partial differential equations that they believe describe the essential dynamics of the physical system; that is, the model isolates the important processes that might explain the behavior of narrow ocean currents.

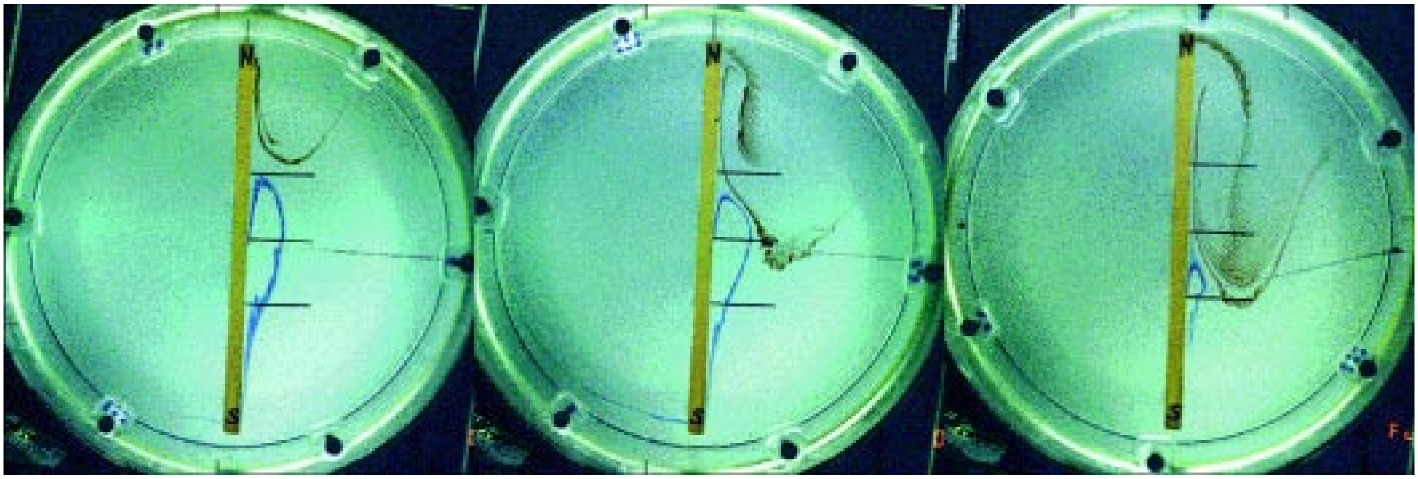


Study results show that the combination of stratification (vertical density variations) and a sloping bottom fundamentally alters the simple scenario described above. As bottom friction slows the current, it also redistributes waters of different densities within the frictional bottom boundary layer. This, in turn, changes the speed and shape of the overlying current, reducing the effectiveness of bottom friction. A strong coupling or feedback occurs between the bottom boundary layer and the overlying ocean current, each causing an adjustment of the other. Eventually, the bottom boundary layer and the ocean current adjust to a balance in which the stress at the bottom vanishes everywhere, and the bottom appears frictionless to the overlying flow! The current can then persist indefinitely in this equilibrium form despite the presence of bottom friction. The current neither slows nor widens, but rather maintains its narrow structure.

In addition to providing a basic explanation of the dynamics of numerous observed ocean currents, Chapman and Lentz's theory produces simple estimates of the equilibrium structure of both the ocean current and the bottom boundary layer. They plan to compare these estimates with observations to test their ideas in more detail and to suggest improvements to the model. In this way, they hope to extend their highly idealized model to more realistic situations.



The figure at left shows examples of long, narrow, persistent ocean currents in the North Atlantic. The schematic above depicts the model current flowing within the white dotted region, with speed and direction shown by the red arrows. Color bands indicate variations in density. A bottom boundary layer grows beneath the overlying current (below white dashed curve), introducing horizontal density variations that ultimately reduce the bottom stress to zero.



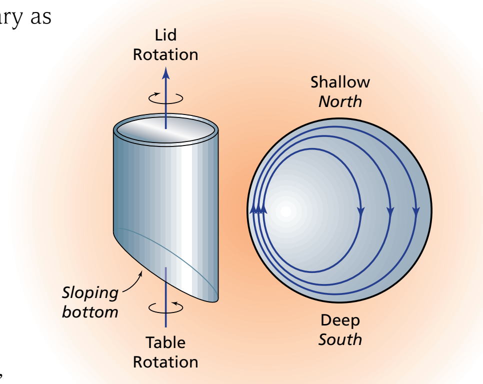
Laboratory experiments showing the closed recirculation cell to the east of a long, thin meridional ridge. The extent of the linear recirculation is indicated by the dye streak near the center of the ridge. As the forcing (either wind stress in the upper ocean or upwelling in the abyssal ocean) is increased, the linear recirculation is replaced by a flow-separation recirculation at the northern end of the ridge.

Ocean Circulation Around Ridges and Large Islands

Much of our theoretical understanding of the basin-scale ocean circulation—both the upper ocean wind-driven flow and the abyssal flow—comes from idealized models in which the ocean basins usually have simple shapes (for example, a rectangle or a circle) and flat bottoms. Yet a quick examination of a map of the ocean basins shows that the oceans are far from uniform in depth. The most prominent feature in the abyssal ocean is the mid-ocean ridge system, which separates the abyss into separate sub-basins. Also present in the upper wind-driven ocean are large islands, such as Australia and Madagascar. Oceanographers do not entirely understand just how these features affect, or control, the observed circulation.

With funding from the National Science Foundation, Karl Helfrich and colleagues have begun to explore the fundamental fluid dynamics of large-scale oceanic flow when the ocean basin is partially blocked by a ridge or large island (scales of 100 to 1,000 kilometers). Their approach is to use a combination of theoretical analysis, numerical models, and laboratory experiments to help give a more complete understanding than is possible with each individual technique.

The laboratory study uses an apparatus called the lid-driven sliced cylinder. It consists of a cylinder with a uniformly sloping bottom and a flat lid that can be rotated at a prescribed rate. The whole apparatus is placed on a rotating table to simulate Earth's rotation (Coriolis acceleration). The sloping bottom mimics the increase in the Coriolis effect from the equator (the deep end) to the poles (the shallow end). The rotating lid provides the equivalent of wind stress. The figure below shows the circulation in this apparatus without a ridge. The flow proceeds up the left-side boundary as a narrow "western" boundary current (for example, the Gulf Stream) and returns to the south in the interior of the tank as a broad, slow flow.



When a ridge oriented north-south is introduced, the flow is dramatically altered. The principal new feature is a recirculation zone to the east of the ridge. In the absence of the ridge, the flow is all in the same direction. The first photograph, at left above, shows a laboratory experiment in which this recirculation is marked by the release of blue dye near the eastern side of the ridge. It flows to the north (top of the photo) along the ridge and then turns into the interior and flows south to close the recirculation. Red dye released at the northern end of the ridge heads directly down the ridge until it encounters the recirculation. The next two photographs show the effect of increasing the strength of the forcing (that is, increasing the lid rotation rate). The recirculation zone is diminished and ultimately replaced by a recirculation zone (marked by the red dye from the northern source) associated with flow separation at the northern end of the ridge.

These simple experiments and companion theoretical and numerical work highlight just some of the qualitative changes in the general circulation that occur in the presence of ridges or large islands. In the example above, just one new feature, a single ridge, drastically alters the observed flow; this is important because much of the interpretation of large-scale ocean circulation observations comes from models that do not include the complicating effects of topography. Although Helfrich's work is still very idealized, it is a step towards understanding the complex role of ocean-basin topography in the general circulation.

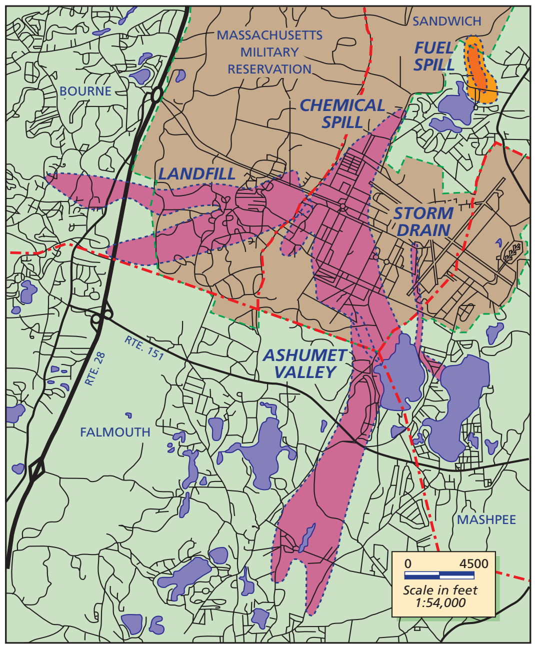
Marine Policy Center

The Marine Policy Center (MPC) conducts social scientific research to advance the conservation and management of marine and coastal resources. The usefulness of such research depends upon its grounding in the best available scientific information. The work of MPC scholars integrates economics, policy analysis, and law with WHOI's basic strengths in the ocean sciences.

In 1996, MPC staff extended their research and writing in a number of areas for which the Center is well known, including measurement and valuation of biological diversity, detection of climate change, marine transportation technology and safety, ocean waste disposal, and management of historic shipwrecks. A study of marine area governance and management in the Gulf of Maine Region, completed in 1996 for the Marine Board of the National Research Council, spanned several traditional MPC research areas, including marine fisheries management and coastal zone management. The study identified the New England groundfish fishery as the most important regional-scale marine resource and industry, and also the resource most seriously undermined by chronic failures of governance and management. MPC's conclusions emphasized the need for a better separation of science and management from politics and for the federally mandated Fishery Management Councils to be made more accountable to the general public whose interests they were established to serve.

MPC also devoted considerable attention in 1996 to such new research areas as the sources of productivity change in marine sector industries, the costs and benefits of pollution remediation strategies in the coastal zone, and development of the aquaculture industry.

A two-year study supported by the Sloan Foundation is designed to improve understanding of marine sector productivity change at both the sectoral and the industry level. The research will also contribute to the broader study of economic growth in the United States and to the debate about public sector investment strategies. The study includes site visits to firms in the fisheries, marine transport, shipbuilding, offshore oil and gas, marine electronics, and cruise tourism industries to determine how the production inputs of labor, capital, and investments in research and development, as well as production outputs, have changed over time. The site visits will permit a better understanding of industry structure and organization, which



Jack Cook

Marine Policy Center researchers are examining property value effects of the contaminant plumes (pink) emanating from the Massachusetts Military Reservation as part of a study that will provide important new economic information about the costs and benefits of groundwater pollution remediation strategies.

is important for aggregating the results to the sectoral level and for understanding how the marine sector as a whole interacts with other sectors of the US economy.

An MPC pilot study launched in 1996 is investigating property value effects associated with a $179 million interim strategy to contain seven contaminant plumes emanating from the Massachusetts Military Reservation (MMR) and affecting groundwater supplies in four surrounding towns on upper Cape Cod. Property-value effects are central to an evaluation of the economic costs and benefits associated with alternative pollution mitigation strategies and timetables, yet engineering studies that measure the costs of proposed strategies typically fail to measure such effects. In addition to providing valuable information to Cape Cod residents and those involved in the MMR cleanup, the MPC research will have implications for groundwater pollution evaluation and mitigation in general.

MPC research has also begun to address the policy problem of whether and how best to promote the development of aquaculture as part of an economically efficient mix of wild harvest fisheries and other uses of federal and state waters. At present there is no coordinated federal policy governing the use of the US Exclusive Economic Zone for ocean mariculture operations. Similarly, decisions about the siting of aquaculture operations in state waters may be determined as much by variations in jurisdictional authority, regulatory stringency, competing uses, and the availability of investment capital as by the physical conditions that favor biological productivity.

Two new MPC projects deal with the policies and economics governing aquaculture operations in New England state waters. One focuses on legal and capital formation issues affecting development of the industry in Rhode Island. The other is a comparative study designed to measure the magnitude of the effects of regulatory and environmental factors on siting decisions for hard clam aquaculture operations in Maine, Massachusetts, and Rhode Island. Plans for other MPC aquaculture research projects include design of an optimal access system for ocean mariculture, a comparative economic analysis of global aquaculture production, and an analysis and quantification of the economic factors affecting the future international competitive position of the US marine biotechnology industry.

