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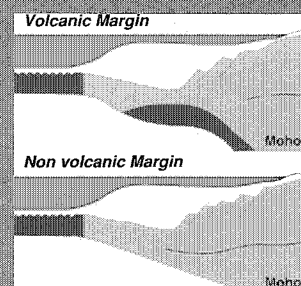

Cover Photos: Some of the Institution's major 1989 events and activities are represented. They are, from the top, arrival of Director Craig Dorman, celebration of DSV *Alvin's* 25th anniversary, refit of R/V *Knorr,* and a second addition to the Clark Laboratory.

Cover Photo Credits: R/V *Knorr* lift courtesy of McDermott Shipyard, others by Tom Kleindinst

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R/V *Oceanus* steams out of Woods Hole harbor on a research voyage.

Shelley L

Director's Comments

IF 1989 was a good year for WHOI, it was a great one for me. My first year as Director has been fun and full of learning – settling with Cynthia into Meteor House and life in Falmouth and Woods Hole Village, meeting with the scientists and staff and trying to understand their work and needs, and becoming acquainted with the sponsors, Trustees, Corporation members, and Associates, who are so critically important to our research. I even had a chance to go to sea in three oceans, more than I'd done in my last decade in the Navy: with Bob Ballard and the JASON Project in the Mediterranean, for a short cruise in the Atlantic on *Oceanus,* and in the Pacific on *Kaiyo,* a Japanese SWATH ship. And coming aboard during Alvin's 25th anniversary gave me a great sense of our history and helped prep me for 1990, WHOI's 60th year.

In the process of becoming acquainted, we've made a few changes to strengthen WHOI's posture of leadership in oceanography. A full scale effort is underway to identify and review the most important issues in ocean science and what our role should and could be with respect to them. On the more immediate front, WHOI now has several new committees to improve information flow and broaden effective participation in Institutional governance. We've created Engineering and Information Systems career ladders for technical and graded staff that will parallel the traditional research track. Our needs for both land-based and seagoing facilities are under extensive review so that we will be able to update our Master Building Plan and effectively direct our course towards optimal research at sea. We got top grades from a Visiting Committee review of our Joint Program with MIT, and, after a nationwide search have selected John Farrington Associate Director of Education and Dean of Graduate Studies so our educational activities may be broadened. Finally, we have established, under Charley Hollister, a Directorate of External Affairs (comprised of Development, Communications, and Industrial and International Affairs), which will extend our outreach and strengthen our base of support.

We have also worked hard to keep our administration lean and flexible and to reinforce the community spirit and scientific competitiveness of the WHOI staff. My respect for the efficiency of our procedures and the quality of our people has only grown as I have become more familiar with them over the past year. We must continue to capitalize on the strengths of our men and women, and to minimize bureaucracy.

At the same time, implicit in the changes we are making is a recognition that the traditional system of support and funding for our work is changing and that WHOI must evolve. One dominant trend in the United States is the resurgence of social consciousness as the nation grapples with its educational and economic problems and a degrading environment. Another is the struggle to respond to the dramatic changes in international political and economic structures as the failure of communism sets in. And while such global events may at times seem far removed from our quiet village, the nature of our science, our leadership role in it, and our dependence upon the federal government mandate attentiveness and action.

It is likely that concern for global change and protection of the environment will remain high throughout the '90s. Oceanography, an observational science with great relevance to the health of the world and an intrinsic appeal to youth, will be an important component of national research and education plans. However, federal funding for oceanography is apparently shifting toward mission-oriented and regulatory agencies like the

Craig Dorman

Terri Corbett

National Oceanic and Atmospheric Administration and the Environmental Protection Agency, with a less dominant role for our traditional sponsors, the National Science Foundation and the Office of Naval Research.

Thus, as our field becomes even more important to the health of the world, it will be difficult to maintain our traditional approach to science. The pressure on NSF is already stressing the peer review process of selecting the best science (although WHOI continues to outcompete all others in its field), and we must quickly evolve supportive relationships with agencies that have had little experience in working with academia. The concern is that just when the expertise of the U.S. ocean science community is needed the most, the federal structur that has helped make us the best in the world will ignore our strengths.

WHOI is working hard locally, natic ally, and internationally in scientific forums to sustain the strength and qual of our research and education. As a private institution with a recognized wo leadership position, we have tremendou flexibility. The challenge, as a "soft money" institution, will be to maintain (independence and the ability to define a conduct the very best science. I'm excite about the possibilities inherent in this challenge and enthusiastic about WHOI potential for the coming decades.

Craig E. Dorm
Direc

The 133-meter Soviet research vessel *Academik Vernadskiy* arrived at the Institution pier June 16 for a two-day visit, the first Woods Hole port call by a Soviet vessel in more than eight years. A large crowd gathered to greet the vessel, the largest to dock in Woods Hole since World War II. Special tours and activities were arranged for the Soviet crew and scientists during their visit, and several WHOI staff members were aboard the ship when it departed June 17 for a month-long Gulf Stream cruise.

Davic

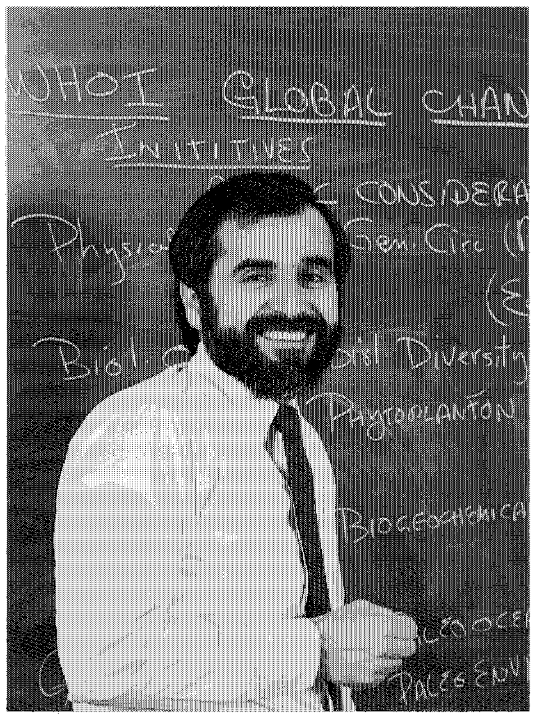
Comments from the Associate Director for Research

THIS year closed out a decade of success for the Woods Hole Oceanographic Institution in spite of mixed performances in support from the federal sector for Ocean Sciences. Competition for federal funding sources, such as the Office of Naval Research (ONR) and the National Science Foundation (NSF), dramatically increased as the decade came to a close. As a result, our Scientific and Technical Staffs have had to sharpen their focus and spend more time trying to market and sell their science. Scientists at the Institution today write more than twice as many proposals as they did in 1980. As an Institution, we can no longer rely only on the National Science Foundation and the Office of Naval Research for the majority of our research support. Our challenge for the new decade is to broaden our funding base into other federal, as well as private, arenas.

The scientific excellence of our staff has allowed us to weather the increasing competitive storm. We are extremely fortunate that we have such high quality, world-class scientists and engineers at this Institution. During the past decade, for example, the NSF Ocean Sciences Division budget rose by 78 percent and the ONR budget by 57 percent. Our overall research budget during this time period increased by 107 percent with our NSF and ONR (and other Navy) support increasing by 95 percent and 154 percent, respectively. We currently rank in the top 20 of all U.S. institutions competing for NSF funds in all disciplines. Clearly, this is a reflection of the excellence of our Staff and a vote of confidence for our thorough and competitive appointment and promotion procedures.

In a sense, 1989 was a watershed year for the environmental sciences. It was pivotal in convincing Congress and the White House to commit significant funds to some of the major global environmental programs that have been in the planning stages for the past five years. Through the 1980s, the NSF and ONR continued to provide the major resources for the academic ocean sciences community including approximately three-quarters of WHOI's research support. However, significant increases are in the offing for the National Oceanic and Atmospheric Administration (NOAA), National Aeronautics and Space Administration (NASA), and Environmental Protection Agency (EPA) budgets presented to Congress by the President. If Congress agrees with the President, the increase in the 1991 budget for the environmental sciences will be the highest since the early 1970s when the NSF Ocean Sciences Division budget approximately doubled as the International Decade of Ocean Exploration Program began. Many of our scientists participated in that program and have been instrumental in planning and formulating some of the major research initiatives for the 1990s.

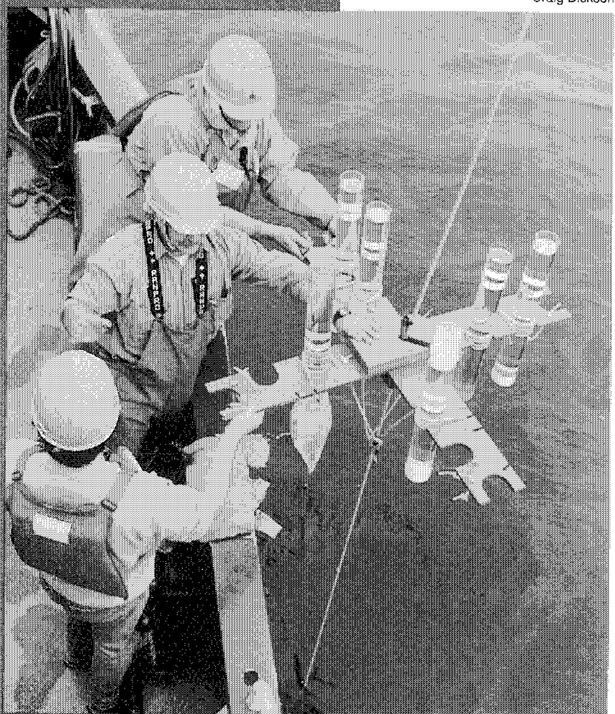
A renewed and concerned interest in man's impact on his environment began to emerge in the late 1980s. Among the concerns are the effects of global climate change, the wise use and protection of the oceans, and the effects of new policies dealing with economic and military security. This Institution has played a major role in the planning of several initiatives dealing with these issues. A number of the World Ocean Circulation Experiment (WOCE) components are located at WHOI, including the WOCE hydrographic office, the WOCE water sampling bottle design and construction project, and the National Tandem Accelerator Mass Spectrometer facility. The WOCE program was designed to better understand the general circulation of the ocean and the processes by which it can be altered due to climate changes.



Bob Gagosian

The Joint Global Ocean Flux Study (JGOFS), which intends to identify the physical, chemical, and biological processes controlling the biogeochemical cycles in the ocean, has its U.S. planning office at WHOI. Many of our scientists are participating in both the WOCE and JGOFS programs and in the planning for the GLobal Ocean ECosystems Dynamics (GLOBEC) program, whose goal is to integrate theoretical and practical ecological studies of marine and terrestrial systems. Likewise, our scientists are involved in planning for the Ridge Inter-Disciplinary Global Experiment (RIDGE) program, which proposes to study the Earth's mid-ocean ridges as a single dynamic system transferring energy from the Earth's interior to the lithosphere, hydrosphere, and atmosphere.

Craig Dickson



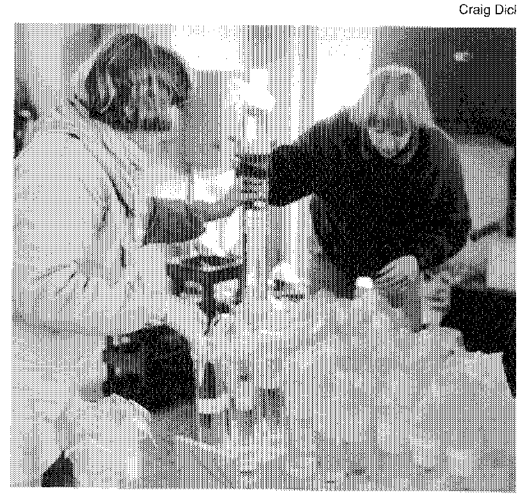
The field program of the international Joint Global Ocean Flux Study (JGOFS) began in 1989 with several cruises aboard *Atlantis II*. The photo above shows the launch of a set of floating sediment traps developed by the Moss Landing Marine Laboratory. In the photo at right, water samples are being filtered.

Institution scientists are also participating in a number of other major new initiatives to help us better understand how the Earth works. In the ONR Subduction Experiment, processes that inject surface layer ocean water into the flow regime of the interior ocean (the thermocline and the abyss) are being defined. The ONR-sponsored Surface Wave Dynamics Experiment (SWADE) program is looking at growth and equilibria of wind-generated surface waves. The role of the polar oceans in the world's biogeochemical cycles are being studied, and our joint initiative with the Marine Biological Laboratory, to apply molecular biological techniques to answer biological oceanography questions, is progressing well.

In addition, 1989 was a year for many technical achievements. A major ocean bottom seismometer facility was awarded to WHOI by the ONR. These instruments will help us obtain new data to measure the acoustic and seismic noise fields of tl deep ocean, which, in turn, will lead to new information about microearthquake on the ocean floor. New software techniques and more powerful computers no allow us to synthesize and integrate optical and acoustic data in order to obta a more detailed, real-time, three-dimensional, fly-over pattern of the ocean floor from remote vehicles. This past year's breakthrough in our modeling capabiliti of the acoustic channel has greatly expanded the opportunity to telemeter dat acoustically through the ocean's interior. These new developments will allow us to look at the ocean in very different ways than previously thought possible.

In summary, 1989 was an important transition year for the Institution. As discussed above, major advances were made in our approach to science and engineering. Our new Director, Craig Dorman, initiated changes in the way we manage our science and technology. He has started to put a system in place by which we can best respond to the opportu nities and challenges of the 1990s. This, combined with the recognition by the

Craig Dic



federal and private sectors that to understand what man is doing to his environment requires a major change in the way we address funding research in this country, is creating an environment at Woods Hole of excitement and anticipatio not seen since the early days of the environmental movement.

Robert B. Gagosia
Associate Director for Researc

Applied Ocean Physics &Engineering

IN 1989, the name of the department was changed from Ocean Engineering to Applied Ocean Physics and Engineering to reflect our work more accurately. In acoustics and in coastal and boundary layer flow, we apply basic physics and fluids to oceanic problems. At the same time, we develop observational technology toward understanding a broad range of problems in geology, biology, physical oceanography, and geophysics. Vehicles and platforms including the *Argo-Jason* remotely operated team, *Alvin*, and a number of telemetering moored buoys already have impacted and will increasingly impact our ability to observe and understand ocean processes.