MPC is planning to establish a Mariculture Policy Center for the study of technical and policy issues concerning offshore mariculture activities. Support for this initiative has been provided by the Environmental Systems Research Institute in the form of geographic information systems (GIS) software, data, and training to help establish a GIS capability as part of the new center.

Rinehart Coastal Research Center

1996 was an exciting year for the WHOI Coastal Research Center. Long-time Institution supporter Gratia "Topsy" Rinehart Montgomery of South Dartmouth, Massachusetts, committed $5,000,000 to endow coastal research at the Woods Hole Oceanographic Institution. In October, WHOI celebrated this remarkable gift by formally dedicating the Gratia Houghton Rinehart Coastal Research Center.

Dave Gray

Cheryl Ann Butman explains her work to Topsy Montgomery at the open house that followed the October ceremony dedicating the Gratia Houghton Rinehart Coastal Research Center in Mrs. Montgomery's honor. Center Director Rocky Geyer stands behind the two women.

The mission of the Gratia Houghton Rinehart Coastal Research Center is to support and enrich the coastal research activities of the WHOI community, particularly projects that affect the protection and enhancement of coastal resources. Established in 1979 as an intellectual center without walls, the center brings together scientists, engineers, and students from each of the Institution's five science departments, the Marine Policy Center, and other scientific organizations in Woods Hole.

The coastal ocean and the continental margin are increasingly affected by the pressure of the growing coastal population. Research supported by Mrs. Montgomery's endowment will provide a solid base for wise management of nearshore resources both locally and throughout the world. It will also provide a resource for WHOI researchers who wish to take on new challenges and initiatives, and it will sustain long term studies, which traditional funding agencies are reluctant to support. This new endowment will allow WHOI scientists the freedom to be bold and visionary in their research pursuits. Mrs. Montgomery's lifelong desire to "pass along the love of science and nature to future generations" is exemplified in this gift and represents a commitment to oceanography that will have broad impact for many years to come.

Dave Gray

Director Bob Gagosian, left, joined Topsy Montgomery, her husband Gordon Montgomery, at right, and her son Peter Allatt at the new Coastal Research Center sign following the dedication ceremony.

Several research priorities, outlined below, were selected to focus the efforts of the Rinehart Coastal Research Center (RCRC) in 1996. These priorities build on the experience, knowledge, and strengths of the center's past efforts and on the scientific excellence found in the Institution as a whole.

• *New Instrumentation for Coastal Ocean Measurements:* The complexity of the coastal ocean is partly defined by its incredible spatial variability. RCRC research supports the development of new instruments and methods to measure variations, to manipulate experiments on-site, and to provide new, accurate, and more detailed information. For example, researchers are assessing a new method for indicating the accumulation of metals in phytoplankton populations. This study could have important implications in the monitoring and regulation of water quality.

• *Exchange Processes at the Seafloor:* Chemical contamination appears initially and most intensely where the coastal ocean meets the seafloor. Contaminants can degrade habitat quality, and they compromise commercial resources (for example, fish and shellfish) and possibly human health. RCRC researchers study the complex mix of physical, biological, and chemical processes that move contaminants across the sediment-water interface. For example, scientists are conducting on-site experiments in Buzzards Bay to learn how a polychaete worm (*Nepthys incisa*) affects the movement of chemicals and particles at this interface. Knowledge of the natural cycling of bioactive chemicals and sedimentary pollutants helps society to develop rational resource management and remediation policies.

• *Modeling to Predict Changes:* The scientific community often uses predictive tools (models) to address coastal resource management questions. RCRC studies are designed to examine how well models can—or cannot —predict the outcome of natural or human-induced changes in coastal environments. One modeling study is designed to determine how physical processes affect the distribution of phytoplankton in the western Gulf of Maine. Such model experiments improve understanding of coastal circulation dynamics and their effects on biological productivity.

• *Coastal Marine Biodiversity:* Understanding the patterns and processes that control diversity of life in the coastal ocean is a complex challenge. RCRC researchers seek to identify changes in biodiversity that result from natural and human-induced processes. For example, a study that focuses on blooms of "brown tide" alga (*Aureococcus anophagefferens*) in shallow coastal bays will help to define the relationship between the blooms and other organisms in the pelagic food web.

Tom Kleindinst

WHOI Research Associate Dale Leavitt (center) along with members of the first annual Quahog Farmers' Forum check the larval rearing tank's temperature.

Sea Grant

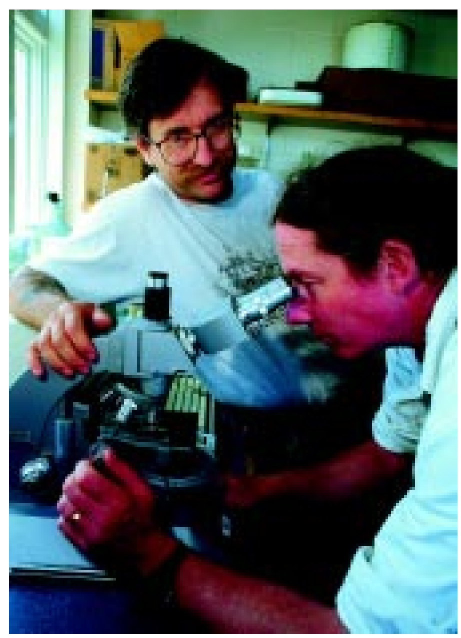
The WHOI Sea Grant Program supports research, education, and advisory projects to promote the wise use and understanding of ocean and coastal resources for the public benefit. It is part of the National Sea Grant College Program of the National Oceanic and Atmospheric Administration, a network of 29 individual programs located in each of the coastal and Great Lakes states. The goal of the program is to foster cooperation among government, academia, and industry. WHOI Sea Grant-supported projects provide linkages between basic and applied aspects of research and promote communication among the scientific community and groups that utilize information on the marine environment and its resources.

During 1996 WHOI Sea Grant supported 13 concurrent research projects in addition to 18 new-initiative awards for project development. Many of the projects address local and regional needs; some have national or even global implications. Investigators from the Woods Hole scientific community, universities throughout Massachusetts, and scientists from industry and other states all participate in WHOI Sea Grant's competitive funding process. Examples of currently funded projects include:

- quantifying flushing rates of estuaries,
- ecosystem level measurements of denitrification in estuaries,
- a stable isotopic approach for early detection of wastewater nitrogen in estuarine food webs,
- school structure and individual feeding behavior of bluefin tuna,
- development of genetic markers for identification of seeded scallops,
- development of species-specific immunofluorescent markers for bivalve larvae with an application to fisheries management,
- molecular biological approaches for nondestructive assessment of chemical effects on marine mammals,
- impact of environmental contaminants on aquatic bird populations,
- an optimal risk sharing strategy for marine oil transport, and
- transport of fine-grained sediments.

Transferring the results of research and providing general marine-related information are important components of the WHOI Sea Grant Marine Advisory and Communications Programs. Both programs facilitate communication among users and managers of marine resources, including members of the fishing community, local officials, environmental regulatory agency managers, and the general public. Two areas of particular interest in the marine advisory program are coastal processes and fisheries and aquaculture. Both topics have been the focus of numerous workshops and outreach efforts with an emphasis on better management of resources at the local and regional levels.

WHOI Sea Grant provides information to broad audiences through a variety of means. These include a new WHOI Sea Grant World Wide Web site (http://www.whoi.edu/seagrant), annual publication of a *Directory of Cape and Islands Coastal Outreach Organizations*, management of a Web mailing list to encourage networking among the *Directory* organizations, and dissemination of Sea Grant and other marine-related videos and publications such as *WHOI Sea Grant Publications Catalog, 1971-1995* and *Marine Science Careers: A Sea Grant Guide to Ocean Opportunities*. In addition, WHOI Sea Grant Fisheries and Aquaculture Specialist Dale Leavitt conducted the first annual Quahog Farmers' Forum, directed at all individuals associated with the quahog aquaculture industry in the region. Leavitt also organized a nine-month training program for local growers on quahog cultivation techniques.



Tom Kleindinst

Shellfish farmer John Winslow examines bivalve larvae raised in the hatchery. Dale Leavitt, WHOI Sea Grant's Fisheries and Aquaculture Specialist, conducted the Quahog Farmers' Forum.

The historic success of WHOI Education Programs is founded in the dedication of many Institution people. We see it in the dynamic and engaging interaction of postdocs, graduate students, undergraduate Summer Student Fellows, Minority Trainees, Guest Students, Scientific and Technical Staff (our faculty), administrators, Education Office personnel, and other staff throughout the Institution. Since 1968 a key catalyst in our education programs has been Associate Dean and Registrar A. Lawrence " Jake" Peirson III, who retired at the end of 1996.

Jake Peirson joined the Institution initially as an "Administrative Aide" in the summer of 1967. The following year he became involved with the WHOI education programs, working with the first Dean, K.O. Emery, at the beginning of the MIT/WHOI Joint Program. Since that time he has served with all the Deans and Acting Deans.

Two receptions were held to celebrate Jake's career at WHOI. The first was a "traditional" Institution retirement party in the Clark Laboratory fifth floor conference room on November 21. More than 200 students, postdocs, and Institution employees gathered to hear tributes liberally sprinkled with humor. The festivities began in the best WHOI spirit with a thorough "roasting" by Scientist Emeritus Geoff Thompson, who regaled us with the story of Jake's "equator crossing" cruise and an admonition to Jake about his golf game. The second reception brought more than 150 WHOI Scientific and Technical Staff, MIT faculty, students, and friends of Jake together at the December 1996 American Geophysical Union (AGU) meeting in San Francisco.

Judy McDowell, Biology Department Senior Scientist accepted appointment as Associate Dean effective January 1, 1997. With her is John Farrington, Associate Director for Education and Dean of Graduate Studies.

Tom Kleindinst

Degree Statistics

		1996	1968-96
WHOI	Ph.D.	–	3
MIT/WHOI	Ph.D.	13	315
MIT/WHOI	Sc.D.	1	29
MIT/WHOI	Engineer	1	54
MIT/WHOI	S.M.	13	82
Total Degrees Granted		28	483

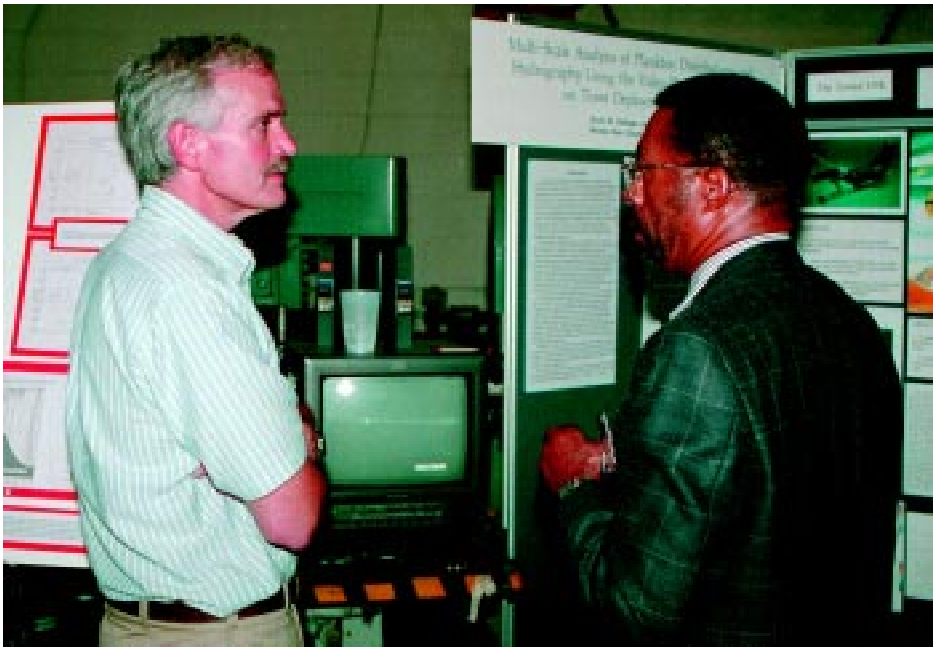
At the suggestion of current MIT/WHOI Joint Program students, Jake was honored with an office located in the Student Center in Clark Laboratory South. This office is reserved for Jake to use as he transitions into retirement over the next several years. MIT/WHOI Joint Program Alumni/ae Association President Christopher Tapscott (a 1979 graduate) announced establishment of the A. Lawrence "Jake" Peirson III Fund "to support graduate student needs such as travel to scientific meetings and workshops, travel to research cruises or field programs, use of special facilities, and small equipment purchases for thesis research, and the like."