Our work on acoustic telemetry and geographical information systems for combining data from diverse sensors on remotely operated vehicles has moved us in a major way into signal processing. Our staff is developing transputer-chip-based underwater systems and deck equipment to match, components of which equal the speed of a Cray 3. Our sensors are becoming more stable and smaller, and, eventually, they will become expendable, to permit new densities of point measurements for global, remote observations. Autonomous vehicles that will carry some of these sensors are being designed for use later in the decade while improvements to water sampling and density profiling techniques are being completed for use in global programs during 1990.

Air-sea interaction work is important for climate studies, acoustics, and the general circulation. We are developing marine meteorological sensor packages, buoys to support them, microwave and optical studies of wave generation processes, and surface layer turbulence studies of momentum transport into the mixed layer. We are concerned with sediment transport on the shelf, mixing in coastal regions, and animal/sediment-flow interaction.

Some of our longest range developments remain in acoustic ocean tomography where we can now measure small temperature changes averaged over an ocean basin and resolve directional surface wave spectra from the signals. We are on the verge of basin-scale coverage and real-time data return.

Arctic work continues with ice tomography on the small scale and telemetry buoys for year-round observations on the large scale. Ocean bottom seismic arrays, down-borehole seismometers, and tomographic techniques are permitting deep examinations of crust and mantle.

Nine appointments were made to the department technical staff in 1989, and one to the scientific staff. The addition of Bill Plant as a Senior Scientist in late 1988 strengthened the department's capabilities in air-sea interactions and microwave remote sensing of the ocean. Bill's work contributes to the understanding and development of spaceborne microwave sensors such as scatterometers, wave spectrometers, and synthetic aperture radars, which enable global monitoring of near-surface ocean conditons.

Albert J. Williams 3rd
Department Chairman

Alessandro Bocconcilli

Henri Berteaux and colleagues in the Applied Ocean Physics & Engineering Department, along with Battelle Ocean Sciences, are developing a new oceanographic water sampler in response to needs of such international programs as the World Ocean Circulation Experiment. The photo shows a prototype being tested in Woods Hole harbor.

Biology

THE broad aim of biological oceanographers is to study the temporal and spatial distributions of populations of marine organisms and their interactions with each other and their environment. The work is predominantly ecological in its attempts to provide the basic information required to understand how the ocean works biologically. Among the specific research interests of Institution biologists are microbiology, biochemistry, molecular biology, planktonology, ichthyology, benthic biology, physiology, biogeochemistry, bioacoustics, mathematical ecology, and animal behavior.

A major recent initiative introduces molecular biological tools and techniques into the mainstream of biological oceanography and allows many longstanding but current problems to be addressed in an entirely new way. Recent efforts using these techniques include studies of jellyfish bioluminescence, cancer in Boston Harbor flatfish, and toxic dinoflagellate blooms ("red and brown tides") in coastal waters. In collaboration with the Marine Biological Laboratory, a molecular biology core facility was established at WHOI in 1989. Some of the work envisioned for this facility includes analysis of marine species by identification of intragenic species-specific DNA sequences, systematics of marine cyano- and nitrogen-fixing bacteria, dinoflagellate physiology, ecology, toxin biosynthesis, development of species-specific tags for marine protozoa, speciation in benthic communities, and transformations in fish caused by pollutants.

A second new thrust is in the mathematical modeling of biological systems with potential areas of research that include physiological processes; recruitment, population dynamics, and life histories; nonlinear dynamics in marine systems; and food web structure and dynamics.

Another departmental thrust is in the area of bioacoustics. Recent developments in digital signal processing offer new tools that promise advances in the study of the distribution of organisms ranging in size from microscopic plankton to whales.

Among the awards to department members in 1989, Hal Caswell received a Guggenheim Fellowship for his models of ecological communities in patchy environments, and John Stegeman was elected a Fellow of the American Association for the Advancement of Science and to membership in the American Society for Biochemistry and Molecular Biology.

Peter H. Wiebe
Department Chairman

Richard Ridge sets up the protein sequencer in the new Protein and Nucleic Acid Center established during 1989 jointly by WHOI and the Marine Biological Laboratory.

Tom Kleindinst

Chemistry

THE efforts of individual investigators continue to form the backbone of research in the Chemistry Department with forefront research ranging from the glacial history of the antarctic ice sheet and the formation of surface films in the upper micron of the ocean to the cycling of carbon through various ocean reservoirs and the history of ocean circulation recorded in the growth bands of coral. Significant work is underway on carbon cycles, an area of intellectual ferment and strong societal interest, as we try to understand global changes, energy issues, and waste disposal. Our staff measures all of the carbon isotopes in surface, mid-level, and deep waters, in sinking particles, in sediments, and in newly measurable forms such as dissolved organic carbon. We are substantially involved in pioneering efforts in such areas as marine photochemistry and the origin and effects of surface microlayers. Organic geochemistry on the molecular to global scale remains a strength with studies ranging from the cycling of pigments and composition of surface films to the origin and migration of petroleum

A major chemistry research effort is based in the waters around Bermuda, where WHOI investigators are conducting some half-dozen programs. The measurements made constitute one of the most comprehensive data sets available for the some 70 percent of the world ocean that falls into a category similar to the waters around Bermuda. The emphasis in this work is on time series studies to define the seasonal and interannual variations in the rates of oceanic processes and to define the links between atmosphere, surface, and deep ocean.

In 1989, several department members participated in the North Atlantic Bloom Experiment, the first seagoing component of the Joint Global Ocean Flux Study (JGOFS), a decade-long, international program to examine how ocean life interacts with seawater chemistry on a global scale. WHOI participation includes hosting the planning office for U.S. participation in JGOFS.

Derek Spencer was welcomed back to the department in 1989 following more than 10 years as Associate Director for Research. He is working with other department members on his longstanding interest, the integration of models of the upper ocean with the distribution of chemical tracers.

Mark Kurz received the Rosenstiel Award this year for his contributions to marine geochemistry, particularly helium isotopic systematics and the evolution of the earth, mantle processes, and the cosmogenic connection. Peter Brewer was elected a Fellow of the American Geophysical Union for the "development of insight and observational leadership in a wide range of chemical oceanography, especially the global carbon flux problem and the cycling of nutrients," and an ONR Young Investigator Award, which provides three years of research support, went to Jim Moffett in 1989.

Frederick L. Sayles
Department Chairman

Geology & Geophysics

THE desire to determine the forces that have shaped the planet Earth drive research in marine geology and geophysics. One thrust of work in this department is to provide a relative time frame for Earth-shaping events through biostratigraphic and geophysical studies and an absolute time chronology through isotopic measurements. Work on the seafloor spreading cycle ranges from morphological descriptions of ocean basins to studies of processes at work in the mantle and along mid-ocean ridges and the development of ocean basins by rifting, drifting, subduction, and continental collision. The wide range of research in the department also includes studies of sedimentation from the shallow coastal zone to the deepest ocean, global refrigeration events and subsequent melting, and changes of sea level with time.

Gary Hayward, Hugh Poponoe, and Beecher Wooding, front to back of picture, were photographed during final preparations for launch of NOBEL, the Near Ocean Bottom Explosive Launcher, aboard the Canadian vessel C.S.S. *John P. Tully* operated by the Pacific Geoscience Centre of Sidney, British Columbia.

Jim Broda

Two important 1989 research accomplishments in the department deal with the production of North Atlantic Deep Water and with geological processes along the mid-ocean ridge. Research shows that the flux of North Atlantic Deep Water from the Greenland-Norwegian Sea to the North Atlantic was reduced four times in the period from 15,000 to 10,000 years ago. These reductions are associated with a major discharge of glacial meltwater whose southward advection increased the stability of the water column and affected the climate of the North Atlantic region. The mid-ocean ridge study involved extremely detailed mapping of tectonic and magmatic processes at work on the Mid-Atlantic Ridge between the Kane and Alantis fracture zones using an unprecedented combination of high resolution swath bathymetry, magnetics, and gravity field information.

We look forward to new capabilities when the Accelerator Mass Spectrometer (AMS), a national facility sponsored by the National Science Foundation and based in this department, becomes operational in the near future. Construction of an addition to the McLean Laboratory to house the AMS began in 1989. The facility will be able to measure radiocarbon content, and hence the age, of samples a thousand time smaller than with conventional radiocarbon methods. It will reduce the time required to compile the detailed chronology needed for such paleoceanographic studies as the North Atlantic Deep Water reductions, and it will play an important role in the use of carbon-14 as a tracer in the World Ocean Circulation Experiment (WOCE).


Terri Corbett

Sus Honjo was named to the newly established Columbus O'Donnell Iselin Chair for Excellence in Oceanography.

Six new assistant scientists were appointed in 1989, and our expertise on mantle processes was substantially expanded with addition to the staff of two senior scientists, Stanley Hart and Nobumichi Shimizu, who will add new dimensions to our future investigations on intraplate and plate boundary magmatic processing. Hart is a member of the National Academy of Sciences, and William Berggren was elected to that prestigious body in 1989. Another honor came to the Geology & Geophysics Department this year when Susumu Honjo was awarded the Institution's newly established Columbus O'Donnell Iselin Chair for Excellence in Oceanography.

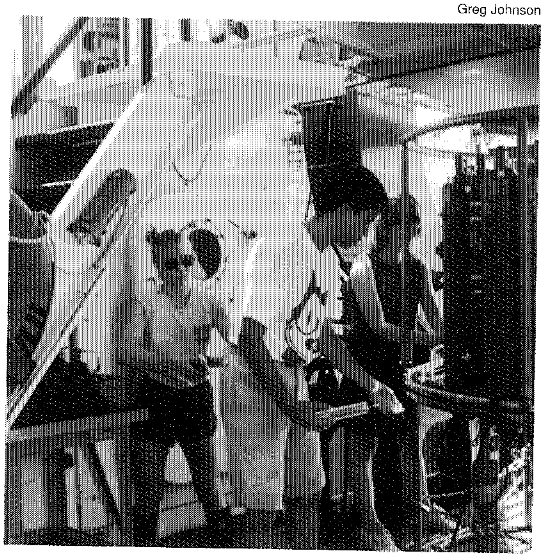
David A. Ross
Department Chairman

Physical Oceanography

THE Department of Physical Oceanography is global in scope, comprehensive in the scales of the physical processes currently studied, and holds a leadership position in national and international physical oceanography research. Department members investigate the dynamics and thermodynamics of ocean circulation. They work globally from the Arctic to the Antarctic and from the Strait of Gibraltar to the Philippine shelf on the full range of oceanic processes from mixing on centimeter scales to heat balance on the global scale. Their tools include observations at sea, analysis of experimental data, and theoretical and numerical modeling.

The traditional core of the department has been study of general ocean circulation, particularly the dynamics of subtropical gyres, including western boundary currents such as the Gulf Stream. Recent advances in thermocline modeling have extended these studies into investigations of equatorial and subpolar gyre circulation.

Over the last 10 years, department scientists have taken international leadership in the research areas of air-sea interaction, mesoscale oceanography, coastal circulation, and mixing. Air-sea interaction, at the heart of long-term global climate change problems, has both local aspects, such as how short-term atmospheric variability generates ocean currents, and large-scale aspects, such as determining the ocean's role in maintaining the Earth's heat budget. Mesoscale

Greg Johnson


Becky Schudlich, left, Chris Johnston, and Nurit Cress of Oregon State University draw samples following a CTD cast aboard R/V *Moana Wave* of the University of Hawaii in the spring of 1989.

oceanography consists of the study of fronts and eddies. These fluctuations involve time scales of weeks and space scales of about 100 kilometers and are the most energetic component of ocean currents. Coastal circulation focuses on understanding the dynamic processes controlling currents over the continental shelf and through straits connecting semi-enclosed seas with the open ocean. Understanding these processes is the key to predicting the fate of pollutants and the effective turnover time for a basin, issues of societal importance. Mixing on the smallest scales ultimately determines the sinks for mechanical energy, buoyancy, and internal energy in the ocean. Instruments under development in the department should allow these mixing processes to be measured simultaneously for the first time.

Significant accomplishments during 1989 include the following list.

- Senior Scientist Henry Stommel received the National Medal of Science from President Bush in November. He was one of 17 scientists, and the only oceanographer, in the physical and mathematical sciences to receive the medal.
- The International Hydrographic Program office for WOCE (World Ocean Circulation Experiment) was established at WHOI in 1989 under the direction of Senior Scientist Terrence Joyce to process and analyze all hydrographic measurements for the largest scientific program ever attempted by physical oceanographers.
- Bob Beardsley was elected a fellow of the American Association for the Advancement of Science.
- The longest hydrographic section ever made was directed by Associate Scientist John Toole and Senior Scientist Harry Bryden from February to May aboard R/V *Moana Wave* operated by the University of Hawaii. The work extended 16,000 kilometers across the Pacific Ocean from the Philippines to Costa Rica and included 220 full-depth hydrographic stations. Its objective is to measure the meridional ocean heat transport across 10°N.

Robert C. Beardsley
Department Chairman

Henry Stommel received the National Medal of Science from President Bush at the White House in October of 1989. His award was for "original, penetrating and fundamental contributions to the physics of ocean circulation." He is one of only 245 scientists and engineers to receive the medal since it was first presented by President Kennedy in 1962.

David Valdez, The White House

Barbara Gaffron

This is one of the 221 hydrocasts that made up the longest hydrographic section ever undertaken. Harry Bryden, closest to the camera, and John Toole directed the work on the R/V *Moana Wave* cruise.

Centers & Special Programs

Charlotte Fuller collects larvae from water flowing through the 17-meter recirculating flume into the holding basin at the Coastal Research Laboratory.

Cheryl Ann Butman

Coastal Research Center

THE primary emphasis of the Coastal Research Center (CRC) is clarification and understanding of both natural and human-induced variability in coastal processes. The Center provides both an intellectual forum and research support in the form of funding, small boats, and research facilities such as experimental flumes. CRC is also active at the science-policy interface so that the results of the scientific effort can be efficiently and effectively used in resource management decisions. In 1989, CRC studies continued in five primary programmatic areas.

1) *Impact of Global Climate Change on the Coastal Zone:* Building on previous research in river deltas, this program focuses on how present-day coastal environments might be altered by natural and human-induced climate change. Regional sensitivities to global change are being examined in such areas as the Caribbean, the northern Indian Ocean, and the Pacific archipelagos where impacts from relative sea-level rise may include changes in estuarine circulation, altered sedimentation patterns, increased salinity intrusion into aqui-fers, and modifications of the storm climate.

2) *Assimilative Capacity-Ecotoxicology:* A CRC research effort at the NOAA Waquoit Bay Estuarine Research Reserve supports studies of nutrient flux to coastal embayments via groundwater and studies of factors that influence shellfish recruitment. In addition, CRC has helped coordinate the academic response to environmental problems in Massachusetts Bay and Boston Harbor and is participating in studies of coastal circulation and the transport of toxics.

3) *Coastal Instrumentation:* CRC provided partial funding for a tide gauge and its long term deployment in the Philippines for a study of coastal seiches and the role of internal waves in their creation. In addition, CRC purchased a current meter to support physical oceanographic research on tidal, wind-driven, and density-driven water movements that affect contaminant flux in Massachusetts and Cape Cod bays. This work includes scientists from WHOI, the U.S. Geological Survey, and the Universities of New Hampshire and Massachusetts, Boston.

4) *Rapid Response:* As a response to Hurricane Hugo, a new research initiative in the Caribbean is designed to describe more precisely the impacts of hurricanes on the coastal environment and to investigate climatic issues that affect the strength and tracks of hurricanes. From this, we hope to improve our understanding of the relationship between major storms and the structure of coastal tropical ecosystems in order to provide technical guidance for appropriate coastal zone management in the Caribbean.

5) *Education:* CRC provides support for student research projects, creating seed funds for promising research initiatives. CRC also provides support for postdoctoral fellows that help recruit the most promising young scientists to continue the tradition of coastal research at Woods Hole.

David G. Aubrey
Center Director

Center for Marine Exploration

THE Center for Marine Exploration (CME) fosters new technologies, including unmanned sytems, for the deep ocean and provides a focal point for marine scientists and others exploring the deep sea. CME has four primary goals:

- to provide scientists with advanced engineering and cost-effective techniques for deep ocean exploration and experiments,
- to provide marine archaeologists and other social scientists opportunities to utilize this technology for cultural and historic purposes,
- to increase public awareness of the marine environment, and
- to stimulate career interest in engineering and the physical sciences.

CME provides a meeting ground where skilled technicians and experts in such areas as materials science, electronics engineering, image processing, acoustics, optics, mechanical engineering, computer sciences, robotics, and telecommunications come together with marine scientists to develop technology for unmanned exploration of the deep ocean. The objective is to provide a scientific and cultural window to the deep ocean and to further basic knowledge and man's ability to use the marine environment wisely.

The center played a key role in the early organization of the JASON Project and continues this work along with the new JASON Foundation for Education. Please see the discussion of the first year's activities and exciting future plans on pages xx and xx. In 1990 the JASON Project will focus on *Hamilton* and *Scourge*, two ships sunk during the War of 1812, and in 1991 the Galapagos Islands will be featured.

CME is working with the Center for Marine Policy to form an international study group to discuss ethics and policy pertaining to the discovery, exploration, and exploitation of undersea cultural resources, namely shipwrecks. WHOI is a leader in the development of new undersea survey technologies that will allow efficient access to nearly 95 percent of the ocean floor. Many of these technologies have been tested on highly-publicized expeditions such as those to the *Titanic* and *Bismarck* sites and to the wreck of the Roman merchant ship *Isis*. The high ethical standards set by WHOI in these instances have drawn worldwide acclaim.

In December 1989, CME and the Deep Submergence Laboratory (DSL) conducted a joint oceanographic expedition with Submarine Development Group One (SUBDEVGROUP ONE) of the U.S. Navy. The program, called the Tactical Terrains Experiment (TACTEX), was designed to utilize a suite of real-time imaging tools from a single oceanographic platform (DSVSS *Laney Chouest*) in order to map the seafloor at a variety of scales and resolutions. These tools included

- Sea Beam (SUBDEVGROUP ONE: hull-mounted multibeam bathymetry),
- the DSL-120 (WHOI: deep-towed, split-beam, side-looking sonar),
- the DSL-200 (WHOI: ROV-mounted, split-beam, side-looking sonar, the *Medea-Jason* system), and
- the manned Deep Submergence Vehicle *Turtle* (SUBDEVGROUP ONE).

The survey area was the San Clemente Escarpment, a seismically active offshore strand of the San Andreas fault system. TACTEX '89 demonstrated the concept of tactical oceanography, the ability to acquire and manipulate multiscale, multisensory data in near real time.

Robert D. Ballard
Center Director

Marine Policy Center

THE WHOI Marine Policy Center (MPC) is one of a small number of research centers in the world dedicating scholarship to public policy issues involving the world's oceans and coastal areas. Issues being examined include progress in science and technology, access to and control of resources, conservation and environmental protection, and international relations. MPC research concentrates on four theme areas:

1) *Global Climate Change:* MPC research contributed to initial estimates of the potential impacts of global sea-level rise from greenhouse warming on low-lying developing countries like Bangladesh and Egypt. As calls have intensified for massive and immediate policy responses to feared global warming, MPC researchers have carefully elucidated the substantial uncertainties remaining and the value of added scientific information in devising an effective response.

2) *Ocean Use and Protection:* Balancing greater use of the oceans with environmental protection is an increasingly complex challenge. Ongoing MPC work, combining the efforts of scientists, economists, lawyers, and resource managers, has identified marine biological diversity as an important natural resource and has also identified opportunities for its conservation. At a local level, careful coastal planning and management are the objectives of an innovative, citizen-sponsored MPC project at Edgartown Harbor on Martha's Vineyard. At the international level, MPC researchers are embarking, with counterparts at the Institute for World Economy and International Relations of the Soviet Academy of Sciences, on a two-year cooperative project entitled "Environmental Security and the World Ocean – Analytic Approaches and Shared Solutions."

3) *Marine Technology:* Our ability to understand and use the oceans effectively depends on progress in marine electronic instrumentation, a "high technology" field

in which U.S. leadership is subject to growing international challenge. Research at MPC is providing a clear understanding of international market dynamics in this field and of the sources and pathways of invention and innovation.

4) *Arctic Studies:* Arctic regions and the polar oceans are of vital importance in international strategic relations, of growing importance for natural resources, and of great scientific interest. During 1989, the Marine Policy Center compiled a volume of authoritative articles on Soviet maritime Arctic policy, including several contributions by Soviet scholars, to provide the first comprehensive survey of factors shaping Soviet marine policy in the vast Arctic domain. This work, as well as research on ocean use and protection, was facilitated by the assignment of a senior U.S. Coast Guard officer to MPC as a Research Fellow.

Throughout the year, MPC research staff and fellows have worked on many levels to inform marine policy decisions with careful analysis and independent scholarship. Again this year, the Center hosted a Congressional Fellow, selected from applicants who serve House and Senate staffs with ocean interests, for a brief research term. MPC researchers forged a link between academic research and policy applications through Congressional testimony, Senate briefings, and participation in national and international advisory bodies.

James M. Broadus III
Center Director

Sea Grant "pond watchers," including Armand Ortins, right, and Edmund Wessling, help with studies of coastal pond water quality.

Sea Grant Program

THE WHOI Sea Grant Program supports research, education, and advisory projects to promote wise use and understanding of ocean and coastal resources. It is part of the National Sea Grant College Program of the National Oceanic and Atmospheric Administration (NOAA), a network of 30 individual programs located in each of the coastal and Great Lakes states to foster cooperation among government, academia, and industry. WHOI Sea Grant channels the expertise of Institution scientists toward meeting the research and information needs of users of the marine environment.

WHOI Sea Grant supports 12 to 15 research projects and a number of smaller "new initiative" efforts aimed at taking the first steps into promising new areas, sometimes involving sponsorship of workshops and conferences. Program thrusts generally address local and regional needs. Emphases include fisheries degradation, water quality, coastal processes and erosion, and marine resources development.

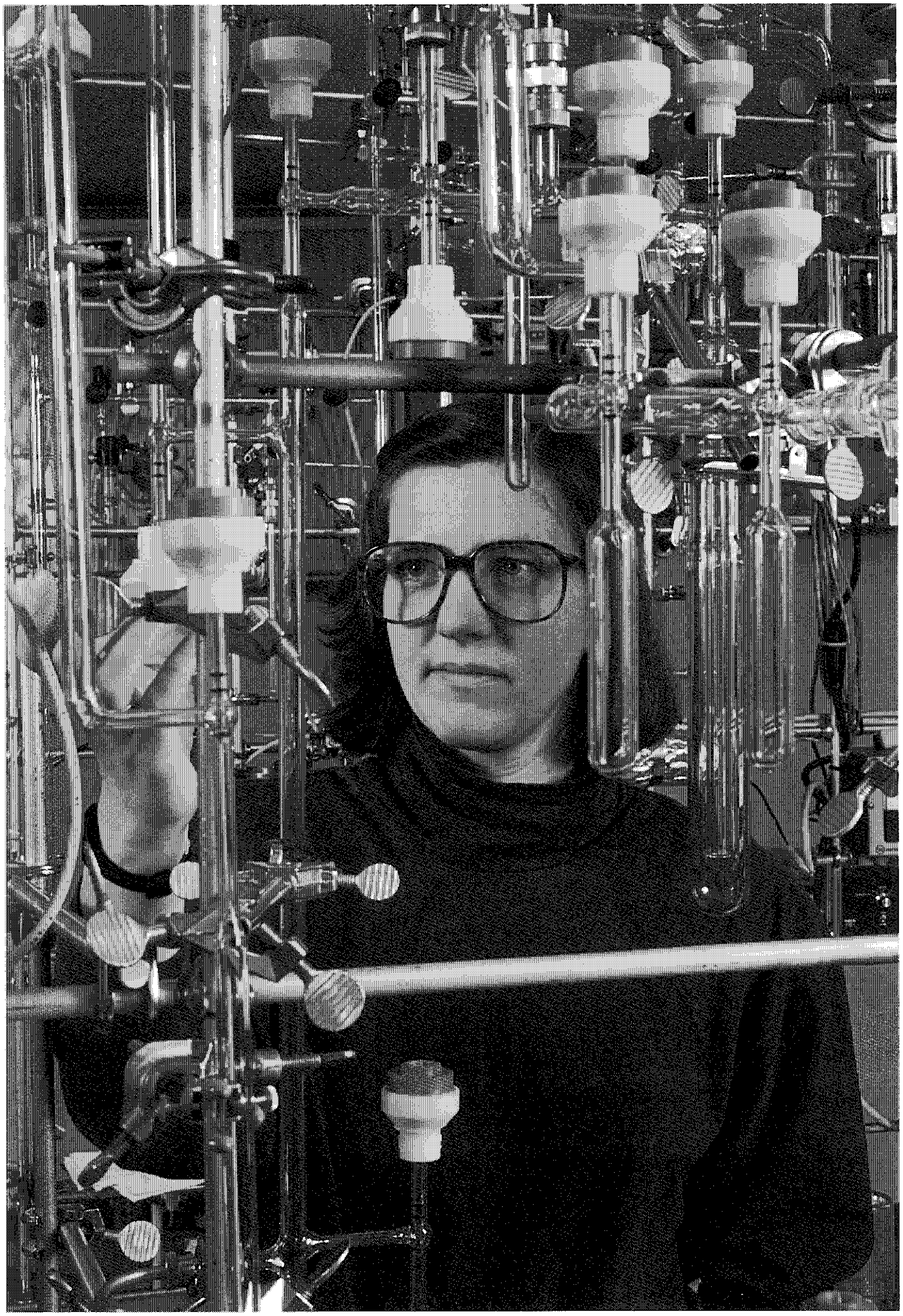
Sea Grant's 1989 projects included studies of:

- the impact of Hurricane Hugo on the Caribbean,
- the physiology and ecology of toxic red and brown tides,
- the water quality of coastal ponds in Falmouth using local volunteers,
- the effects of suspended sediments on coastal currents,
- cyclical behavior in marine minerals research and development, and
- international marine science cooperation.

"Oceans Alive," a marine science lecture series for the general public, was initiated this year. Topics addressed by WHOI staff members and other lecturers on seven Thursday evenings in Redfield auditorium included coastal erosion and sea-level rise, communication in whales and dolphins, ocean hot springs, recreational fishing around CapeCod, and coastal water quality.

David A. Ross
Sea Grant Coordinator

Tom Kleindinst



Reports on Research

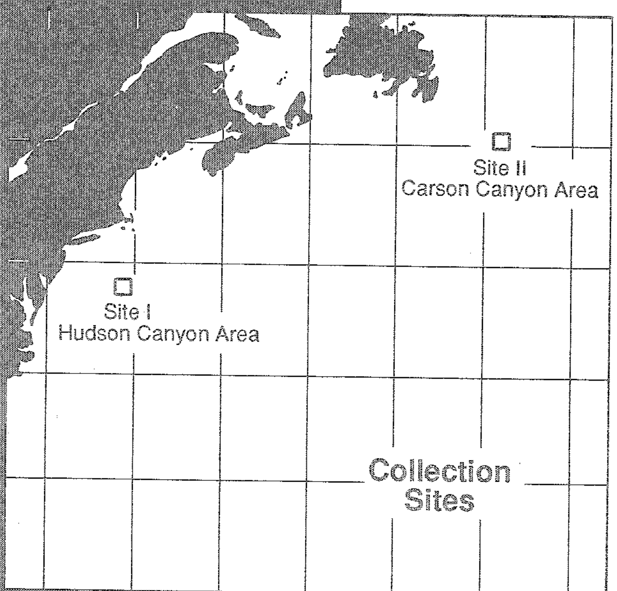
Ann McNichol transfers gases on the Accelerated Mass Spectrometer (AMS) target preparation line. This laboratory is part of the start-up for a national facility to be based at WHOI and sponsored by the National Science Foundation. Construction of a McLean Laboratory addition to house the AMS began in 1989. This will be the first high precision carbon-14 dating facility dedicated to the ocean research community and one of only seven in the world available for radiocarbon dating.

Assessing the Health of the Oceans: Chemical Effects in the Deep Sea

John J. Stegeman,
Senior Scientist,
Biology Department

TWO decades ago the health of the world's oceans was called into question by a series of oil spills and by public figures including Thor Heyerdahl and Jacques Cousteau. Recent events, such as the appearance of medical waste on beaches and massive oil spills at several sites around North America, have rekindled public concern about how human activities affect the health of the oceans. For many marine scientists this has been a continuing concern – biologists and chemists have persisted in efforts to separate fact from fancy regarding effects of contaminants on animals and plants in the oceans.