Looking to the future, we are very pleased that Judy McDowell, Senior Scientist in the Biology Department and former J. Seward Johnson Chair as Education Coordinator, accepted appointment as Associate Dean effective January 1, 1997. Judy will concentrate her efforts with the graduate programs, particularly the MIT/WHOI Joint Program. This program's alumni/ae body increased this year with the award of fourteen doctoral degrees, one Electrical Engineer degree, and thirteen Master's Degrees. In fall 1996, a total of 138 graduate students, including 16 new students, registered for the Joint Program, and one was registered in the WHOI Graduate Program.

We are particularly proud of the high scholarly standards of our graduate students. This is reflected in many ways, including various awards and fellowships. This year our students were supported by fellowships from the National Science

Tom Kleindinst

Shane Cotter, a 1996 Summer Student Fellow from the University of North Carolina, describes the work he did in John Waterbury's lab on marine microbial physiology.



Shelley Lauzon

Office of Naval Research (ONR) Program Manager Chuck Luther, at right, discussed the summer student fellowship project with Scott Gallagher during the ONR 1996 site visit.

Foundation (4), Office of Naval Research (5), the Howard Hughes Medical Institute (2), a National Defense Science Education Grant (5), the National Atmospheric and Space Administration (1), the Department of Energy Global Change Program (1), the Ford Foundation (1), and the Environmental Protection Agency (5).

Former Director Paul Fye was a leader in establishing the MIT/WHOI Joint Program, and he was also one of the early and consistent supporters of Sea Education Association (SEA). Upon his retirement, friends established the Paul M. Fye Fellowship Endowment at WHOI. We recently allocated a portion of this endowment to expanding teaching experience for our graduate students. The first two Paul M. Fye Teaching Fellow appointments at SEA went to Joint Program biological oceanography students Linda Martin and Bonnie Ripley. This program expands our successful partnership with SEA: In summer 1996, for the sixth year, we embarked our incoming Joint Program class on a special 10-day SEA cruise as an introduction to sea-going oceanography and intensive "get acquainted with your classmates" experience.

WHOI summers are also enlivened by H. Burr Steinbach Visiting Scholars, Geophysical Fluid Dynamics Summer Study Program participants, undergraduate Summer Student Fellows, and Minority Trainees (see pages 42 and 43 for the 1996 lists). We welcomed 28 Summer Student Fellows and eight Minority Trainees in 1996. Three fellowships were supported by a new grant awarded to the Institution by the Office of Naval Research to increase participation of minorities in the marine sciences.

The long-standing philosophy of our Summer Student Fellow and Minority Trainee Programs was endorsed recently by a former WHOI Postdoctoral Scholar. I had the pleasure of being in the audience at the December 1996 AGU meeting when David A. L. Bercovici received the James B. Macelwane Medal for significant contributions to geophysical sciences by a young scientist of outstanding ability.

Bercovici received his Ph.D. in geophysics and space physics from UCLA in 1989 and then came to WHOI as a Postdoctoral Scholar. Following this appointment he joined the faculty at the University of Hawaii. Bercovici concluded his Macelwane Award acceptance speech with an eloquent call for expansion of undergraduate involvement in research. He said that "undergraduate research gives students firsthand experience in how to apply their education: It lets them witness and participate in the excitement of doing original science, of discovering something new, of learning how to solve heretofore unsolved problems." It is our privilege to participate in this process through the Summer Student Fellowship and Minority Traineeship Programs.

This year's Postdoctoral Scholars (see page 42), chosen from 140 applicants, continue in the fine tradition of earlier Postdoctoral Scholars exemplified by David Bercovici. Some 25 to 35 postdoctoral appointees (Scholars, Fellows, Investigators) supported by Institution funds or grants and contracts are in residence each year at the Institution. These early career scholars add significantly to the intellectual vitality of the Institution's research and education activities in many ways.

—John Farrington
Associate Director for Education
& Dean of Graduate Studies

Shelley Lauzon

Joint Program graduate student Susan Schultz Tapscott presented one of many gifts Associate Dean Jake Peirson received at a retirement party honoring his contributions to WHOI education programs.

R/V *Atlantis II* & DSV *Alvin*

Total Nautical Miles in 1996—9,882
Total Number of Alvin Dives—49

Atlantis II completed a long and illustrious WHOI career in 1996. Following a gala farewell on the WHOI pier in July, the ship was delivered to Shaula Navigation based in Boulder, CO, for rechristening as *Antares* and a planned new career as a fisheries research vessel in the north Pacific and Gulf of Alaska. From January through March, *Atlantis II* worked off the California coast, largely for bioturbation studies of deep-sea sediments. Nighttime work included bottom trawling, box coring, and multiple coring stations. Four dives were conducted off Catalina Island in March for engineering tests and evaluation. The two observers on one of these dives were Congressman Jerry Lewis (R-California), chair of the House Appropriations Committee that allocates funds to the National Science Foundation (NSF), and Neal Lane, Director of NSF. In April, *Atlantis II* and *Alvin* worked along the East Pacific Rise for biological community and light emission studies at hydrothermal vents and investigations involving osmium and carbon isotopes in vent systems. Following transit of the Panama Canal, the ship visited home port before traveling to Deep Water Dumpsite 106 in the New York Bight for bottom sampling, oxygen profile measurements, and other work that continued a long-term monitoring program at the dumpsite ecological observatory. *A-II*'s last WHOI cruise took the ship to the continental slope south of Woods Hole for benthic flux and sediment process studies. With these 1996 voyages, *Atlantis II* concluded 34 years of service, over one million miles sailed for science, and more than 8,000 days at sea—a record unequaled by any research vessel.

Chief scientists for 1996 were: C. Smith, University of Hawaii (Voyages 132-XXI, 7 dives, and 132-XXIII, 3 dives); D. Foster (132-XXII, 4 dives); A. Chave (132-XXV, 13 dives); F. Grassle, Rutgers University (133, 10 dives); and W. Martin (134, 12 dives).* (see footnote on page 28)

Atlantis II Farewell Celebration

Tom Kleindinst

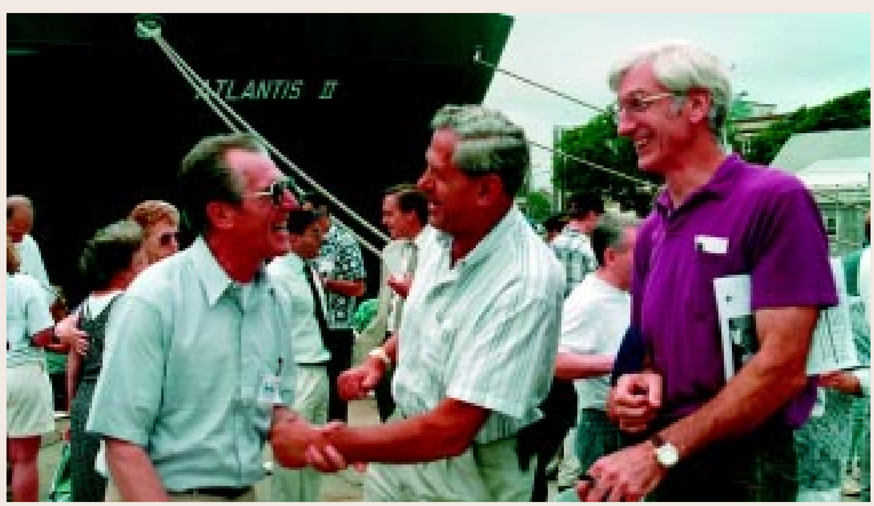
R/V Atlantis II *leaves the WHOI pier for the last time following a gala July celebration of the ship's 34 years of service to oceanography.*

Shelley Lauzon

The ship's sponsor, biologist Mary Sears, was presented a bouquet by her grand-nephew Freddie Denton.

Shelley Lauzon

Atlantis II*'s first WHOI master Emerson Hiller, right, and Gary Chiljean, the last master, were both at the celebration.*



Shelley Lauzon

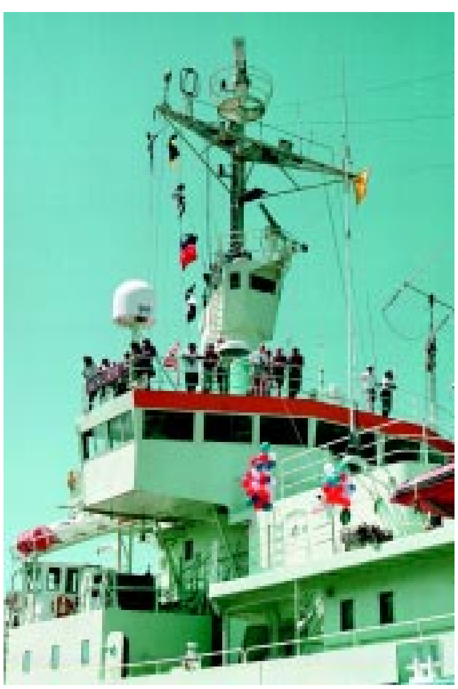
Three of the more than 200 Atlantis II *chief scientists, from left, Dave Ross, Bruce Warren, and Fred Sayles, swap sea stories at the* A-II *celebration.*

R/V *Knorr*

Total Nautical Miles in 1996—42,317

In January, *Knorr* steamed into Mombasa, Kenya, completing the World Ocean Circulation Experiment (WOCE) Indian Ocean hydrographic survey that had occupied all of the ship's 1995 cruise time. The following cruise, devoted to a SeaBeam, gravity, and magnetics survey of the Southwest Indian Ridge, set a WHOI distance record for a single cruise—10,832-miles. Moving to the Atlantic, *Knorr* scientists collected extensive basaltic rock samples on the southern Mid-Atlantic Ridge for work designed to determine the temporal variation of mantle composition and the extent of melting associated with magma generation. A May-June cruise was a component of the International Oceanographic Commission Contaminant Baseline Survey. It included collection of meteorological data, water samples, and conductivity/temperature/depth data with the objective of determining concentrations and distributions of trace metals and synthetic organic compounds at various levels in both South and North Atlantic waters. Research on the last (19th) leg of Voyage 145, from late June to early August, was devoted to investigating the relations between volcanic, tectonic, and hydrothermal activity at "Lucky Strike," a Mid-Atlantic Ridge segment influenced by the Azores Hotspot. Returning to WOCE service, *Knorr* engaged in a November voyage to collect hydrographic data in the southern and eastern subpolar North Atlantic for the Atlantic Circulation and Climate Experiment. During the last two 1996 cruises, Fronts and Atlantic Storm Tracks Experiment (FASTEX) scientists first tested instrumentation for the experiment and then participated in a field program designed to advance scientific understanding of eastern oceanic storm life cycles and their associated cloud and precipitation systems.