Seawater is a complex mixture of chemicals. Today, this mixture includes both synthetic chemicals and increased abundance of natural products contributed by human activities. Chemicals such as dioxins, polychlorinated biphenyls (PCBs), and polynuclear aromatic hydrocarbons (PAHs) are now ubiquitous in the global ocean. Many of these compounds are known to be biologically active, and some are reputed to be among the most toxic of chemicals. Some, too, have been associated with disease, including cancer, and with other adverse effects, including reproductive impairment, in mammals. Is there evidence that these chemicals might be contributing to biological change in marine systems? If so, are the changes adverse?

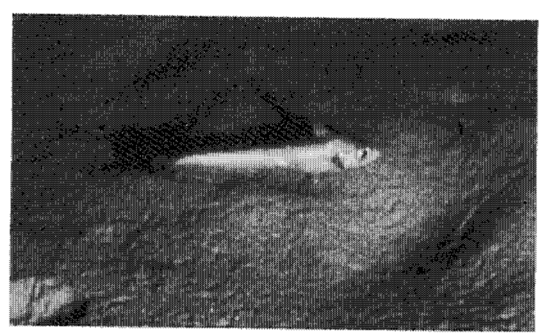


Deep ocean fish were collected at these two sites for studies of biological change in marine systems.

Similar questions concerning chemical-biological interactions are central to investigations in toxicology, pharmacology, and chemical carcinogenesis, in animals as well as humans. Research is devoted to linking precise chemical structures with specific biological changes. Knowing exactly how a given chemical causes a specific change, in other words knowing the *mechanism of action*, is vital to understanding and evaluating health effects and could lead to prognosis and possibly prevention. Detailed study of chemical-biological interactions requires combining analytical chemistry, biochemistry, physiology, molecular biology, and pathology, and may draw on several fields including endocrinology and immunology. While there is concern for changes in populations, it is at the level of individual animals that chemically-induced changes are being detected.

For nearly 15 years, my colleagues and I have been researching mechanisms of chemical effects on marine animals, particularly fish. This research has focused on a biochemical process central to the toxicity of many compounds, a process by which organisms are able to effect a change in the structure of a foreign chemical. Such structural change, or metabolic transformation, can alter the properties of chemicals, often aiding in the elimination of the chemicals from the body. The products of chemical change, however, can be more toxic or more hazardous than the original structure. For example, many of the chemicals that cause cancer in animals do so only after being converted in the body to products that bind to DNA and result in mutations that can lead to cancer.

Our studies on chemical transformations in marine species have centered on the enzymes that actually cause the structural changes in chemical pollutants, including carcinogens. Studies in our laboratory have shown that marine fish have one particular enzyme that converts polynuclear aromatic hydrocarbons to products that cause mutations. This enzyme is one of several called cytochrome P450. Our studies show that in a complex process of gene regulation, the amount of this enzyme in marine fish is increased (induced) by those same aromatic hydrocarbons. Cytochrome P450 is also induced by the highly toxic dioxins and polychlorinated biphenyls. This



The liver tissue of deep-sea-dwelling rattail fish, *Coryphaenoides armatus*, was analyzed for an enzyme that indicates exposure to certain pollutants.

induction is proving to be a "biomarker," an early, explicit biochemical effect of contaminants We are developing sensitive measurement techniques – use of antibodies, enzyme activity, DNA probes – to detect this induction and other similar molecular changes in the biota.

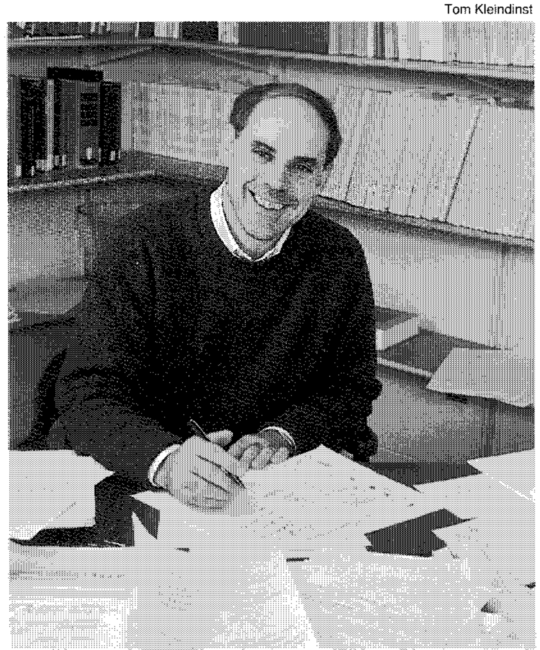
There is cause for serious concern about the health of some coastal waters. In an increasing number of urban harbors, pathologists find cancer in bottom-dwelling fish, often in the liver and often at high prevalence. Work in our laboratory and with collaborators at MIT has revealed important mutations in the DNA from tumors in flounder from Boston Harbor, mutations we believe are caused by chemicals occurring there. In these fish, and those in many other areas, we have also seen greatly elevated levels of the biotransformation enzyme cytochrome P450.

Is evidence for chemically-induced biological change restricted to coastal regions, where human population is concentrated, or does it extend further in the oceans? To address this question we undertook a study of animals in a region removed from any point-sources of chemicals, benthic fish from the deep ocean. We first surveyed a number of deep-sea species, to identify those which could be retrieved from depth (3,000 meters) with little or no apparent change in the biochemistry of cytochrome P450. The rattail fish (*Coryphaenoides armatus*), a widely distributed deep-sea species, was the best candidate. Samples of this fish were obtained on cruises at two widely separated sites in the North Atlantic, one off the eastern United States and one off Newfoundland. Liver tissue from these fish was frozen in liquid nitrogen and returned to Woods Hole where it was prepared and analyzed for the presence of cytochrome P450. Using enzyme assay and antibodies to P450, we found high levels of P450 in the liver tissue of the southern fish but very low levels in that of the northern group. Chemical analysis revealed a similar difference in the concentration of polychlorinated biphenyls in the livers of these fish.

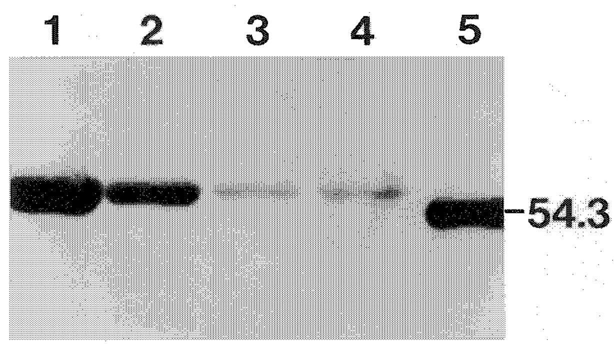
This was the first use of antibodies to detect this type of biochemical change linked to pollutants in the environment and the first direct evidence that contaminants may be causing biological change in the deep ocean. Subsequent studies in a number of coastal regions of North America and Europe have each shown a close relationship between the content of the induced enzyme and the content of contaminant, whether PCBs or PAHs. Such findings strengthen our interpretation of the results obtained on deep-sea fish. In a more recent collection of rattails near a deep-water (2,500 meters) dumpsite off the eastern seaboard, we again detected high levels of the chemically-inducible P450 enzyme. In addition, we have seen widespread induction of P450 not only in liver tissue, but in hearts, kidneys, brains, and embryos of fish, and we have evidence for similar effects in some whales.

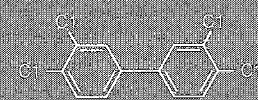
The origin of high contaminant levels in many coastal systems is known. The origin of higher concentrations of contaminants in the deep-ocean is not known. Likewise, the precise environmental chemicals that cause the induction are not known. Our studies are revealing that this response is strongly dependent on the structure of the chemicals and that it is precisely those compounds thought to be most hazardous that cause this change. Further studies to define the structural features of induction-causing chemicals are needed to interpret more accurately

Tom Kleindinst

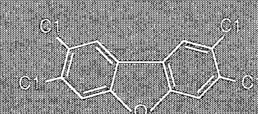


A "western blot" shows antibody detection of P450 in rattail fish. Samples 1 and 2 are from the southern group, and 3 and 4 are from the northern group. Darkness of band relates directly to amount of enzyme.

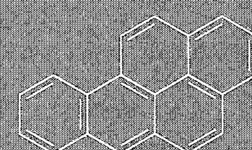




3, 4, 3', 4' – Tetrachlorobiphenyl



2, 3, 7, 8 – Tetrachlorodibenzofuran



Benzo(a)pyrene (B(a)P)

These are structures of hazardous chemicals that are potent inducers of P450 enzymes in fish.

John Stegeman

the causes and the full biological importance of this biochemical change. Now that we know the role of the induced enzyme and the toxicity of chemicals that cause the induction, we may find additional effects. Then we will tackle the complexities of linking these biochemical changes to chemical effects on populations or ecosystems.

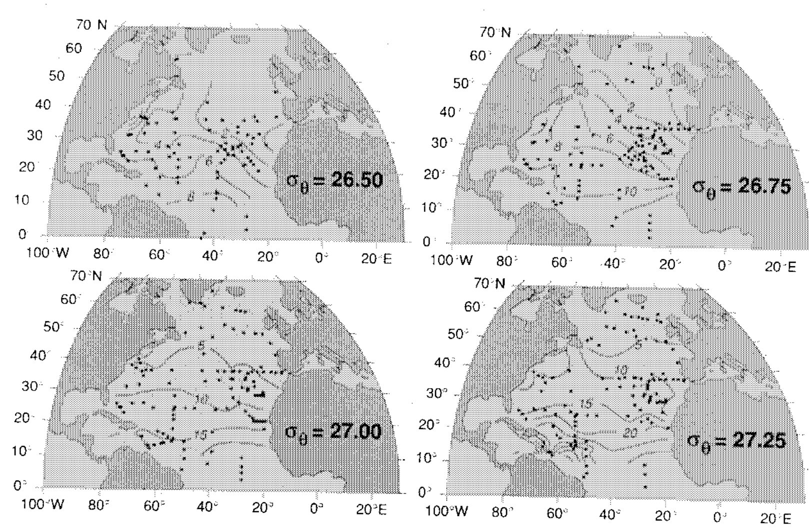
Research on many aspects of chemical-biological interactions in marine species will continue to provide means for assessing chemical effects on the oceans. The present methods for detecting biochemical effects might be used to monitor global trends in exposure of oceanic biota to toxic chemicals, in much the same way that monitoring atmospheric carbon dioxide at selected sites is used to chart trends in global carbon dioxide content. The roles of oceanic biota in global processes, the importance of marine species as food resources, and the potential for new uses of the sea, coupled with growing population, argue that we must fully understand the nature and consequences of human influence on the oceans. Facts concerning chemical effects and the health of the oceans are hard won and can be achieved only through basic research.

Using Geochemical Tracers in Physical and Biological Oceanography

William J. Jenkins,
Senior Scientist,
Chemistry Department

THE world ocean plays an important role in maintaining global climate, in the movement and regulation of geochemicals, and in supporting the global foodweb. Understanding the ocean's present state and predicting its future response to a changing environment requires the study of the physics, chemistry, and biology of the ocean. In many ways, the three are intimately linked – the biota are carried by fluid motion and they experience (and control) a chemical environment. Moreover, important feedback mechanisms exist. For example, the ocean plays a role in the regulation of radiatively important gases such as carbon dioxide and dimethyl sulfide, which affect the earth's climate. Two marine processes important to the global environment are ocean ventilation (by gas exchange, convection, and sinking of water) and primary production (the biological fixing of carbon from dissolved inorganic constituents). Both are difficult to observe and quantify since they occur over large space scales and can be both patchy and sporadic. However, geochemists have at hand powerful tools to study these processes. Tracers, substances occurring in the marine environment in sufficiently minute (but detectable) quantities that they do not affect ocean processes, have much to offer:
1) They provide visibility, serving in some cases as a dye to highlight freshly ventilated water or subsurface ocean currents.
2) They measure rates of processes, acting like a clock or dating tool (analogous to radiocarbon dating of artifacts).
3) They can be averaged (or "integrated") over space and time scales to provide representative measures of spatially varying or episodic processes.

Two examples of the application of tracers to oceanography are studies we have conducted on the physics of ocean ventilation and on biological production in oligotrophic waters.



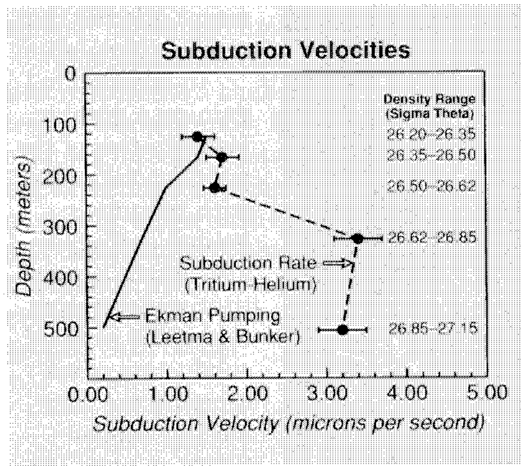
Tritium–Helium Age
on four isopycnals (years)
from TTO-NAS/TAS and NATS (1981)

Tritium-helium age is shown on four density horizons in the North Atlantic. These horizons occupy a depth range of 100 to 1,000 meters in the main thermocline.

Ocean Ventilation

The ventilation of the ocean takes place in a number of ways. Abyssal ventilation, for example, is driven by global scale meridional thermohaline convection (the sinking of cold, dense water in the polar regions and its flow toward the equator). We can "see," or identify, the deep water because it is tagged with anthropogenic tracers, substances resulting from human activities. These "transient tracers" are particularly valuable in that we gain important rate information as we observe their distributions evolving with time. Tritium, the heaviest and the radioactive isotope of hydrogen, was produced by atmospheric nuclear weapons testing in the 1950s and 1960s and travels as part of the water molecule. It appears as a dye, tagging surface water and highlighting its penetration into the abyssal oceans. An additional bonus comes from the fact that tritium decays to the stable, inert, very rare isotope helium-3. We can use the two tracers, tritium and helium-3, in combination to calculate a "tritium-helium age," which supplies us with the time elapsed since the water was last in contact with the surface of the ocean. This technique permits us to date water on time scales ranging from months to decades, precisely the time scales that characterize the processes we need to study.

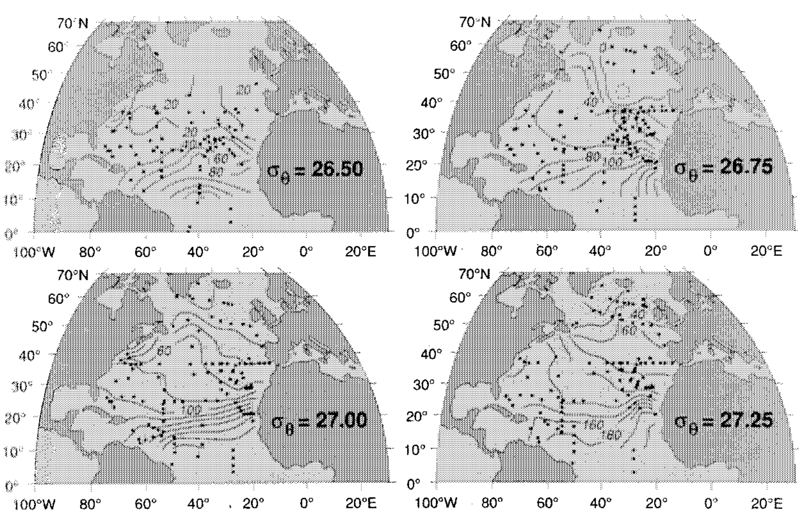
Using this dating technique, we can examine the subduction of surface water into the main thermocline in the subtropics. The main thermocline, a region of



Estimated subduction rates of water on several density horizons is compared here to the rate at which water is forced downward by wind-induced convergence of surface waters.

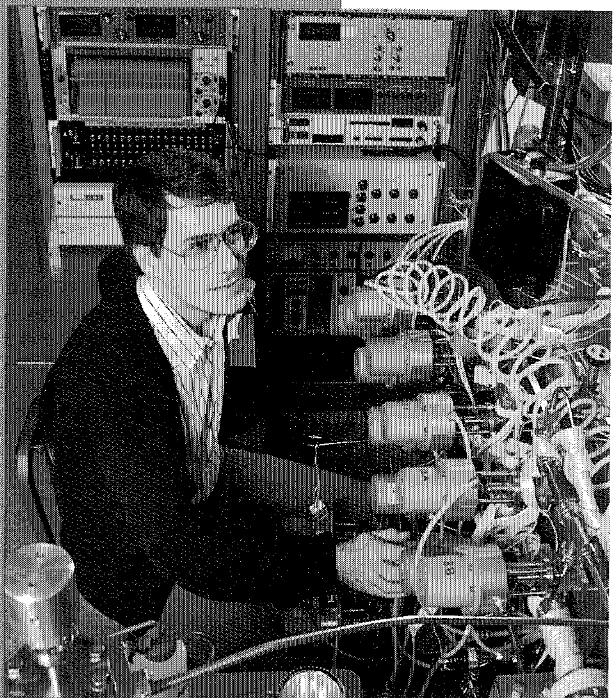
rapidly decreasing temperature with depth, usually occupies the range from 100 meters to 800 meters in the subtropical ocean and is thought to represent a partial barrier to ventilation of the deeper waters. The degree to which the thermocline actually is ventilated, and the manner in which this ventilation takes place, is a critical part of our understanding of ocean ventilation and circulation. Observations of the penetration of man-made tracers into the thermocline indicate that ventilation of the thermocline occurs on time scales of decades or less, time scales ideally suited to tritium-helium dating.

The figure opposite shows the aging of waters on a few "isopycnal surfaces" in the North Atlantic Ocean. Isopycnal surfaces are layers of constant density (recall that the ocean is stratified, with denser water overlain by less dense water) along which water preferentially moves and mixes. These layers outcrop or reach the ocean surface in northerly latitudes. They slope down into the main thermocline in the subtropics, reaching depths ranging from 100 to 800 meters in the "bowl" of the subtropical gyre. In this figure, the curves indicate the tritium-helium age of the water in years, and they show the aging of waters after they leave the ocean surface and are



Apparent Oxygen Utilization (A.O.U.)
on four isopycnals (micromoles per kilogram)
from TTO-NAS/TAS and NATS (1981)

This figure shows AOU or dissolved oxygen deficit on the four density horizons depicted in the figure opposite.



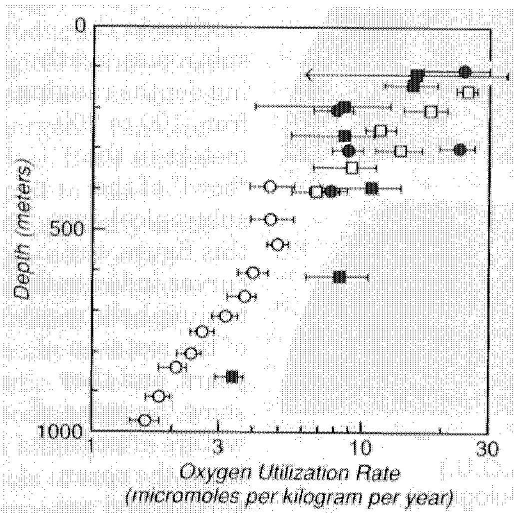
Tom Kleindinst

Bill Jenkins runs samples on the mass spectrometer in his laboratory.

swept into the thermocline circulation.

In addition to gaining a graphic visualization of the ventilation process with tritium-helium dating, we also obtain a quantitative determination of the rates of subduction of waters into the thermocline (upper figure on page 19). Surface water can be forced downward into the main thermocline by two processes. The first is convergence of surface waters by wind stress (referred to as "Ekman pumping"), and the second is underthrusting of deeply convected water caused by the southward decrease in the depth of winter convection. Comparison of the total rate of subduction, obtained by tritium-helium dating, with estimates of the Ekman pumping rate clearly shows where each process dominates.

The tritium-helium dating technique is providing us with a picture of ocean ventilation never seen before and unobtainable in any other way. It is but one tool that geochemists have available to study important physical processes in the ocean.



This figure shows estimates of oxygen utilization rates versus depth using various techniques and data sources. The vertically integrated (total) consumption rate is linked to the flux of organic carbon into the water column from above.

Primary Production

The pictures of water aging on isopycnal levels that we saw in the first figure have a remarkable counterpart in dissolved oxygen distributions. As the water ages, there appears a growing deficit in oxygen (called AOU, short for Apparent Oxygen Utilization) due to the consumption of oxygen by bacteria (lower figure, page 19). Carbon, photosynthetically fixed by plankton in the upper ocean, is oxidized as it sinks toward the ocean floor. The rate at which carbon is fixed at the ocean surface is known as primary production. The carbon that leaves the upper ocean and sinks downward is referred to as "new production" by biological oceanographers and is important to understanding the role of the oceans in geochemical and climate models. For example, new production represents an effective "carbon pump," which can transport man-made carbon dioxide directly to the deep ocean. By combining the tritium-helium dating tool with observed oxygen deficits, we can compute oxygen utilization rates (OURs). More importantly, the vertically integrated OUR, i.e., the total water column oxygen demand, is a measure of new primary production (figure below left.) The kind of new production rates obtained by this approach represent large-scale, long-term average estimates that can only be acquired this way. The levels of new production we see are surprisingly large, exceeding estimates from more conventional biological techniques by as much as a factor of 10. This implies that the oceans are much more productive than previously thought, and also that the biogeochemical cycling of substances in the upper ocean is a much more dynamic and responsive part of the global ecosystem.

By itself, this unusual observation would seem suspicious, since it was so completely unexpected. However, other evidence, largely based on independent tracer techniques, now give the same results. For example, the seasonal cycling of photosynthetically produced oxygen in the upper ocean gives an estimate of new production virtually identical to the OUR estimates. In addition, observations of the seasonal cycling of noble gases in the upper ocean yield a wealth of information about gas exchange, bubble injection, and other processes. We have also used the time history of very slight excess amounts of helium-3 in the surface layer of the ocean to deduce the upward flux of nutrients necessary to fuel this biological production. Again, this estimate yields the same results: the open ocean is much more productive than previously thought. The picture emerging, as the evidence comes in, is of a vigorous and dynamic upper ocean. This has important ramifications in how we model and predict the ocean's response to human activities and our changing climate.

The piecing together of such information represents a challenging aspect of tracer oceanography, for it involves a complex interplay between often demanding experimental techniques, computer modeling, and a dash of intuitive insight and imagination. This is an exciting time in oceanography – our understanding is evolving rapidly, and there are surprises around each corner.

Laboratories on the Seafloor

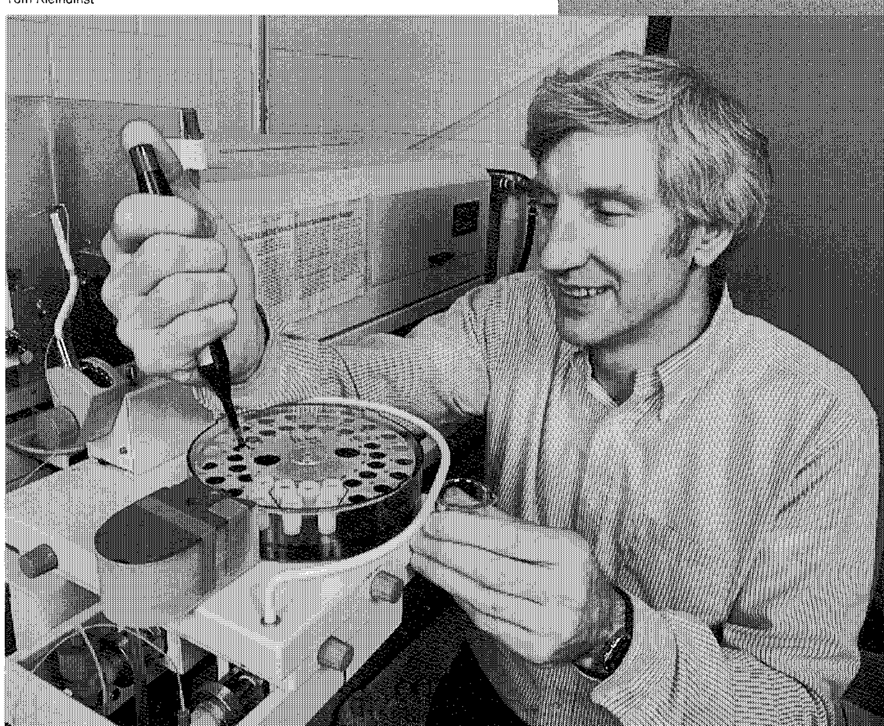
Frederick L. Sayles,
Senior Scientist,
Chemistry Department

THE revolution in microelectronics that has changed all of our lives over the past decade has had a major impact on the science of oceanography. Indeed, the size and power requirements of sophisticated electronics have been far more limiting for those of us who investigate the depths of the oceans than for most: miniaturization allows us to put computers of increasing sophistication in pressure cases and send them to any depth in the ocean. As an additional benefit, the "solid" in solid state electronics has meant that many components are "pressure tolerant," so that a variety of circuits can be used in the deep ocean without the need for heavy and expensive pressure cases. The electronics must be protected from seawater, but this is easily accomplished with oil-filled cases at ambient pressure that require little in the way of strength. With these technological advances, powerful onboard computers can now control the operations and experiments that employ deep-sea research vehicles.

Remotely operated vehicles (ROVs), such as *Argo-Jason* developed at WHOI, are changing the way we explore the depths of the ocean and greatly enhancing our survey capability. A very different type of vehicle born of microelectronics is beginning to bring laboratory style experiments to the seafloor. Called Benthic Landers, these instruments are not mobile, as are the ROVs, but rather are designed to carry out involved manipulations, experiments, and analyses unattended on the ocean floor for weeks at a time. During the past five years we have developed what is perhaps the most complex lander yet designed. A year ago we began regular deep-sea deployments.

One might reasonably ask what led us to invest such time and energy, as well as substantial resources, in a single development task. Five years is, after all, a significant part of a scientist's career, and the deep seafloor is perhaps the most remote real estate on the planet. The compelling reasons all center on the fact that the deep sea, remote as it seems, is an integral and important part of the ocean-atmosphere system. If we are to decipher past climates, understand present day cycling of many compounds in the ocean, and predict future climatic conditions, we must gain a thorough knowledge of seafloor processes. The importance of this knowledge becomes increasingly apparent as we begin to understand the close links between events in the surface ocean and those on the seafloor. While once we thought of seafloor processes as essentially invariant in time, we now know

Tom Kleindinst



Fred Sayles works with the automated sample changer on an atomic absorption spectrophotometer.

better. Not long ago it was believed that the settling of material to the deep seafloor required as much as a year, but now we know that this process takes less than two months. Thus, events occurring at the surface, such as spring blooms that result in greatly enhanced biological productivity, are felt on the seafloor shortly thereafter. Developing an understanding of the response of seafloor processes to varying input has become a major goal of benthic research. It has led to our efforts to develop a benthic lander that would enable us to define the rates of benthic reaction and the extent to which material falling to the seafloor is modified by reaction and either returned to the ocean (recycled) or buried.

Our benthic lander has been designed with three goals in mind:

1) We seek to measure directly the reactions occurring on the seafloor and their rate. This is the most basic information needed to understand the transformations that settling materials undergo as they become part of the sedimentary record. In addition, these data are essential to assessing how quickly the seafloor can respond to changes in the rest of the system, such as the atmosphere.

2) We wish to know where reactions occur – specifically, whether material reacts as it lies on the surface of the sediment or after it is buried.

3) We want to know how much of the material arriving at the seafloor is returned to the oceans as a result of reaction and what controls the proportions that are recycled and buried. This information provides the key to reading the record of past oceans preserved in the sediments.