Chief scientists for 1996 were: B. Warren (Voyage 145-XIV-B); B. Walden (145-XV); J. Madsen, University of Delaware (145-XVI); P. Michael, University of Tulsa (145-XVII); G. Cutter, Old Dominion University (145-XVIII); D. Fornari (145-XIX); H. Swartz (147-I) M. McCartney and R. Curry (147-II); and O. Persson, NOAA (147-III, IV).*



Shelley Lauzon

R/V Knorr *returned to Woods Hole from Voyage 145 in August 1996 with flags flying.*

Kathy Patterson

Craig Marquette inspects tiedowns for a variety of buoys and other equipment loaded aboard Oceanus *for a summer cruise for the Coastal Mixing and Optics Experiment off Nantucket.*

R/V *Oceanus*

Total Nautical Miles in 1996—15,972

Oceanus worked in and out of Woods Hole in 1996 on a wide variety of investigations. The first cruise, which initiated the Department of Energy's Ocean Margins Program, included deployment of a large instrumented mooring array consisting of 17 subsurface moorings and three tripods. The array was recovered in May, redeployed in June, and recovered again in October. Four cruises in March, April, October, and December served Global Ocean Ecosystems (GLOBEC) scientists for biological sampling, collection of environmental and other data, and mooring deployment and recovery. An early May cruise was devoted to water sampling and anaylsis for studies of naturally occurring radionuclides in seawater. A second May cruise included collection of data on planktonic size spectra from Woods Hole into the Sargasso Sea as well as studies of iron limitation, picoplankton growth rates, and zooplankton grazing. The first of five 1996 *Oceanus* cruises for the Coastal Mixing and Optics Experiment began in early July with hydrographic and bottom surveys followed by deployment of surface moorings. After two short cruises for studies of microorganism growth in the deep sea and the seasonality of deep-sea benthic foraminifera, Coastal Mixing and Optics Experiment scientists returned to *Oceanus* to deploy a large array of instrumented moorings, several tripods, and a synthetic aperture sonar array. They also conducted a chemical tracer experiment, and recovered and redeployed instruments. A quick early September run to New Bedford's sheltered harbor in response to a hurricane warning, and a November shipyard visit rounded out a full schedule for *Oceanus*.

Chief scientists for 1996 were: G. Weatherly, Florida State University (Voyages 274, 277, 280, and 289); P. Wiebe (275); J. Irish (276, 291, and 294); M. Bacon (278); P. Chisholm, Massachusetts Institute of Technology (279); M. Levine, Oregon State University (281 and 288); Holger Jannasch (282); B. Corliss, Duke University (283); S. Lentz (284-I, II, III); S. Stanic, NRL (285); J. Ledwell (287); J. Kemp (290); and R. Pickart (292).*

*Gaps in cruise numbers generally indicate transits or short trips for engineering tests where no chief scientist was named.

Tom Kleindinst

The May meeting dinner brought, from left, Bill Kealy, John Bockstoce,Ellen Kealy, Breene Kerr, and Dorothy McGee together at Table 3.

Tom Kleindinst

Al Bradley, one of six 1996 Senior Technical Award recipients, explains the inner workings of the Autonomous Benthic Explorer *to Trustee George Moss, center, and Chairman of the Board Frank Snyder at a reception held during the May annual meetings.*

Trustees & Corporation Members

Tom Kleindinst

Ed Woollen and Dusty Howland chat during a break in the May annual meetings.

Tom Kleindinst

With Mr. and Mrs. Smith nearby, Bob Beardsley is congratulated during the May meetings by Director Bob Gagosian as the recipient of the first Walter A. and Hope Noyes Smith Chair.

Director's Council

As of December 31, 1996

Director's Council

Robert B. Gagosian
Director

James R. Luyten
Senior Associate Director and Associate Director of Research

John W. Farrington
Associate Director for Education and Dean of Graduate Studies

Paul Clemente
Associate Director for Finance and Administration

Richard F. Pittinger
Associate Director for Marine Operations

Charles D. Hollister
Vice President of the Corporation

Pamela C. Hart
Executive Assistant to the Director

Karen P. Rauss
Ombudsperson and EEO Officer

Shelley Lauzon

Alvin group members, from left, BLee Williams, George Meier, and Pat Hickey place the sub's personnel sphere in its cradle for overhaul operations.

Scientific & Technical Staff

Applied Ocean Physics and Engineering Department

George V. Frisk
Department Chair and Senior Scientist

Lane J. Abrams
Research Engineer

John J. Akens
Senior Engineer

Ben G. Allen
Research Engineer

Richard I. Arthur, Jr.
Engineer II

Thomas C. Austin
Senior Engineer

Robert D. Ballard
Senior Scientist

Alessandro Bocconcelli
Research Associate

Erik J. Bock
Associate Scientist

Andrew D. Bowen
Research Engineer

Martin F. Bowen
Research Associate

Albert M. Bradley
Senior Engineer

Neil L. Brown
Principal Engineer

Cheryl Ann Butman
Associate Scientist

Josko Catipovic
Associate Scientist

Dezhang Chu
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Assistant Scientist

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Research Associate

Timothy F. Duda
Associate Scientist

Alan R. Duester
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Calvert F. Eck
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James B. Edson
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Dudley B. Foster
Research Associate

Janet J. Fredericks
Information Systems Associate II

Lee E. Freitag
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Denzel E. Gleason
Research Associate

Robert G. Goldsborough
Research Engineer

Mark A. Grosenbaugh
Associate Scientist and J. Seward Johnson Chair as Education Coordinator

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Engineer II

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Research Engineer

Alan A. Hinton
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Jonathan C. Howland
Research Engineer

Kelan Huang
Research Engineer

James D. Irish
Research Specialist

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Research Engineer

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Stephen P. Liberatore
Research Engineer

James F. Lynch
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Assistant Scientist

Wade R. McGillis
Assistant Scientist

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Roger P. Stokey
Research Engineer

Dajun Tang
Associate Scientist

Xiaoou Tang
Postdoctoral Investigator

Eugene A. Terray
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Fredrik T. Thwaites
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Senior Engineer

Keith von der Heydt
Senior Engineer

Barrie B. Walden
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Susan Wetzel
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Associate Scientist

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Senior Scientist

Warren E. Witzell, Jr.
Engineer II

Dana R. Yoerger
Associate Scientist

Jia Q. Zhang
Engineer II

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Research Associate

Donald M. Anderson
Senior Scientist and Stanley W. Watson Chair for Excellence in Oceanography

Carin J. Ashjian
Assistant Scientist

Richard H. Backus
Scientist Emeritus

Stephen M. Bollens
Assistant Scientist

David A. Caron
Associate Scientist

Hal Caswell
Senior Scientist

Alexander M. Chekalyuk
Visiting Investigator

Nathaniel Corwin
Research Specialist

James E. Craddock
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Associate Scientist

Cabell S. Davis III
Associate Scientist

Mark R. Dennett
Research Associate

Paul V. Dunlap
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Scott M. Gallager
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Dale D. Goehringer
Research Associate

Joel Goldman
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J. Frederick Grassle
Adjunct Scientist

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Information Systems Specialist

Mark E. Hahn
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George R. Hampson
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G. Richard Harbison
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Robert Haselkorn
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Sibel I. Karchner
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Bruce A. Keafer
Research Associate
Dale F. Leavitt
Research Associate
Frank J. Mather III
Scientist Emeritus
Judith E. McDowell
Senior Scientist and Sea Grant Coordinator
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Research Associate
Michael J. Moore
Research Specialist
Lauren S. Mullineaux
Associate Scientist
Michael G. Neubert
Assistant Scientist
Robert J. Olson
Associate Scientist
Jesús G. Pineda
Assistant Scientist
John H. Ryther
Scientist Emeritus
Howard L. Sanders
Scientist Emeritus
Rudolf S. Scheltema
Scientist Emeritus
Mary Sears
Scientist Emeritus
Heidi M. Sosik
Assistant Scientist
John J. Stegeman
Senior Scientist
Craig D. Taylor
Associate Scientist
John M. Teal
Scientist Emeritus
Peter L. Tyack
Associate Scientist
Frederica W. Valois
Research Specialist
Jeffrey R. Van Keuren
Postdoctoral Investigator
John B. Waterbury
Associate Scientist
William A. Watkins
Oceanographer Emeritus
David S. White
Postdoctoral Investigator
Peter H. Wiebe
Senior Scientist and Adams Chair
Carl O. Wirsen, Jr.
Research Specialist
Bruce R. Woodin
Research Associate
Erik R. Zettler
Research Associate

Geology and Geophysics Department

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Department Chair and Senior Scientist
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Senior Scientist
Wolfgang Bach
Postdoctoral Investigator
William A. Berggren
Senior Scientist
Jerzy S. Blusztajn
Research Associate
Carl O. Bowin
Scientist Emeritus
James E. Broda
Research Specialist
Wilfred B. Bryan
Senior Scientist
Elizabeth Bunce
Scientist Emeritus
Kenneth D. Burrhus
Research Specialist
Johnson R. Cann
Adjunct Scientist
Alan D. Chave
Senior Scientist
Peter D. Clift
Assistant Scientist
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Research Associate
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Senior Scientist and J. Seward Johnson Chair as Education Coordinator
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Senior Scientist and W. Van Alan Clark, Jr., Chair for Excellence in Oceanography
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Research Associate
Joanne C. Donoghue
Engineer I
Neal W. Driscoll
Assistant Scientist
Katherine Ellins
Research Specialist
Kenneth O. Emery
Scientist Emeritus
Robert L. Evans
Assistant Scientist
John I. Ewing
Scientist Emeritus
Daniel J. Fornari
Associate Scientist
Alan R. Gagnon
Research Associate
Graham S. Giese
Research Specialist
Kathryn M. Gillis
Associate Scientist
Tracey Gregg
Postdoctoral Scholar
Stanley R. Hart
Senior Scientist and Columbus O'Donnell Iselin Chair for Excellence in Oceanography

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Senior Scientist
James G. Hirth
Assistant Scientist
W. Steven Holbrook
Associate Scientist
Susumu Honjo
Senior Scientist
Emily E. Hooft
Postdoctoral Investigator
Susan E. Humphris
Research Specialist
Lloyd D. Keigwin, Jr.
Senior Scientist
Peter B. Kelemen
Associate Scientist
Grant M. Kent
Assistant Scientist
Richard A. Krishfield
Research Associate
Graham D. Layne
Research Specialist
Scott J. Lehman
Associate Scientist
Peter C. Lemmond
Research Associate
Jian Lin
Associate Scientist
George P. Lohmann
Associate Scientist
Steven J. Manganini
Research Specialist
Daniel McCorkle
Associate Scientist
Ann P. McNichol
Research Specialist
Peter S. Meyer
Adjunct Scientist
Maria Mutti
Visiting Investigator
Richard D. Norris
Associate Scientist
Delia W. Oppo
Associate Scientist
Dorinda R. Ostermann
Research Associate
John C. Peden
Information Systems Associate II
Gregory E. Ravizza
Associate Scientist
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Scientist Emeritus
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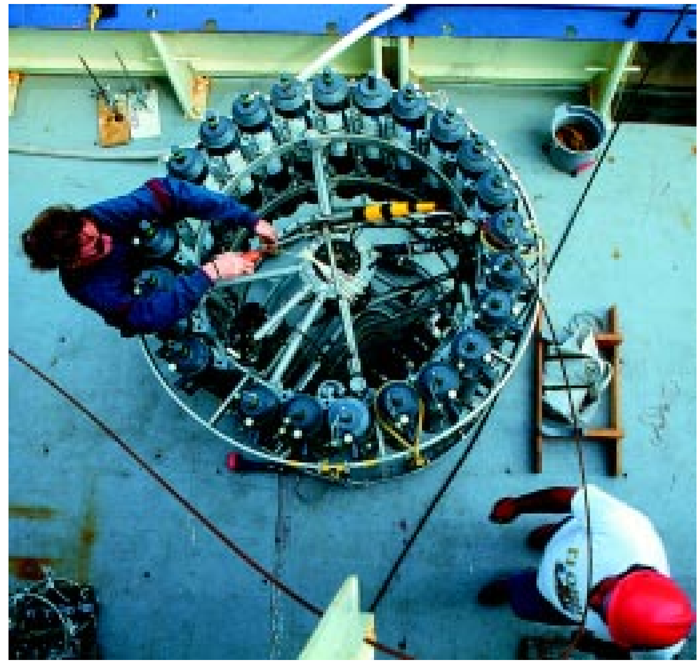
Senior Research Specialist
Hans Schouten
Senior Scientist
Yang Shen
Assistant Scientist
Nobumichi Shimizu
Senior Scientist and W. Van Alan Clark, Sr., Chair for Excellence in Oceanography
Deborah K. Smith
Associate Scientist
Wayne D. Spencer
Research Associate
Ralph A. Stephen
Senior Scientist


Tom Kleindinst

Laura Stein rigs a conductivity/temperature/depth rosette sampler in preparation for an Oceanus *cruise in summer 1996.*