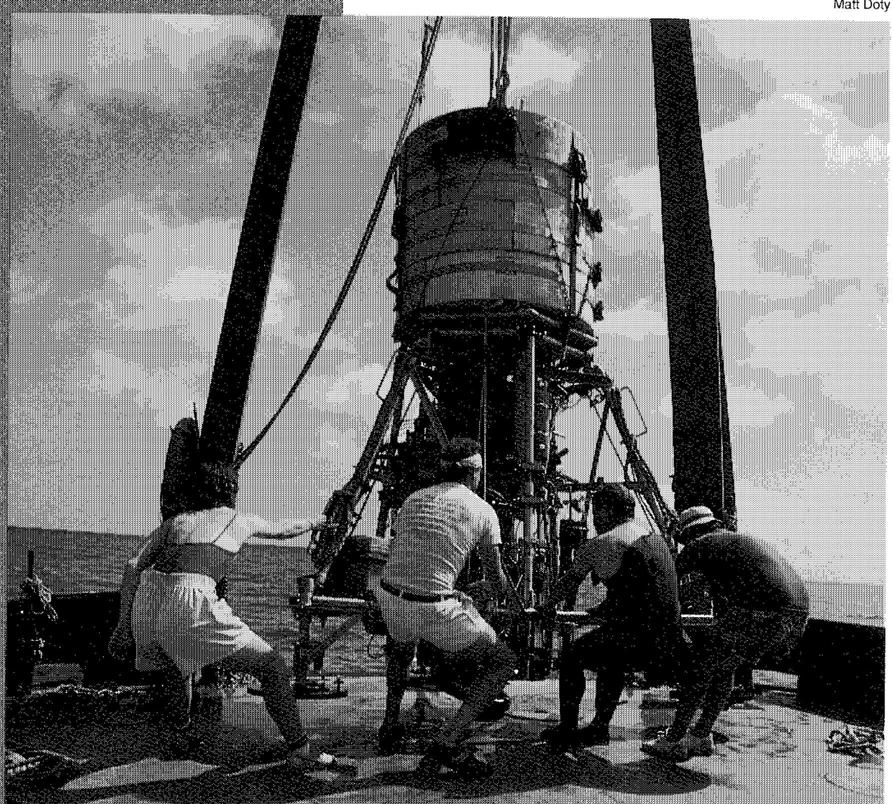
It is in meeting these objectives that the analogy to a seafloor laboratory becomes apparent. To acquire the data we need, the instrument package manipulates samples, adds chemical tracers, carries out chemical analyses, tests the condition of equipment on the platform, makes decisions based upon results, and sends information to a surface ship. As in any modern laboratory, much of the work requires the use of computers.

Today, no self-respecting instrument goes forth into the world without a proper acronym, and our lander is no exception. It has been dubbed ROLAID. Technically, this stands for Robotically Operated Lander for the Analysis of Interfacial Diagenesis. The similarity to a well-known antacid is not coincidental – the five years of development have included more than a little anxiety and associated heartburn.

ROLAID is a type of instrument known as a "free-vehicle," one that is not tethered to the ship. When ready for deployment, ROLAID is picked up off the deck and lowered into the water via the ship's winch. When the top of the lander reaches the surface, the handling cable is released and the lander begins its descent to the seafloor completely disconnected from the ship. It checks its landing sensors during the descent and reports back on their status. On approach to the bottom, buoyancy is adjusted to make possible a very slow and controlled landing. This is essential in order to avoid disturbing the easily suspended material at the surface of the sediment. Sensors tell the computer that ROLAID has landed and a second buoyancy adjustment is made to increase the weight of the lander by 250 pounds. This weight provides stability as it carries out its various experiments. Once on the seafloor, ROLAID initiates its preset sequence of experiments that include inserting chambers into the sediment and sealing them in order to isolate portions of the bottom from the surrounding seawater. The ship leaves the site after receiving data confirming the initia-

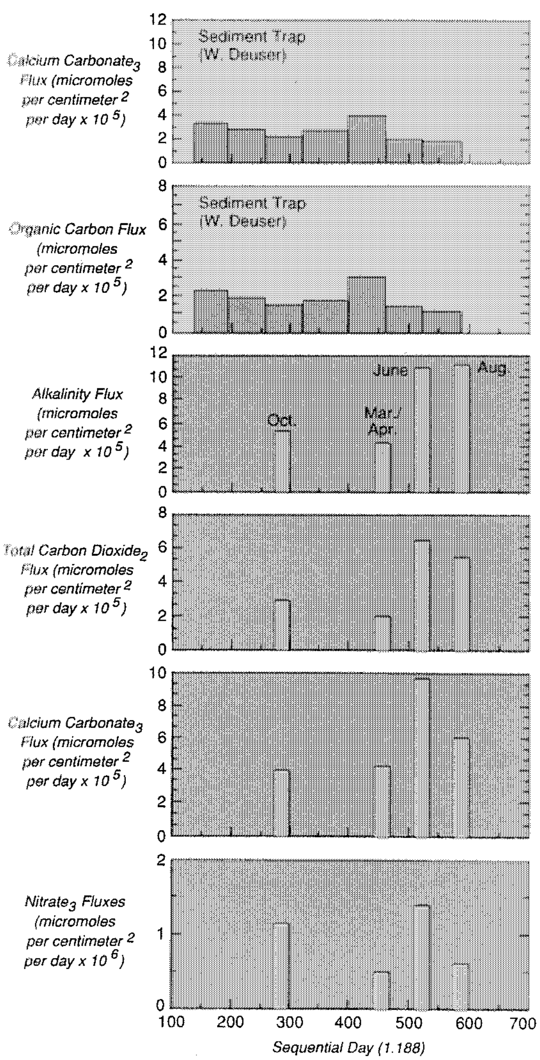
The benthic lander ROLAID is shown being launched from R/V *Weatherbird* near Bermuda.

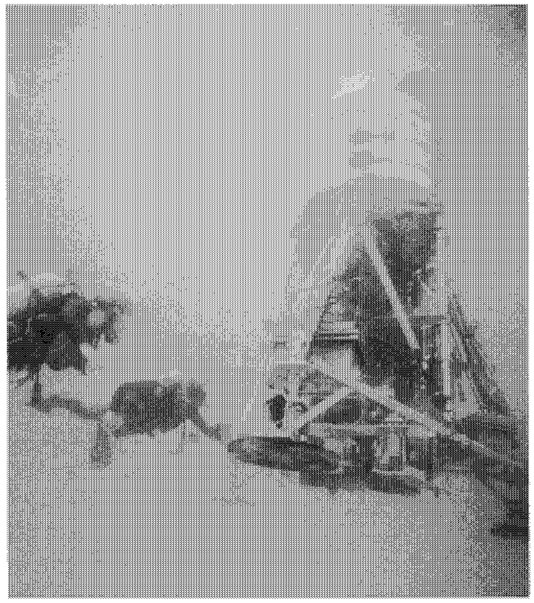
Matt Doty



tion of the programmed sequence. ROLAID continues its experiments, analyses, and sampling for several weeks. At the end of the programmed experiment, we return to the site and send a command that initiates final experiments as well as a "close-down" sequence to retract ROLAID's sensors and equipment in order to protect them during recovery. The last event in the sequence is to drop 275 kilograms of ballast, releasing the instrument from the seafloor and starting it on the 5.5 kilometer ascent to the surface.

The concept of "micro" as it applies to ROLAID is largely limited to the electronics. The equipment needed to complete the program described above makes the instrument as a whole anything but micro. With its various flags for visibility and antennae for communication with ships and satellites, ROLAID stands over five meters tall and weighs in at more than 2,000 kilograms in air. However, it weighs essentially nothing (i.e., is neu-





Matt Doty

trally buoyant) as it approaches the bottom of the ocean. The photo opposite shows the lander being launched from the fantail of the Bermuda Biological Station research vessel *Weatherbird*. The round tan syntactic foam structure at the top of the lander provides buoyancy to bring the lander to the surface at the end of a deployment. The pads upon which it stands are the ballast released to initiate ascent to the surface. They double as foot pads while ROLAID is sitting on the sediment surface. The orange case at lower left is one of three batteries that provide power for operations on the seafloor. In the photo above, the lander settles to the bottom under the watchful eyes of divers in shallow water tests.

While only in use for a year, ROLAID has already begun to provide new insight into the link between events occurring at the surface of the ocean and processes on the seafloor. Our measurements of reactions on the seafloor clearly show that benthic processes respond extremely rapidly to changing conditions at the surface. The "rain" of particles to the seafloor has been measured continuously at Bermuda for more than a decade by WHOI Senior Scientist Werner Deuser. He has clearly demonstrated the existence of a peak in particle flux that follows, and is due to, the spring bloom at the surface of the ocean. The results from ROLAID show that this pulse has a counterpart in the reaction rates in and on the seafloor. Between one and two months after the peak in particle rain, we see a corresponding jump in benthic "remineralization"

ROLAID settles to the bottom with divers nearby for shallow water tests.

The figure shows a summary of particulate and benthic fluxes measured in 1988 and 1989. The two upper graphs show sediment trap measurements, and the four lower graphs show benthic lander measurements. The height of each bar is a direct measure of the rate at which material is delivered either as particles to the sediments or as dissolved chemicals to the lander chambers.

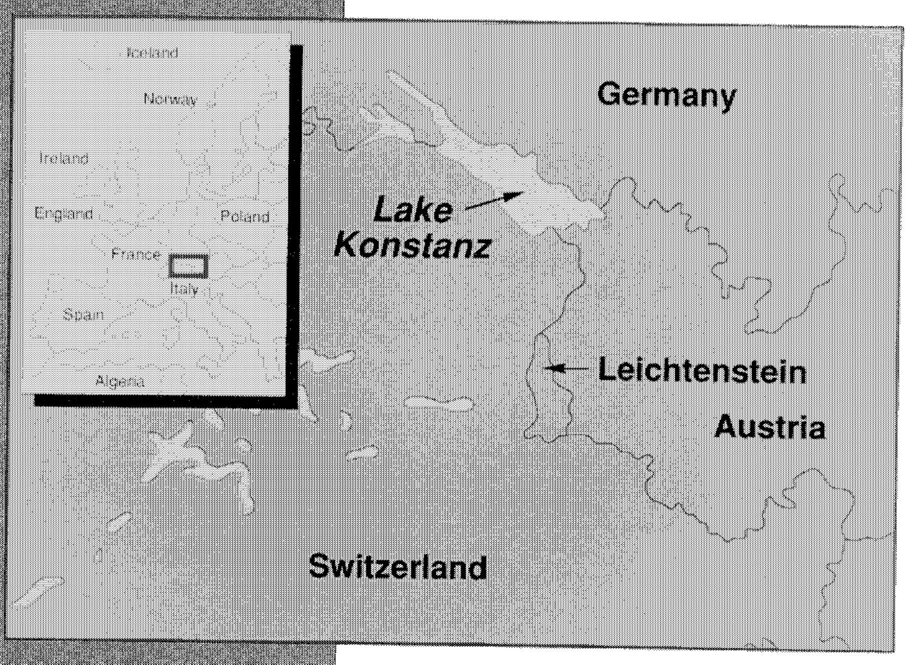
(reactions that break down solid materials and recycle them to the ocean in dissolved form). We observe this as a flux of dissolved substances into the chambers ROLAID implants in the seafloor. This relationship is illustrated in the figure overleaf where some of our results are compared with Deuser's. While we do not see any increase in the deployment immediately following the particle flux spike, fluxes have fully responded two months later. The enhanced benthic activity persists for at least three months. Further, the size of the benthic fluxes are comparable to the particle fluxes. The time lag and the amplitude of the response can be modeled to provide quantitative information on the nature of the reactions occurring, the rates of reaction, the location of reaction relative to the sediment-water interface, and the character of the material undergoing reaction. These data form the basis for understanding how the seafloor responds to events in the surface ocean as well as how fast it occurs. This information, in turn, is essential in predicting the feedback loops of the ocean-atmosphere system and hence the consequences of perturbations in any part of that system.

Long-Term Climate Change and the Freezing of Lake Konstanz

Andrew R. Solow,
Assistant Social Scientist,
Marine Policy Center

AS every reader of the science section of the newspaper knows by now, the greenhouse effect refers to the process by which water vapor, carbon dioxide, and other trace gases trap reflected solar radiation and warm the atmosphere. Since the Industrial Revolution, and especially over the past 30 years, the levels of greenhouse gases have been increasing in the atmosphere due to such human activities as the consumption of fossil fuels. This change in atmospheric composition threatens to enhance the greenhouse effect and cause the Earth to warm at an unprecedented rate, a threat that promises to be the premier environmental issue of the 1990s.

Lake Konstanz is the third largest lake in Europe.



Fears about global warming rest in part on the instrumental temperature record that begins around 1850. On a global basis, this record shows an irregular warming amounting to somewhat less than 0.5°C (1°F). Although the magnitude of this warming and its detailed temporal and spatial behavior are inconsistent in important ways with what is expected under an enhancement of the greenhouse effect, some have claimed that its mere existence constitutes detection of greenhouse warming.

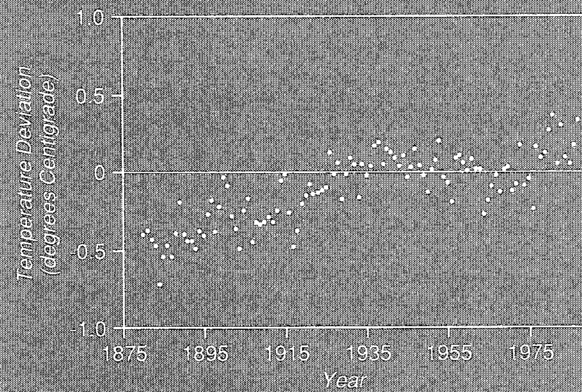
Scientists know that global climate exhibits natural variability at many time scales. Global temperature has varied by 10°C (9°F) or more over the past two million years. Since the end of the last major ice age 11,000 years ago, the Earth has been subject to alternating periods of warming and cooling. In understanding global climate generally, and in interpreting the instrumental temperature record specifically, it is therefore very important to extend the climate record back beyond 1850.

Instrumental temperature measurements are not available before 1850 except for a few locations. There are, however, many types of indirect information about temperature. Of these, measurements based on growth rings of trees are probably the best known. Other indirect information comes from harvest records, ships' log records of sea ice extent, and even anecdotal information from personal diaries. Information of this type is very different from direct measurements (which are themselves not without problems). Serious questions about reliability and geographic representativeness arise, as well as about methodological issues concerning the translation of indirect measurements into estimates of temperature. Nevertheless, provided that it is interpreted cautiously, information of this type can be very useful in understanding the historic behavior of climate.

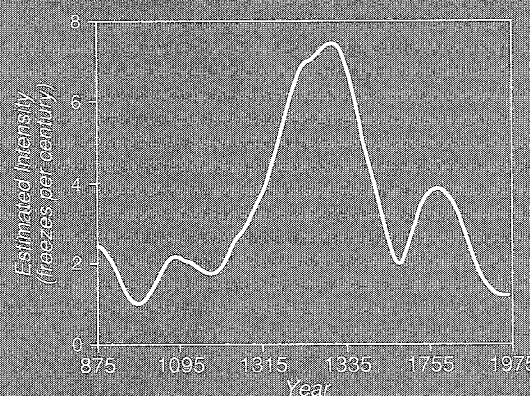
One of the oldest European climate records concerns the occurrence of major freezes of Lake Konstanz. Bordered by Austria, Germany, and Switzerland, Lake Konstanz is the third largest lake in Europe with a surface area of 539 square kilometers (210 square miles). It is customary to distinguish between various minor parts of the lake and the larger upper lake. While minor parts of Lake Konstanz freeze rather frequently, it is extremely rare for the upper lake to freeze. A major freeze of Lake Konstanz is said to occur if the upper lake, which ranges in width from 7 to 14 kilometers (4 to 8 miles), is frozen to the extent that it can be crossed on foot. A record of such freezes has been kept from 875 A.D.

In statistical terminology, data of this type – that is, the times at which certain events occur – are said to have arisen from a "point process." A point process is characterized by an intensity function, which gives the mean number of events (in this case, freezes) per unit time interval. In this case, the unit time interval was taken to be one century. Using a flexible method called kernel estimation, it is possible to determine the way in which the intensity function of the Lake Konstanz record has varied over time. The estimate shows a low rate of freezing around 1000 A.D. followed by a rapid increase until around 1500 A.D. The rate has been falling since 1500 A.D., although there was a brief increase during the first half of the 19th century. This overall pattern is in general agreement with what is currently believed about European climate over this period. The low rate of freezing near the beginning of the record corresponds to a period called the Medieval Optimum. The peak around 1500 corresponds to the height of the Little Ice Age. The smaller peak around 1800 corresponds to the terminal pulse of the Little Ice Age. While the existence of this overall pattern can be confirmed from many indirect climate records, its cause remains a mystery.

As far as greenhouse warming is concerned, these results carry an important message: natural climate change is the rule, not the exception. When greenhouse warming occurs, it will be superimposed on a climate that will be changing for other reasons. This complicates the detection question considerably and means, for example, that the existence of a warming trend does not by itself constitute greenhouse warming. The details of the estimate show that the period of the instrumental record coincides with a warming period, at least near Lake Konstanz. This suggests that those who claim detection based on the warming of the past century may be too hasty.

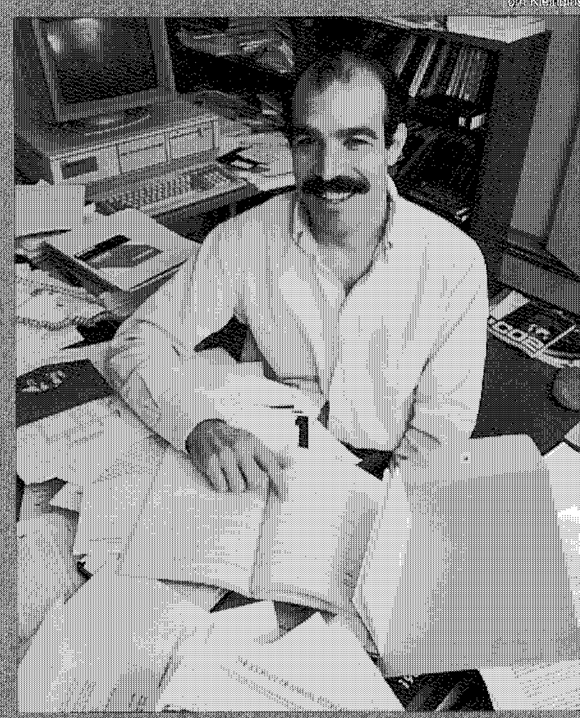


Above: For this estimate of mean global surface temperature from 1880-1988, the average for the period 1951-1980 has been subtracted from each point to give a temperature deviation.



Above: In this estimate of the intensity of major freezes of Lake Konstanz from 875-1976, intensity is measured in freezes per century.
Below: Andy Solow with paper and computer.

Tom Kleindinst



Monitoring the Monsoon of Southern Asia

William B. Curry,
Associate Scientist,
Geology & Geophysics Department

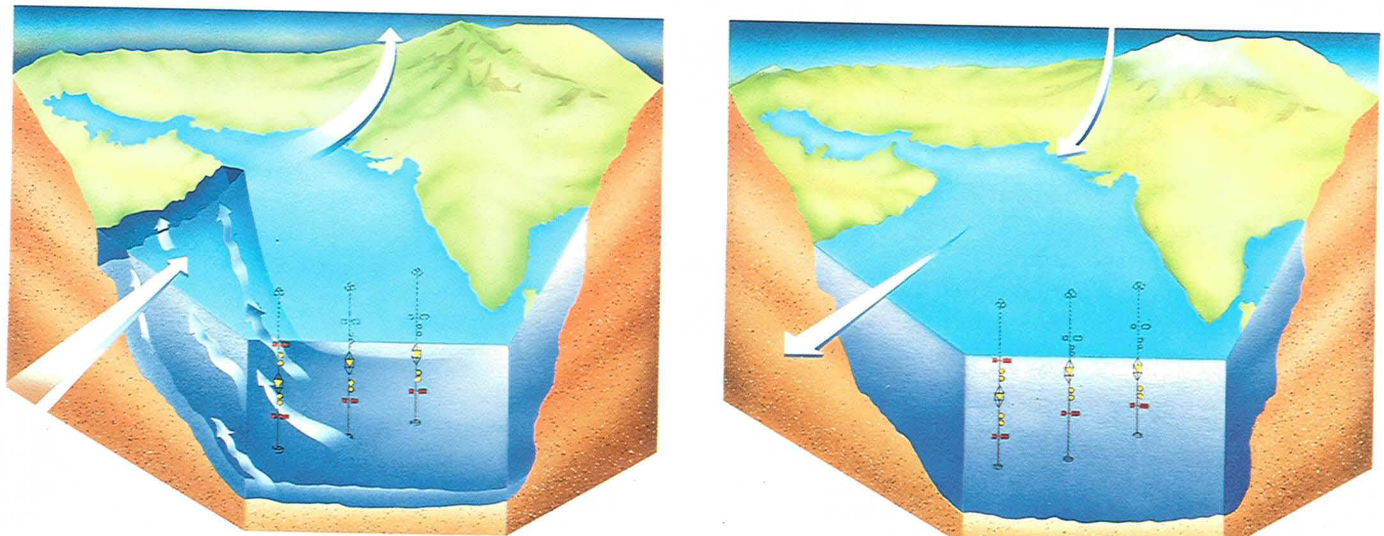
The schematic representation below shows southern Asia monsoon circulation with summer at left and winter at right. In summer, the Asian continent warms faster and to a greater extent than the northern Indian Ocean. This produces a cell of rising air over the continent and onshore winds, which parallel the Oman coast and force the warm surface waters of the Arabian Sea offshore to be replaced by cold, upwelling, nutrient-rich subsurface waters. Along the Oman coast, these replacement waters may be as much as 10°C cooler than the surrounding seawater, and their high nutrient concentrations provide a fertile environment for active biological production. During winter, the reverse circulation results as the continent cools faster and to a greater extent than the ocean. Because the winds parallel the Oman coast in the opposite direction, upwelling does not occur, surface waters remain warm, and productivity in the surface waters is low.

ABOUT one-half of the world's population lives on the one-quarter of the earth's surface where monsoons are an important feature of climate. Since this population is largely agricultural, changes in the intensity of the monsoon, and the resulting heavy rainfall or drought, have a clear and important impact on their lives. Written records of monsoon variability over the last century for southern Asia show that while interannual variability is the norm, successive, decade-long intervals of drought or high rainfall have also been common. Our work with sediment traps in the Arabian Sea has recently confirmed the hypothesis that the history of the monsoon is graphically recorded in changes in the fossil assemblage found in deep sea cores from the region. By reconstructing the history of the monsoon as it is recorded in deep-sea sediments, we will begin to understand what factors cause variations in monsoon intensity and timing.

Monsoons occur in tropical regions where differential heating of the land and adjacent ocean causes seasonal changes in the pattern of atmospheric circulation (see figure below). During summer, continents heat up much faster and to a greater extent than the surrounding ocean. This unequal heating causes the air to rise above the continents and moisture-laden surface winds to flow from the ocean to the warm continent, where the heavy monsoon rains fall. In winter, the reverse flow is produced because the continents cool more quickly and to a greater extent than the nearby ocean. This pattern of seasonally reversing winds occurs throughout tropical Africa and southern Asia.

During summer in southern Asia, when the Tibetan Plateau heats up, the resulting atmospheric cell produces winds that parallel the Oman coast, producing Ekman transport (divergence of surface water by wind stress) and strong upwelling in the western Arabian Sea. During winter, when the land surface is cooler than the sea surface, the cell reverses, and no upwelling occurs. This seasonal contrast in ocean circulation, one of the most extreme observed in the oceans, produces a sharp seasonal change in surface water productivity (figures at bottom of opposite page), in the types of organisms inhabiting the region, in the ocean chemistry of the subsurface waters, and, consequently, in the rain of particles through the water column to the seafloor.

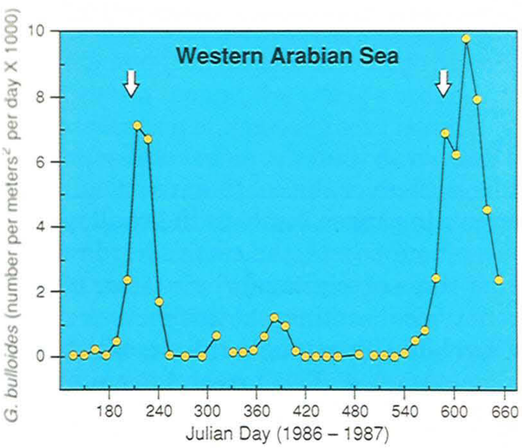
Since May 1986, skeletal remains of surface-dwelling organisms have been collected in sediment traps deployed in the Arabian Sea by WHOI's Particle Flux Experiment research group in collaboration with the University of Hamburg and the National Institute of Oceanography in Goa, India. We use these samples to measure the response of a group of single-celled animals, called planktonic foraminifera, to the seasonal variations in productivity by counting the number of their shells caught in our traps in various seasons. Our goal is to develop quantitative geological measures of monsoonal variability in order to: 1) document the natural variability of monsoon circulation during different climate regimes, and 2) predict changes in monsoon circulation



E. Paul Oberlander

that may occur in response to future changes in climate.

In the sediments under the upwelling cell, the predominance of a single species of planktonic foraminifer, *Globigerina bulloides*, has led previous researchers to use its variations in sediment cores to reconstruct the history of the south Asian monsoon for the last 100,000 years. Our measurements of the foraminifera in the sediment trap samples show that both abundance and species composition change in response to seasonal changes in upwelling (figure below). The foraminiferal productivity record for 1986 and 1987 indicates that the production rate of the species *Globigerina bulloides* parallels the changes in monsoon upwelling, with the highest *Globigerina bulloides* productivity occurring during monsoon season.



These changes in foraminifera production are dramatic, the largest seasonal changes in productivity observed in any sediment trap samples to date. They confirm the hypothesis that the history of the monsoon is recorded in the changes in foraminifera assemblage observed in deep-sea cores from the region. Work published in 1981 by Warren Prell of Brown University and the author showed that the geographic distribution of *Globigerina bulloides* in core-top sediments parallels the geographic pattern of upwelling during the southwest monsoon, with highest concentrations of this species found under the area of most intense upwelling. Later, Prell and John Kutzbach of the University of Wisconsin found that higher and lower concentrations of *Globigerina bulloides* in sediment cores vary in concert with past variations in solar intensity over the Tibetan Plateau. Changes in the geometry of the earth's orbit affect the distribution of sunlight on the surface of the earth on time scales of thousands of years. By altering the distribution of heat, which affects the temperature contrast between the continent and nearby ocean, orbital variations provide the mechanism to control monsoon intensity and timing on very long time scales.

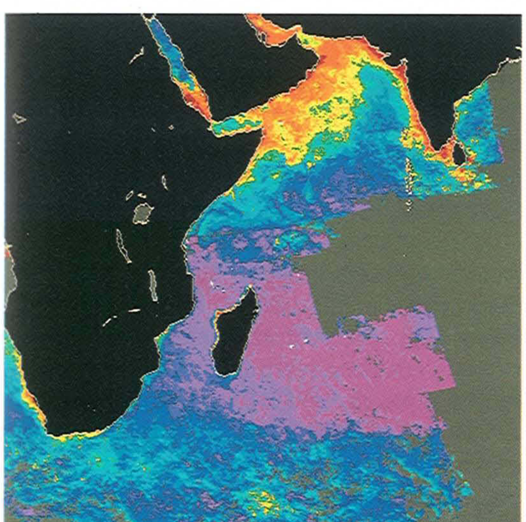
The mechanisms affecting monsoon intensity on shorter time scales are less

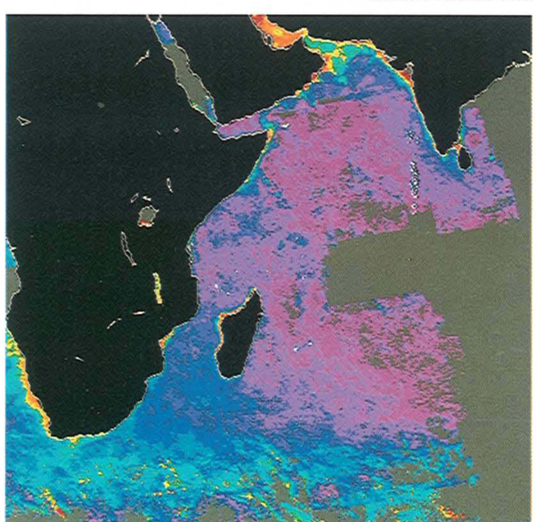
Tom Kleindinst

Above: Bill Curry, who spent most of 1989 shuttling to Washington to serve as an associate program manager at the National Science Foundation, works at his laptop computer.

Left: The record of *Globigerina bulloides* production during 1986 and 1987 is plotted here. During the summer months, when upwelling is greatest in the western Arabian Sea, the productivity of this species increases by three orders of magnitude, the highest productivity of a foraminiferal species observed in the oceans. The arrows document the onset of monsoonal upwelling as recorded in 1986-87 infrared images from the Nimbus 8 and 9 satellites. Both the onset of the monsoon and the increase in productivity for this species occurred about two to three weeks later during 1987. The strong relationship of this species' abundance to the summer monsoon suggests that its preserved shells in the sediments may be used to quantify past changes in the intensity of the monsoon.