Craig Dickson

Alvin *pilot Dudley Foster logged his 500th dive on March 21, 1996, during* Alvin*'s 3,059th plunge.*

Scientific & Technical Staff

Stephen A. Swift
Research Specialist

Maurice A. Tivey
Associate Scientist

Brian E. Tucholke
Senior Scientist

Elazar Uchupi
Scientist Emeritus

Richard P. Von Herzen
Scientist Emeritus

Karl F. Von Reden
Research Specialist

Christopher R. Weidman
Postdoctoral Investigator

Cecily J. Wolfe
Assistant Scientist

Frank B. Wooding
Research Specialist

Marine Chemistry and Geochemistry Department

Michael P. Bacon
Department Chair and Senior Scientist

Lary A. Ball
Research Associate

Peter G. Brewer
Adjunct Scientist

Ken O. Buesseler
Associate Scientist

Cynthia L. Chandler
Information Systems Associate I

Maureen H. Conte
Assistant Scientist

Michael D. DeGrandpre
Adjunct Scientist

Werner G. Deuser
Scientist Emeritus

Geoffrey Eglington
Adjunct Scientist

Lorraine Eglinton
Research Associate

Timothy I. Eglinton
Associate Scientist

Judith Fenwick
Research Associate

Alan P. Fleer
Research Associate

Roger François
Associate Scientist

Nelson M. Frew
Senior Research Specialist

David M. Glover
Research Specialist

Catherine Goyet
Associate Scientist

Terence R. Hammar
Research Associate

Christine Hammond
Information Systems Associate II

Richard J. Healy
Information Systems Associate I

Xicheng Hu
Postdoctoral Investigator

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Scientist Emeritus

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Research Associate

Mark D. Kurz
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Hugh D. Livingston
Senior Research Specialist

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Information Systems Associate I

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Research Associate

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Scientist Emeritus

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Information Systems Associate II

Geoffrey P. Allsup
Engineer II

Steven P. Anderson
Assistant Scientist

Frank Bahr
Research Associate

Mark F. Baumgartner
Research Associate

Tom Kleindinst

Martin Bowen wires a junction box for LEO-15, the Long-Term Ecosystem Observatory installed in 15 meters of water off the coast of New Jersey in August 1996.

Robert C. Beardsley
Senior Scientist and Walter A. and Hope Noyes Smith Chair

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Associate Scientist

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Research Specialist

Kenneth H. Brink
Senior Scientist

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Ruth G. Curry
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Jerome P. Dean
Oceanographer Emeritus

Nick P. Fofonoff
Scientist Emeritus

David M. Fratantoni
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Nancy R. Galbraith
Information Systems Associate II

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Associate Scientist

Karl R. Helfrich
Associate Scientist

Nelson Hogg
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Senior Engineer

Rui X. Huang
Associate Scientist

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Information Systems Associate II

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Postdoctoral Investigator

Joanna E. Muench
Postdoctoral Investigator

W. Brechner Owens
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Richard E. Payne
Research Associate

Joseph Pedlosky
Senior Scientist and Henry L. and Grace Doherty Oceanographer

Robert S. Pickart
Associate Scientist

Albert J. Plueddemann
Associate Scientist

Kurt L. Polzin
Assistant Scientist

Lawrence J. Pratt
Associate Scientist

James F. Price
Senior Scientist and J. Seward Johnson Chair as Education Coordinator

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Assistant Scientist

Roger M. Samelson
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Senior Scientist and W. Van Alan Clark, Sr., Chair for Excellence in Oceanography

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Information Systems Associate II

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Christine M. Wooding
Research Associate

Jiayan Yang
Assistant Scientist

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Director and Associate Scientist

Jesse H. Ausubel
Adjunct Scientist

Daniel A. Curran
Senior MPOM Fellow

Arthur G. Gaines, Jr.
Research Specialist

Porter Hoagland III
Research Associate

Denise M. Jarvinen
Assistant Scientist

Di Jin
Assistant Scientist

Hauke L. Kite-Powell
Research Specialist

Woollcott Smith
Senior MPOM Fellow

John H. Steele
Scientist Emeritus

Rinehart Coastal Research Center

Bruce W. Tripp
Research Associate

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Information Systems Specialist

Eric Cunningham
Information Systems Associate I

Roger A. Goldsmith
Information Systems Specialist

Carolyn S. Hampton
Information Systems Associate II

John Krauspe
Information Systems Associate II

William S. Little, Jr.
Information Systems Specialist

Andrew R. Maffei
Information Systems Specialist

Scott A. McIntyre
Information Systems Associate II

Elizabeth Owens
Information Systems Associate I

George Power
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Warren J. Sass
Information Systems Specialist

Patricia Savage
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MBL/WHOI Library

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Information Systems Associate I

Stephen R. Gegg
Information Systems Associate II

Colleen D. Hurter
Information Systems Associate II

Margaret A. Rioux
Information Systems Associate II

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Paul R. Bouchard
John N. Bouthillette
Anne C. Canaday
Rodney M. Catanach
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Michele M. Connor
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Susan M. Grieve
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Jeannine Sisson
John D. Sisson
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Nancy Y. Trowbridge
Karlen A. Wannop
W. David Wellwood
Judith A. White
William J. Williams
Jonathan Woodruff
Martin C. Woodward

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Marjorie K. Clancy
Nancy J. Copley
Mary Ann Daher
Linda H. Davis
Matthew R. Dennett
Sheri D. DeRosa
Nancy A. Dimarzio
Diana G. Franks
Damon P. Gannon
Andrew P. Girard
Linda Hare
Erich F. Horgan
Terrance J. Howald
Elizabeth Howarth
Stephanie Innis
Anne L. Jesser
David M. Kulis
Bruce A. Lancaster
Ethel F. LeFave
Jane E. Marsh
Susan W. Mills
Zofia J. Mlodzinska
Stephen A. Moffett
Stephen J. Molyneaux
Dawn M. Moran
Nancy Perkins
Jane M. Ridge
David R. Schlezinger
Daniel W. Smith
Lisa G. Taylor


Tom Kleindinst

Peter Wiebe accepted the first Adams Chair appointment at the May annual meetings of the Corporation and Trustees.

Geology and Geophysics Department

John W. Bailey
Pamela R. Barrows
Anthony H. Berry
John Billings
S. Thompson Bolmer
Michael G. Braun
Katherine W. Brown
Jennifer E. Burns
Joshua Chessman
Karen L. Coluzzi
Jennifer Crew
Michael J. Dalton
Lori A. Dolby
David L. DuBois
Kathryn L. Elder
Pamela V. Foster
C. Eben Franks
Parker Hackett
Robert E. Handy
Seth H. Hitchings
Daniel Hutton
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Karen Littlefield
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Kara M. Merkle
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Gregory E. Moon
Tracey Morin
Teresa A. Norris
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Anita M. Palm
Julianne Palmieri
Michael J. Railey
May A. Reed
Ellen Roosen
Kimberly A. Sapp
Shirley J. Waskilewicz
Christopher Zafiriou
Luping Zou


Phil Alatalo

Scientists and crew swing a conductivity/temperature/depth rosette sampler into action during Oceanus *Voyage 279 in summer 1996.*

Marine Chemistry and Geochemistry Department

John E. Andrews III
Ellen M. Bailey
Rebecca A. Belastock
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L. Susan Brown-Leger
Laurie E. Christman
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Martha A. Delaney
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William M. Ostrom
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Daniel J. Torres
Toshiko T. Turner
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Bryan S. Way
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Grants Administrator II

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Senior Development Officer

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Sr. Procurement Representative

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Department Administrator, Biology

Kathleen P. LaBernz
Human Resources Manager

Dennis Lander
Network Group Leader

William N. Lange
Research Specialist

Shelley M. Lauzon
Senior News Officer

Tom Kleindinst

Harvard benthic biologist Ruth Turner, an expert on wood-boring mollusks was named the third Woman Pioneer in Oceanography at a WHOI Women's Committee seminar in April 1996. The seminar featured tributes from several colleagues including Judy McDowell, who said, "Her enthusiasm for discovery is contagious, and generations of her students and colleagues have benefited from their friendships with Ruth. She is the complete scholar."

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Payroll Manager

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Director of Major Gifts

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MBL/ WHOI Library Director

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Maeve Thurston
Dacia Tucholke
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Suzanne Volkmann
Margaret M. Walden
Sarah B. Wheeler
Robert Wilson

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3rd Mate, R/V Atlantis

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Master, R/V Oceanus

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Submersible Operations Coordinator

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Assistant Facilities Manager

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Master, R/V Atlantis

Joseph L. Coburn, Jr.
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Arthur D. Colburn III
Master, R/V Knorr

Hugh D. Curran
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Craig D. Dickson
2nd Mate, R/V Atlantis

Robertson P. Dinsmore
Marine Operations Consultant

Richard S. Edwards
Port Captain

Kevin C. Fisk
1st Assistant Engineer, R/V Atlantis

Daniel J. Fornari
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Richard E. Galat
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Robert J. Grieve
Deep Submergence Vehicle Pilot

Matthew C. Heintz
Deep Submergence Vehicle Pilot

J. Patrick Hickey
Expedition Leader and Deep Submergence Vehicle Pilot

Hartley Hoskins
Research Associate

Robert L. Joyce
Distribution Manager

Vicky Cullen

The Oceanus *crew deployed these tall towers for researchers from the University of Washington Applied Physics Laboratory and the Naval Research Laboratory in the summer of 1996.*

Photos by Tom Kleindinst

The 1996 Vetlesen Award, for a variety of exceptional contributions to the WHOI community over a long period of time, went to Dave Simoneau, left photo. Judy Fenwick received the Linda Morse-Porteous Award for leadership, mentoring, dedication to work, and involvement in the WHOI community. In the righthand photo, R/V Knorr *master A.D. Colburn talks with Senior Associate Director and Director of Research Jim Luyten following acceptance of the Penzance Award on behalf of* Knorr's *crew. This award is based on exceptional performance, WHOI spirit, and contributions to the personal and professional lives of Institution staff. The awards were presented at the annual Employee Recognition Celebration in September.*

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J. Douglas Mayer
3rd Mate, R/V Knorr
William E. McKeon
Facilities Manager
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2nd Mate, R/V Oceanus
Donald A. Moller
Marine Operations Coordinator
Patrick S. Mone
2nd Assistant Engineer, R/V Atlantis
Theophilus Moniz III
Marine Engineer
Richard F. Morris
Chief Engineer, R/V Oceanus
David I. Olmsted
Boat Operator, R/V Asterias
Patricia L. Pasanen
Chief Mate, R/V Atlantis
Terrence M. Rioux
Diving Safety Officer
Michael W. Schmitt
1st Assistant Engineer, R/V Knorr
George P. Silva
Chief Mate, R/V Knorr
Laura W. Stein
Research Assistant III
John K. Sweet, Jr.
2nd Mate, R/V Knorr
Wayne A. Sylvia
3rd Assistant Engineer, R/V Knorr
Anne Toal
3rd Assistant Engineer, R/V Atlantis
Barrie B. Walden
Manager, Operational Science Services
Stephen Walsh
Chief Engineer, R/V Knorr
Ernest C. Wegman
Port Engineer
Robert L. Williams
Deep Submergence Vehicle Pilot

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Kent D. Sheasley
Jennifer J. Sirois
Scott A. Sirios
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Robert G. Spenle
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Laura W. Stein
Jeffrey M. Stolp
William B. Strickrott
William R. Tavares, Jr.
Anne M. Taylor
Kevin D. Thompson
Philip M. Treadwell
Rachelle L. Tucholke
Randy Turner
Herman Wagner
Robert A. Waters
Robert Wichterman
Michael W. Williams
Kathleen D. Wilson
Bonnie L. Woodward
Carl O. Wood
Jennifer Wysocki

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Kendall B. Bohr
Eleanor M. Botelho
Marilynn B. Brooks
Jerome M. Cotter
Edward Broderick
Jerome P. Dean
Werner G. Deuser
Kenneth D. Fairhurst
Graham S. Giese
Beverley A. Harper
David L. Hayden
Paul C. Howland
Susan Kadar
Ann Martin
Michael J. Palmieri, Jr.
A. Lawrence Peirson III
Subramaniam D. Rajan
William J. Schmitz, Jr.
Toshiko T. Turner
Earl M. Young, Jr.

1996 Degree Recipients

Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program in Oceanography/Applied Ocean Science and Engineering

Doctor of Philosophy

Einat Aharonov
BSc, Tel-Aviv University, Israel
Special Field: *Marine Geology and Geophysics*
Dissertation: *Solid-Fluid Interactions in Porous Media: Processes that Form Rocks*

Linda A. Amaral-Zettler
BS, Brown University
Special Field: *Biological Oceanography*
Dissertation: *A Molecular Approach to Questions in the Phylogeny and Life History of Planktonic Sarcodines*

Jamie M. Anderson
BSME, University of California, San Diego
SM, MIT/WHOI Joint Program
Special Field: *Oceanographic Engineering*
Dissertation: *Vorticity Control for Efficient Propulsion*

John R. Buck
SB, Massachusetts Institute of Technology
SM, MIT/WHOI Joint Program
Special Field: *Oceanographic Engineering*
Dissertation: *Single Mode Excitation in the Shallow Water Acoustic Channel Using Feedback Control*

Maureen E. Clayton
BS, Eckerd University
Special Field: *Biological Oceanography*
Dissertation: *Lipoproteins and Heat Shock Proteins as Measures of Reproductive Physiology in the Soft Shell Clam* Mya arenaria

Javier G. Escartin
Licence, University of Barcelona, Spain
Maitrise, Perpignan University, France
Special Field: *Marine Geology and Geophysics*
Dissertation: *Ridge Segmentation, Tectonic Evolution and Rheology of Slow-Spreading Oceanic Crust*

Garrett T. Ito
BA, Colorado College
Special Field: *Marine Geology and Geophysics*
Dissertation: *Gravity Modelling of the Temperature Anomaly and Flow Pattern of the Galápagos Hotspot Beneath the Galápagos Spreading Center*

Stacy L. Kim
BS, University of California, Los Angeles
Special Field: *Biological Oceanography*
Dissertation: *Larval Dispersal Between Hydrothermal Vent Habitats*

Joseph H. Lacasce
AB, Bowdoin College
MA, The John Hopkins University
Special Field: *Physical Oceanography*
Dissertation: *Baroclinic Vortices Over a Sloping Bottom*

Bingian Ni
BS, Peking University, People's Republic of China
MS, Peking University, People's Republic of China
Special Field: *Physical Oceanography*
Dissertation: *Temporal, Spatial, and Pulse Instabilities of the Gulf Stream*

Young-Gyu Park
BS, Seoul National University, Korea
MS, Seoul National University, Korea
Special Field: *Physical Oceanography*
Dissertation: *Rotating Convection Driven by Differential Bottom Heating and Its Application*

Xiaoou Tang
BS, University of Science and Technology, People's Republic of China
MS, University of Rochester
Special Field: *Oceanographic Engineering*
Dissertation: *Transform Image Classification*

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BA, Kalamazoo College
SM, MIT/WHOI Joint Program
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Dissertation: *An Integrated Approach to Surface and Volume Scattering in Ocean Waveguides*

Doctor of Science

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Dissertation: *Planktonic Size Spectra in the Marine Environment*

Electrical Engineer

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Dissertation: *Adaptive Estimation of Acoustic Normal Modes*

Master of Science

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Dissertation: *Planktonic Foraminifera in the Sea of Okhotsk: Population and Stable Isotopic Analysis from a Sediment Trap*

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Dissertation: *Marine Sedimentary Organic Matter: Delineation of Marine and Terrestrial Sources through Radiocarbon Dating and the Role of Organic Sulfur in Early Petroleum Generation*

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Dissertation: *Global Barotropic Variability of the Ocean in Response to Atmospheric Forcing Based on Multichannel Regression and Dalman Filter*

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Dissertation: *Water Mass Distribution and Polar Front Structure in the Southwestern Barents Sea*

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Dissertation: *The History of Plutonium and Cesium 137 Contamination of the Ob River Delta Sediments*

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Dissertation: *The Adjustment of Barotropic Currents at the Shelf Break to a Sharp Bend in the Shelf Topography*

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Master of Science in Oceanography

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Joint Program student Elizabeth Minor repairs the sample probe on the mass spectrometer she uses to obtain molecular-level information on lipids, sugars, proteins, and other natural and synthetic substances in oceanic organic matter.

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Geochemistry of Hydrothermal Processes Postdoctoral Scholar

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J. Seward Johnson Postdoctoral Scholar

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J. Seward Johnson Postdoctoral Scholar

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Geophysical Fluid Dynamics Participants

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Sean Avent
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Kevin S. Blake
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Marie-Christine Chevalier
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From left, John Colosi, Peter Clift, Jeff Simmen of the Office of Naval Research (ONR), and George Frisk (blue shirt) enjoy the poster session held in the Clark South high bay during the ONR 50th anniversary year WHOI site visit.

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Financial Statements

If 1995 was a year of change in the financial areas of Woods Hole Oceanographic Institution, then 1996 can be characterized as a year of financial strength and stability. Not only was the largest unrestricted operating surplus in recent memory recorded, but financial reserves were also further strengthened, completing a task begun in 1995. Although a strong caution flag continues to fly on the basis of anticipated declines in federal support for basic research in future years, the Institution's strong financial position gives it stability against such declines.

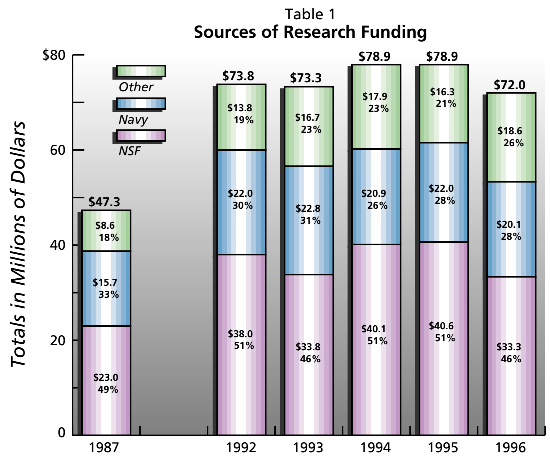
The Institution's unrestricted surplus was largely produced by fulfillment of Capital Campaign pledges, the sale of *Atlantis II*, and bridge support for scientists amounting to less than half the amount budgeted. During 1996 we maintained a healthy cash position, remained debt free, and experienced minimum personnel turnover.

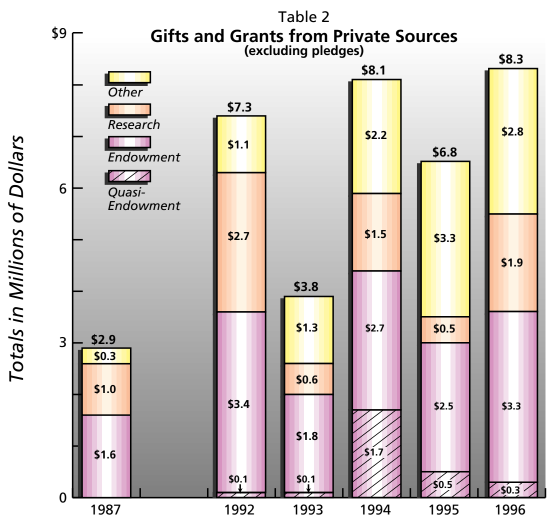
Thanks to strong financial markets and the Capital Campaign, the endowment grew 14 percent, net of distributions, ending 1996 with a market value of $189 million compared to $166 million in 1995. In addition, the Institution's retirement plan assets grew in excess of liabilities, no Institution contribution was required during 1996, and none is foreseen in the near future. Despite strong financial performance, the Investment Committee and the Trustees of the Retirement Trust continue to closely monitor asset allocations in order to preserve and increase the real value of the endowment and the retirement trust.

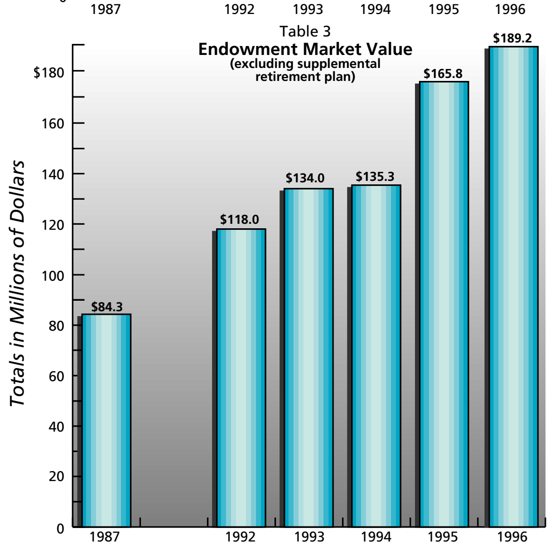
As anticipated, federal support for research continued to decline and finished the year at 90 percent of budget. Part of the decline can be attributed to *Atlantis II* and *Alvin* being out of service for a large part of the year. Although government research was down, Institution scientists made up for much of the decline through nongovernment research, ending the year with total sponsored revenue at 97 percent of budget.

The Institution's labor base, against which fringe benefits and overhead are recovered, finished the year on budget, and actual overhead expenses were slightly below budget, resulting in the second straight year that overhead was fully recovered. We not only closely monitor spending levels, but also remain in full compliance with all federal regulations: In 1996, for the second straight year, all government audits were current.

Sponsored research continues to be the primary source of Institution revenue, comprising 85 percent of total operating revenues (see Table 1 for an overview of Institution sources of research revenue).







Jayne Doucette

In 1996, gifts and grants from private sources totaled $8.3 million, compared to $6.8 million in 1995 and $8.1 million in 1994. Outstanding pledges at the end of 1996 were $6.4 million as compared to $4.7 million in 1995 and $2.1 million in 1994. (Note: For financial statement purposes, only unconditional pledges over $10,000 are booked as revenue). At the end of 1996, the Capital Campaign goal was exceeded with a total of $54 million raised.

During 1996, the Institution established an ad hoc Trustee Committee on Business Development and began negotiations on a traveling museum exhibit, a documentary, and the first *Alvin* model. Negotiations were successful, and in the early part of 1997 all of these projects were underway. In addition, the Massachusetts Biotechnology Research Institute was hired as technology transfer agent. The success of the early business development activities should enhance Institution outreach activities as well as produce alternative sources of revenue in future years.

Although the pace of the decline in government support for research has been slower than first anticipated, the decline is expected to continue and become steeper after the year 2000. In addition to identifying alternative sources of revenue, Institution management has adopted a strategy, in conjunction with a formal strategic plan, to increase efficiency in future years while keeping the overhead rate down and improving service. It is management's goal to be in a position to respond to anticipated declines in government spending and at the same time maintain and improve service and stability.

You are invited to review the Institution's audited financial statements and accompanying notes presented on the following pages.

—Paul Clemente, Associate Director for Finance & Administration

Statements of Financial Position

as of December 31, 1996
(with comparative totals for 1995)

	1996	1995
Assets:		
Cash and cash equivalents:		
Operating	$ 22,361,746	$ 10,704,207
Sponsored research prepayment pool	5,015,903	2,999,081
Endowment	10,544,079	8,095,236
	37,921,728	21,798,524
Accrued interest and dividends	1,390,377	792,039
Reimbursable costs and fees:		
Billed	2,546,825	5,241,352
Unbilled	2,223,422	1,442,220
Other receivables	653,285	565,693
Pledges receivable	6,371,351	4,746,722
Inventory	607,533	630,208
Deferred charges and prepaid expenses	745,955	1,146,129
Investments	183,713,682	167,449,483
Other current assets	1,650,872	826,200
Total current assets	237,825,030	204,638,570
Property, plant and equipment:		
Land, buildings and improvements	44,241,797	43,122,971
Vessels and dock facilities	2,582,769	8,916,264
Laboratory and other equipment	9,821,022	10,081,754
Work in process	117,447	10,264
	56,763,035	62,131,253
Accumulated depreciation	(30,062,749)	(32,910,055)
Net property, plant and equipment	26,700,286	29,221,198
Remainder trusts	1,193,720	951,173
Total assets	$265,719,036	$234,810,941
Liabilities:		
Accounts payable and other liabilities	8,957,647	8,508,284
Accrued payroll and related liabilities	4,589,116	4,478,099
Accrued supplemental retirement benefits	6,060,000	5,480,325
Deferred revenue and refundable advances (research)	10,489,415	7,151,900
Deferred fixed rate variance	1,717,821	989,384
Total liabilities	31,813,999	26,607,992

	Unrestricted		Temporarily Restricted	Permanently Restricted	1996	1995
Net assets:						
Undesignated	$742,631	$7,773,411			8,516,042	7,043,825
Designated	2,704,519				2,704,519	2,062,581
Plant & facilities	30,521,179	34,207			30,555,386	30,656,153
Education	287,844	2,617,606			2,905,450	2,636,557
Endowment and similar funds	50,114,644	112,158,552	$26,950,444		189,223,640	165,803,833
Total net assets	$84,370,817	$122,583,776	$ 26,950,444		233,905,037	208,202,949
Total liabilities and net assets					$265,719,036	$234,810,941

The accompanying notes are an integral part of the financial statements.

Statements of Cash Flows

for the year ended December 31, 1996
(with comparative totals for 1995)

	1996	1995
Cash flows from operating activities:		
Total change in net assets	$ 25,702,088	$ 33,334,059
Adjustments to reconcile increase in net assets to net cash provided by operating activities:		
Depreciation	2,895,184	2,833,288
Gain on disposition of property and equipment	(955,000)	-
Net realized and unrealized (gain) loss on investments	(20,922,716)	(29,303,708)
(Increase) decrease in:		
Accrued interest and dividends	(598,338)	327,312
Reimbursable costs and fees:		
Billed	2,694,527	(1,555,508)
Unbilled	(781,202)	459,782
Other receivables	(87,592)	202,812
Pledges receivable	(1,624,629)	(2,646,658)
Inventories	22,675	(31,860)
Deferred charges and prepaid expenses	400,174	(97,774)
Deferred fixed rate variances	728,437	1,463,730
Other current assets	(824,672)	(826,200)
Remainder trusts	(242,547)	(788,795)
Increase (decrease) in:		
Accounts payable and other liabilities	449,363	4,193,202
Accrued payroll and related liabilities	111,017	(300,854)
Deferred revenue	3,337,515	3,258,697
Accrued supplemental retirement benefits	579,675	913,221
Net cash provided by operating activities	10,883,959	11,434,746
Cash flows from investing activities:		
Capital expenditures:		
Additions to property and equipment	(1,874,263)	(2,527,485)
Proceeds from disposals of property and equipment	2,455,000	225,922
Endowment:		
Proceeds from the sale of investments	144,129,484	111,018,766
Purchase of investments	(139,470,976)	(115,687,717)
Net cash provided by (used) by investing activities	5,239,245	(6,970,514)
Net increase (decrease) in cash and cash equivalents	16,123,204	4,464,232
Cash and cash equivalents, beginning	21,798,524	17,334,292
Cash and cash equivalents, ending	$ 37,921,728	$ 21,798,524

The accompanying notes are an integral part of the financial statements.

Financial Statements

Statement of Activities

for the year ended December 31, 1996
(with comparative totals for 1995)

	Unrestricted Operating	Unrestricted Sponsored Research	Temporarily Restricted	Permanently Restricted	1996	1995
Operating:						
Revenues:						
Fees	$ 444,371				$ 444,371	$ 589,396
Sponsored research:						
Government		$60,468,082			60,468,082	71,894,988
Nongovernment		11,503,622			11,503,622	7,022,791
Sponsored research assets released to operations	71,971,704	(71,971,704)				
Education:						
Tuition	2,690,773				2,690,773	2,547,731
Endowment income	2,588,182		$ 709,972		3,298,154	3,139,361
Gifts and transfers			467,857		467,857	464,538
Education funds released from restriction	858,902		(858,902)		-	-
Investment return designated for current operations	1,816,839				1,816,839	1,483,010
Contributions and gifts	2,383,660		1,794,913	$ 3,155,585	7,334,158	8,107,743
Rental income	680,800				680,800	639,806
Communication & Publications	201,607				201,607	241,003
Other	752,100	-	-	-	752,100	64,483
Total revenues	84,388,938	-	2,113,840	3,155,585	89,658,363	96,194,850
Expenses:						
Sponsored research:						
National Science Foundation	33,278,264				33,278,264	40,580,767
United States Navy	20,100,408				20,100,408	21,946,891
Subcontracts	5,668,390				5,668,390	3,581,893
Advanced Research Projects Agency	1,668,951				1,668,951	3,202,289
National Oceanic & Atmospheric Administration	2,068,189				2,068,189	2,333,449
Department of Energy	1,111,832				1,111,832	1,747,905
United States Geological Survey	673,226				673,226	400,521
Other	7,402,444				7,402,444	5,124,064
Education:						
Faculty expense	1,964,120				1,964,120	1,946,069
Student expense	1,199,730				1,199,730	1,006,342
Postdoctoral programs	438,081				438,081	367,642
Sponsored research	209,718				209,718	-
Other	980,822				980,822	571,678
Development	1,334,767				1,334,767	1,086,948
Business development	88,752				88,752	-
Rental expenses	382,142				382,142	355,667
Communication & Publications	655,941				655,941	711,052
Unsponsored programs	1,818,358				1,818,358	992,272
Other expenses	2,691,031	-	-	-	2,691,031	2,575,365
Total expenses	83,735,166	-	-	-	83,735,166	88,530,814
Change in net assets from operating activities	653,772	-	2,113,840	3,155,585	5,923,197	7,664,036
Nonoperating income:						
Ship overhaul						2,635
Investment return in excess of amounts designated for sponsored research, education and current operations	10,282,965		9,596,702		19,879,667	27,572,686
Nonoperating expenses:						
Nonoperating research and education expense					-	1,801,887
Ship overhaul					-	2,635
Other nonoperating expenses	100,776	-	-	-	100,776	100,776
Change in net assets from nonoperating activities	10,182,189	-	9,596,702	-	19,778,891	25,670,023
Total change in net assets	10,835,961		11,710,542	3,155,585	25,702,088	33,334,059
Net assets at beginning of year	73,534,856	-	110,873,234	23,794,859	208,202,949	174,868,890
Net assets at end of year	$84,370,817	-	$122,583,776	$26,950,444	$233,905,037	$208,202,949

The accompanying notes are an integral part of the financial statements.

To the Board of Trustees of Woods Hole Oceanographic Institution:

We have audited the accompanying statement of financial position of Woods Hole Oceanographic Institution (the "Institution") as of December 31, 1996 and the related statements of activities and cash flows for the year then ended. These financial statements are the responsibility of the Institution's management. We previously audited and reported upon the financial statements of the Institution for the year ended December 31, 1995; totals for that year are shown for comparative purposes only. Our responsibility is to express an opinion on the financial statements based on our audit.

We conducted our audit in accordance with generally accepted auditing standards. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements. An audit also includes assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audit provides a reasonable basis for our opinion.

In our opinion, the financial statements referred to above present fairly, in all material respects, the financial position of Woods Hole Oceanographic Institution as of December 31, 1996 and the changes in its net assets and its cash flows for the year then ended, in conformity with generally accepted accounting principles.

Coopers & Lybrand L.L.P.

Boston, Massachusetts
March 18, 1997

A. Background:

Woods Hole Oceanographic Institution (the "Institution") is a private, independent not-for-profit research and educational institution dedicated to working and learning at the frontier of ocean science and attaining maximum return on intellectual and material investments in oceanographic research located in Woods Hole, Massachusetts. The Institution was founded in 1930.

B. Summary of Significant Accounting Policies:

Basis of Presentation

The accompanying financial statements, which are presented on the accrual basis of accounting, have been prepared to focus on the Institution as a whole and to present balances and transactions according to the existence or absence of donor-imposed restrictions. In 1995 the Institution adopted the provisions of Statement of Financial Accounting Standards ("SFAS") No. 116, *Accounting for Contributions Received and Contributions Made,* and No. 117, *Financial Statements of Not-for-Profit Organizations.* SFAS No. 116 generally requires that contributions received, including unconditional promises to give, be recognized as increases in net assets in the period received at their fair values. SFAS No. 117 requires that the Institution display its activities and net assets in three classes as follows: unrestricted, temporarily restricted, and permanently restricted. Additionally, it requires the presentation of a statement of cash flows.

The financial statements include certain prior-year summarized comparative information in total, but not by net asset class. The prior-year information presented does not include sufficient detail to constitute a presentation in conformity with generally accepted accounting principles. Accordingly, such information should be read in conjunction with the organization's financial statements for the year ended December 31, 1995, from which the summarized information was derived.

Net assets, revenues, and realized and unrealized gains and losses are classified based on the existence or absence of donor-imposed restrictions and legal restrictions imposed under Massachusetts State law. Accordingly, net assets and changes therein are classified as follows:

Permanently restricted net assets

Permanently restricted net assets are subject to donor-imposed stipulations that they be maintained permanently by the Institution. Generally the donors of these assets permit the Institution to use all or part of the income earned and capital appreciation, if any, on related investments for general or specific purposes.

Temporarily restricted net assets

Temporarily restricted net assets are subject to donor-imposed stipulations that may or will be met by actions of the Institution and or the passage of time. Unspent endowment gains are classified as temporarily restricted until the Institution appropriates and spends such sums in accordance with the terms of the underlying endowment funds at which time they will be reclassified to unrestricted revenues.

Unrestricted net assets

Unrestricted net assets are not subject to donor-imposed stipulations. Revenues are reported as increases in unrestricted net assets unless use of the related assets is limited by donor-imposed restrictions. Expenses are reported as decreases in unrestricted net assets. Gains and losses on investments and other assets or liabilities are reported as increases or decreases in unrestricted net assets unless their use is restricted by explicit donor stipulations or law. Expirations of temporary restrictions on net assets, that is, the donor-imposed stipulated purpose has been accomplished and or the stipulated time period has elapsed, are reported as reclassifications between the applicable classes of net assets. Amounts received for sponsored research (under exchange transactions) are reflected in unrestricted sponsored research until spent for the appropriate purpose.

Contributions

Contributions, including unconditional promises to give, are recognized as revenues in the period received. Contributions subject to donor-imposed stipulations that are met in the same reporting period are reported as unrestricted support. Promises to give that are scheduled to be received after the balance sheet date are shown as increases in temporarily restricted net assets and are reclassified to unrestricted net assets when the purpose or items' restrictions are met. Promises to give subject to donor-imposed stipulations that the corpus be maintained permanently are recognized as increases in permanently restricted net assets. Conditional promises to give are not recognized until they become unconditional, that is when the conditions on which they depend are substantially met. Contributions other than cash are generally recorded at market value on the date of the gift (or an estimate of fair value), although certain noncash gifts, for which a readily determinable market value cannot be established, are recorded at a nominal value until such time as the value becomes known. Contributions to be received after one year are discounted at the appropriate rate commensurate with the risks involved. Amortization of the discount is recorded as additional contribution revenue in accordance with the donor-imposed restrictions, if any, on the contributions. Amounts receivable for contributions are reflected net of an applicable reserve for collectibility.

The Institution reports contributions in the form of land, buildings, or equipment as unrestricted operating support unless the donor places restrictions on their use.

Dividends, interest, and net gains on investments of endowment and similar funds are reported as follows:

- as increases in permanently restricted net assets if the terms of the gift or the Institution's interpretation of relevant state law require that they be added to the principal of a permanent endowment fund;
- as increases in temporarily restricted net assets if the terms of the gift or the Institution's interpretation of relevant state law impose restrictions on the current use of the income or net realized and unrealized gains; and
- as increases in unrestricted net assets in all other cases.

Operations

The statement of activities reports the Institution's operating and nonoperating activities. Operating revenues and expenses consist of those attributable to the Institution's current annual research or educational programs, including a component of endowment income appropriated for operations (see Note C). Endowment income and gains of the Institution's unrestricted investments over the amount appropriated under the Institution's spending plan are reported as nonoperating revenue.

Cash and Cash Equivalents

Cash and cash equivalents consist of cash, money market accounts, and overnight repurchase agreements which are stated at cost, which approximates market value. At times the Institution maintains amounts at a single financial institution in excess of federally insured limits.

Included in cash at December 31, 1996 and 1995 is $5,015,903 and $2,999,081 (the sponsored research prepayment pool), respectively, representing advances received from the

United States Navy and other U.S. Government agencies. Such amounts are restricted in use to research programs. Interest earned on unspent funds reverts to the federal government. Cash and cash equivalents also include uninvested amounts from each classification of net assets (e.g., endowment).

Inventories

Inventories are stated at the lower of cost or market. Cost is determined using the first in - first out method.

Investments

Investment securities are carried at market value determined as follows: securities traded on a national securities exchange are valued at the last reported sales price on the last business day of the year; securities traded in the over-the-counter market and listed securities for which no sales prices were reported on that day are valued at closing bid prices. Purchases and sales of investment securities are recorded on a trade date basis. Realized gains and losses are computed on a specific identification method.

Investment income, net of investment expenses, is distributed on the unit method. Unrestricted investment income is recognized as revenue when earned and restricted investment income is recognized as revenue when it is expended for its stated purpose.

Contracts and Grants

Revenues earned on contracts and grants for research are recognized as related costs are incurred.

Investment Income Utilization

Investment of the Institution's endowment fund is based on a total return policy. The Institution distributes to individual funds an amount of investment income earned by each of the fund's proportionate share of investments in the endowment fund (interest and dividends) based on a percentage of the prior three years' endowment market values.

The Institution has interpreted relevant state law as generally permitting the spending of gains on endowment funds over a stipulated period of time. The Board of Trustees has appropriated all of the income and a specified percentage of the net appreciation to operations as prudent considering the Institution's long and short-term needs, present and anticipated financial requirements, expected total return on its investments, price level trends, and general economic conditions. Under the Institution's current endowment spending policy, which is within the guidelines specified under state law, between 4 percent and 5.5 percent of the average of the market value of qualifying endowment investments at September 30 of each of the previous three years is appropriated. This amounted to $6,394,825 and $5,947,126 for the years ending December 31, 1996 and 1995, respectively, and is classified in operating revenues (research, education, and operations).

Property and equipment

Property, plant and equipment assets are stated at cost. Depreciation is provided on a straight-line basis at annual rates of 2% to 12 1/2% on buildings and improvements, 3 1/2% on vessels and dock facilities, and 20% to 33 1/3% on laboratory and other equipment. Depreciation expense on plant assets purchased by the Institution in the amounts of $2,794,408 and $2,732,512 in 1996 and 1995, respectively, has been charged to operating activities. Depreciation on certain government-funded facilities (the Laboratory for Marine Science and the dock facility) amounting to $100,776 in both 1996 and 1995 has been charged to nonoperating expenses as these assets are owned by the Government. Gains on disposals of property, plant and equipment totaled $955,000 and $0 during the years ended December 31, 1996 and December 31, 1995, respectively.

Use of Estimates

The preparation of the financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and the disclosure of contingent assets and liabilities as of December 31, 1996 and 1995, as well as the reported amounts of revenues and expenses during the years then ended. Actual results could differ from the estimates included in the financial statements.

Reclassification of Amounts

Certain amounts in the financial statements for the year ended December 31, 1995 have been reclassified to conform to the December 31, 1996 presentation.

C. Investments:

The cost and market value of investments held at December 31, 1996 and 1995 are as follows:

		1996		1995
	Cost	Market	Cost	Market
U.S. Government and government agencies	$ 15,871,067	$ 15,874,658	$ 17,952,260	$ 18,822,499
Corporate bonds	13,016,798	13,126,042	8,793,317	9,223,161
International bond funds	5,723,594	6,384,442	8,900,476	9,483,318
Other bonds	3,551,636	3,645,641	403,589	403,698
Common stock	94,506,630	141,130,158	90,301,231	125,887,735
Other	4,093,040	3,552,741	4,521,478	3,629,072
Total investments	$136,762,765	$183,713,682	$130,872,351	$167,449,483

The following schedule summarizes the investment return and its classification in the statement of activities:

	Unrestricted	Temporarily Restricted	Permanently Restricted	1996 Total	1995 Total
Dividend and interest income	$4,906,544	$709,972		$5,616,516	$4,204,955
Net realized gains and unrealized gains	11,326,014	9,596,702		20,922,716	29,303,708
Total return on investments	16,232,558	10,306,674		26,539,232	33,508,663
Investment return designated for:					
Sponsored research	(1,544,572)			(1,544,572)	(1,313,606)
Education	(2,588,182)	(709,972)		(3,298,154)	(3,139,361)
Current operations	(1,816,839)			(1,816,839)	(1,483,010)
Investment return in excess of amounts designated for current operations	$10,282,965	$9,596,702	$ -	$19,879,667	$27,572,686

Interest and dividends are reflected net of $569,502 and $513,706 of investment management costs for the years ended December 31, 1996 and December 31, 1995, respectively.

Investment Income

Endowment income is allocated based on a per unit valuation. The value of an investment unit at December 31, 1996 and 1995 is $3.3191 and $3.0058, respectively. The investment income per unit for 1996 and 1995 is $.0906 and $.0731, respectively.

	1996	1995
Unit value, beginning of year	$3.0058	$2.4524
Unit value, end of year	3.3191	3.0058
Net change for the year	.3133	.5534
Investment income per unit for the year	.0906	.0731
Total return per unit	$ .4039	$ .6265

D. Pledges Receivable:

Pledges receivable consist of the following at December 31:

	1996	1995
Unconditional promises expected to be collected in:		
Less than one year	$ 2,656,945	$ 3,259,601
One year to five years	3,714,406	1,487,121
	$ 6,371,351	$4 ,746,722

E. Deferred Fixed Rate Variance:

The Institution receives funding or reimbursement from federal government agencies for sponsored research under government grants and contracts. The Institution has negotiated with the federal government fixed rates for the recovery of certain fringe benefits and indirect costs on these grants and contracts. Such recoveries are subject to carryforward provisions that provide for adjustments to be included in the negotiation of future fixed rates. The deferred fixed rate variance accounts represent the cumulative amount owed to or due from the federal government. The Institution's rates are negotiated with the Office of Naval Research (ONR), the Institution's cognizant agency.

The composition of the deferred fixed rate variance is as follows:

Deferred Fixed Rate Variance asset, December 31, 1994	$ 474,346
1995 indirect costs	31,137,574
1987 - 1994 final settlement	(104,841)
Amounts recovered	(32,496,463)
1995 (over)/under recovery	(1,463,730)
Deferred Fixed Rate Variance (liability), December 31, 1995	(989,384)
1996 indirect costs	29,882,057
1996 adjustment	(59,634)
Amounts recovered	(30,550,860)
1996 (over)/under recovery	(728,437)
Deferred Fixed Rate Variance (liability), December 31, 1996	$ (1,717,821)

As of December 31, 1996 the Institution has a cumulative balance recovered of $1,717,821 in excess of expended amounts which will be reflected as a reduction of future year recoveries and has been reflected as a liability of the Institution.

F. Retirement Plans:

The Institution maintains a noncontributory defined benefit pension plan covering substantially all employees of the Institution. The Institution also maintains a supplemental benefit plan covering certain employees. Pension benefits are earned based on years of service and compensation received. The Institution's policy is to fund at least the minimum required by the Employee Retirement Income Security Act of 1974.

Net periodic pension cost for the two plans consists of the following for 1996:

	Defined Benefit Plan	Supplemental Benefit Plan	Total
Service cost	$ 2,895,445	$ 107,739	$ 3,003,184
Interest cost	6,200,998	216,369	6,417,367
Actual return on plan assets	(17,616,307)	(113,270)	(17,729,577)
Net amortization and deferral	8,224,544	(164,671)	8,059,873
Net pension (income) expense	$ (295,320)	$ 46,167	$ (249,153)

Below is a reconciliation of the funded status of the plans at December 31, 1996:

	Defined Benefit Plan	Supplemental Benefit Plan	Total
Actuarial present value of obligation:			
Vested benefit obligations	$ (72,351,653)	$ (1,307,127)	$ (73,658,780)
Nonvested benefits	(1,831,497)	(1,135,623)	(2,967,120)
Accumulated benefit obligation	(74,183,150)	(2,442,750)	(76,625,900)
Projected benefit obligation	(93,081,214)	(3,200,054)	(96,281,268)
Fair value of plan assets (primarily invested in common stocks and fixed income securities)	133,509,632	-	133,509,632
Plan assets in excess of the projected benefit obligation	40,428,418	(3,200,054)	37,228,364
Unrecognized net transition (asset) obligation	(3,230,503)	643,821	(2,586,682)
Unrecognized prior service costs	314,935	-	314,935
Unrecognized net gain	(37,024,263)	(990,791)	(38,015,054)
(Accrued) prepaid pension cost	$ 488,587	$ (3,547,024)	$ (3,058,437)

The plan assets listed above are held in the Woods Hole Oceanographic Retirement Trust at December 31, 1996. In addition, the Institution has accrued a liability sufficient to fund future supplemental plan benefits earned at December 31, 1996.

The discount rate and rate of increase in future compensation used to determine the projected benefit obligation as of December 31, 1996 were 7.25% and 4.5%, respectively. The expected return on plan assets was 9%.

G. Other Post Retirement Benefits:

In addition to providing pension benefits, the Institution provides certain health care benefits for retired employees and their spouses. Substantially all of the Institution's employees may become eligible for the benefits if they reach normal retirement age (as defined) or elect early retirement with certain time in service limitations.

The Institution has adopted the delayed recognition method as permitted by Statement of Financial Accounting Standards No. 106, "Employer's Accounting for Postretirement Benefits Other Than Pensions" ("SFAS 106"). As such the Institution is amortizing the accumulated postretirement benefit over 20 years.

Net periodic postretirement benefit cost consists of the following for 1996:

Service cost	$ 356,853
Interest cost	1,184,793
Actual return on plan assets	(1,198,768)
Net amortization and deferrals	1,060,823
Net periodic postretirement benefit cost	$ 1,403,701

The Institution has a Voluntary Employees' Beneficiary Association Trust (the "Trust") that will be used to partially fund health care benefits for future retirees. The Institution intends to contribute to the Trust an amount equal to the annual expense of the Plan. During the year ended December 31, 1996 the Institution paid $1,404,000 in retiree health benefits on behalf of the Trust. The following table sets forth the funded status of the Plan as of December 31, 1996:

Financial status of plan:	
Accumulated postretirement benefit obligation:	
Retirees	$ (11,065,132)
Fully eligible, active plan participants	(3,363,347)
Other active plan participants	(4,324,066)
Total obligation	(18,752,545)
Plan assets at fair value	9,173,222
Unrecognized net transition obligation	13,656,789
Unrecognized prior service cost	(5,792,347)
Unrecognized loss	2,406,332
(Accrued) prepaid postretirement benefit cost	$ 691,451

The assumed discount rate is 7.25%. The expected long-term rate of return on plan assets used in determining the net periodic postretirement benefits cost was 8.25% in 1996. The rate of increase in the per capita costs of covered health care benefits is assumed to be 5.5% in 1996 and in future years.

If the health care cost trend rate assumptions were increased by 1%, the accumulated postretirement benefit obligation, as of December 31, 1996, would be increased by approximately $2,992,310; the effect of this change on the sum of the service cost and interest cost components of net periodic postretirement benefit cost for 1996 would be an increase of approximately $314,217.

H. Tax Status:

The Institution is exempt from federal income tax as an organization described in Section 501(c)(3) of the Internal Revenue Code of 1954 as it is organized and operated exclusively for education and scientific purposes.

I. Commitments and Contingencies:

The Defense Contract Audit Agency (DCAA) is responsible for auditing both direct and indirect charges to grants and contracts on behalf of the ONR. The Institution and the ONR settled the contract years through 1994. The 1995 fixed rates include the impact of prior year settlements. Currently 1995 and 1996 remains open to final settlement. The Institution believes that the settlement of 1995 and 1996 will not have a material impact on its results of operations (change in net assets) or its financial position.