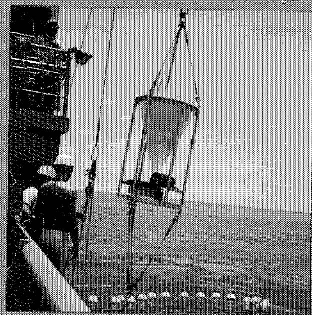
Gene Carl Feldman, NASA





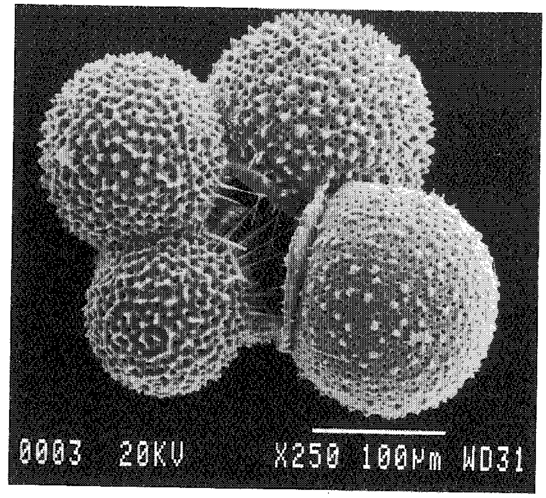
Left: Satellite images of chlorophyll concentration in the upper ocean document the extreme seasonality of productivity resulting from monsoonal circulation. During the summer monsoon (left), the productivity is greatest (indicated by yellow to red) in the coastal zone along the Somali coast in the cooler, nutrient-rich, upwelled water.

Steve Manganini



Above: A sediment trap launch in the Arabian Sea. *Right:* The shell of the planktonic foraminifer *Globigerina bulloides*, the predominant foram species in the sediments of upwelling regions in the northern Indian Ocean and the principal component of summer monsoon sediment trap samples.

clear, but we know that the intensity and timing of the monsoon can vary considerably even year to year. The graph overleaf shows that the onset of the monsoon differed in 1986 and 1987. The large increase in production of *Globigerina bulloides* occurred about two to three weeks later in 1987, consistent with preliminary observations from satellite images, which suggests that the upwelling was delayed during this season. While we do not yet know the reason for changes in the monsoon on these time scales, it is clear that a better understanding of these short-term variations could have a significant impact on the lives of people living in areas affected by the monsoon.



Louis Kerr, MBL Central Microscopy Facility

Poaching Sound for Seismology

G. Michael Purdy, Senior Scientist, &
W. Steven Holbrook, Assistant Scientist, Geology & Geophysics Department

THE earth's crust is a thin skin covering the mantle and core of our planet. The movements of this crust generate earthquakes, its collisions build mountains, its subsidence permits the accumulation and maturation of hydrocarbons, and, fueled by heat losses from the earth's interior, it is the site for separation and deposition of all our mineral wealth. The understanding of crustal processes is thus of fundamental concern to society.

The single largest structural discontinuity in the earth's crust occurs at the margins of the continents. A far greater feature even than the global mid-ocean ridge system or the continent's grandest mountain ranges, beneath the shallow seas off our coasts, the earth's hard rock crust thins precipitously by a factor of five from typical continental thicknesses of around 30 kilometers to the ocean's thin 6-kilometer crust. This massive thinning is due to the processes of continental rifting and break-up that are the precursors to seafloor spreading and the birth of a new ocean (see upper figure opposite).

Our knowledge of how a continent breaks apart is minimal and to understand this better we must learn about the structures and processes occurring at depths 10 to 40 kilometers below our continental shelves. Seismology is one of the few tools available for such studies, but until recently the experimental techniques available to the marine seismologist have been inadequate to the task.

During the past 10 to 20 years, the methods for the collection and processing of marine multichannel seismic reflection data have been revolutionized. These developments have been motivated by the oil industry, which, even in these currently depressed times, is spending worldwide several hundred million dollars annually for the collection of marine seismic reflection data. These techniques are, however, specifically directed towards the search for hydrocarbons and thus are designed to image structures within the

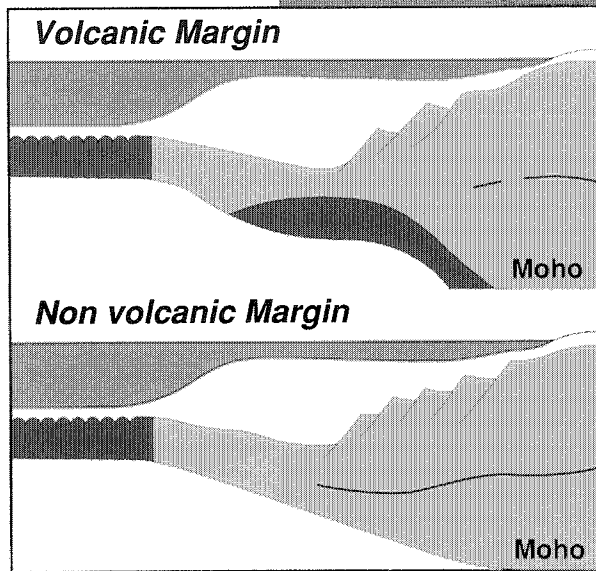
Purdy, left, and Holbrook.

Tom Kleindinst

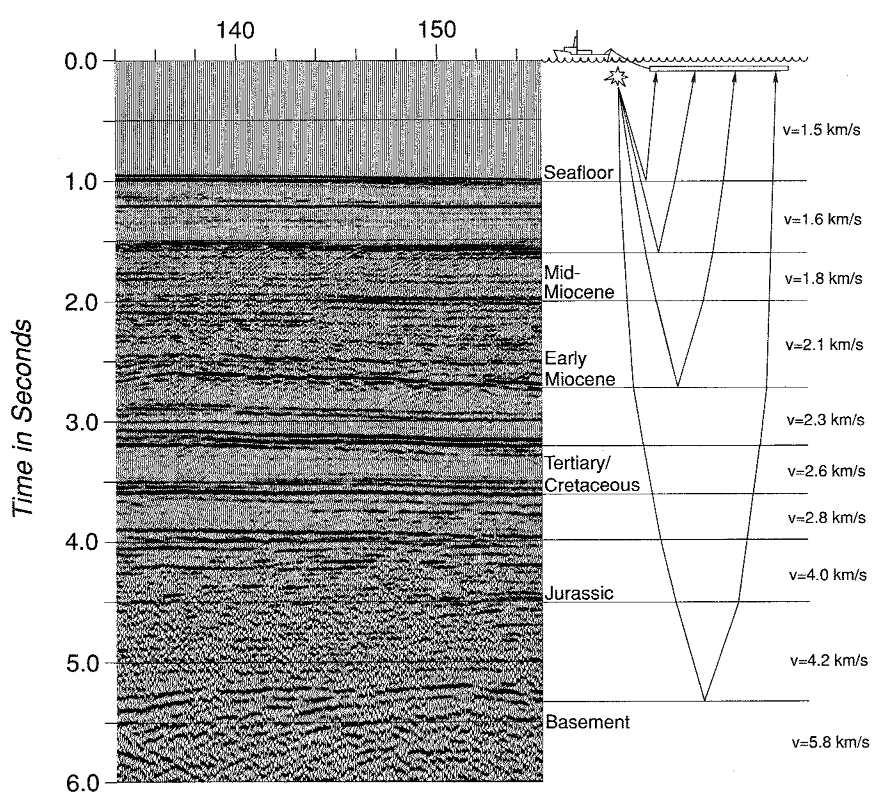
sedimentary strata where such deposits are formed and accumulate. Sedimentary structures formed by depositional processes and then modified by subsidence, faulting, diapirism, or intrusion are an ideal target for the near normal incidence seismic reflection method because they are frequently characterized by laterally extensive acoustic impedance contrasts associated with the boundaries between different strata. These boundaries reflect sound back to the sea surface to be recorded by the research vessel where a direct image of the subseafloor structure can be constructed (see figure below right). Although this method is immensely successful at mapping sedimentary structures as deep as 5 to 10 kilometers below the seafloor, only rarely does it image structures within the hard volcanic basement rocks which hold the clues to continental breakup and formation of the huge discontinuities that bound the world's oceans. The generation of igneous rocks is not a depositional process, so rarely do we find laterally continuous acoustic impedance contrasts within the hard-rock basement that will generate coherent and mappable normal incidence reflections. The seismologist must then use different approaches if the structures within the hard-rock basement are to be probed and understood.

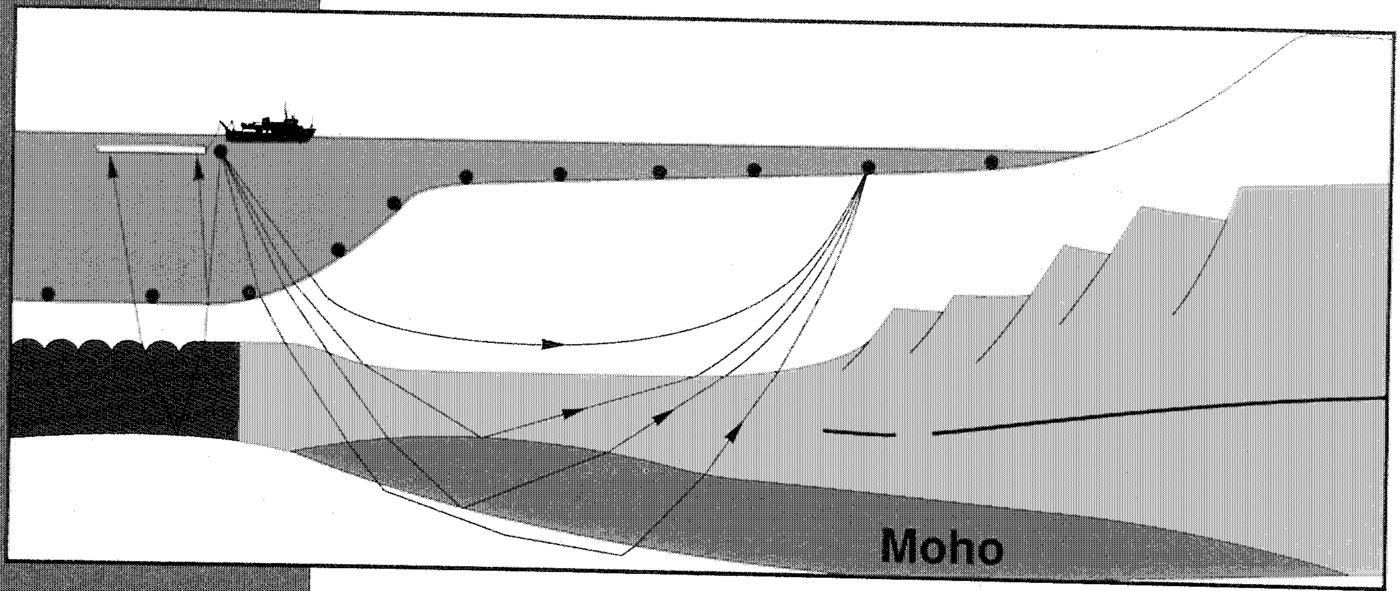
Fortunately for us, although sharp reflecting boundaries rarely exist within igneous rocks, they are almost always characterized by 1) vertical and lateral changes in sound velocity that refract the seismic waves and are relatable to changing mineralogy, crack structure, or temperature, and 2) broad formational boundaries that do not reflect much energy at near normal incidence, but do return energy at wide angles, particularly near the critical (or "grazing") angle of incidence. If techniques could be developed to map these refracted and wide-angle reflected waves, then we can image the interior of the hard-rock crust and map the boundary between the crust and the upper mantle (the "Moho").

The two primary components of any seismic experiment are 1) a system for generating sound, and 2) listening devices to receive and record the energy returned from the earth's interior. In the case of simple reflection profiling, a single ship tows an array of airguns to produce sound and a long string of hydrophones to record the reflections. It is clear, however, that if our goal is to record refracted and wide-angle reflected energy, then the source and receiver must be separated by substantial distances. In practice, required separations reach 100 to 200 kilometers (see figure overleaf) and the returned seismic energy must be recorded by remote seafloor units such as ocean bottom hydrophones (OBHs) that record pressure waves propagating through the water column. Unfortunately, such experiments are very expensive. To generate enough seismic energy to propagate more than a hundred kilometers through the crust, a substantial source must be used. Explosives are a relatively economic solution, but they are not practical for experiments on or near the continental shelf for environmental reasons. Large arrays of airguns (with firing volumes of 10,000



Above: Drawing shows possible deep structures of a volcanic (upper) and a nonvolcanic (lower) passive continental margin. Note the presence of a postulated "underplated" layer of basaltic volcanic rocks (red) beneath the volcanic margin.
Below: A typical multichannel seismic image of subseafloor structure shows reflections (left) from velocity boundaries within seafloor sediments. These reflections are generated by an airgun and recorded by a hydrophone streamer towed behind the multichannel seismic vessel.





Schematic diagram shows a "piggyback" ocean-bottom seismic experiment. Ocean-bottom hydrophones (OBHs) deployed on the seafloor record sound from an airgun source towed behind a multichannel seismic vessel. The OBHs record seismic energy at offsets up to several hundred kilometers, thus greatly expanding the narrow "aperture" of the multichannel streamer.

cubic inches) are available and do produce enough energy, but they are also expensive to operate, requiring a substantial dedicated vessel just to carry the many compressors to produce the required volume of high pressure air. Such vessels are, however, in everyday use by the oil industry for the collection of simple reflection data. And it is this fact that prompts the title of this article.

We have had an active and successful OBH program at WHOI for 15 years, so we already have the recording capability for long-range, wide-angle reflection/refraction experiments. What we need is an economic means of providing a source. If we can "poach" the sound generated for oil industry exploration by deploying our instruments along their track lines, we can listen to the refracted energy at long ranges that otherwise would be wasted. (Given the high costs associated with the production of this sound, it seems irresponsible not to fully utilize it in every possible way.) Such experiments do not interfere with normal operations of reflection profiling vessels.

We have already successfully carried out one such "piggy-back" experiment across the U.S. East Coast continental margin off the Carolinas in 1988. A second operation, funded by the National Science Foundation, is scheduled for June 1990 to provide a second structural profile across the ocean-continent transition off Chesapeake Bay. Both these experiments have "piggy-backed" on reflection profiling for other academic groups: in 1988 for the University of Texas at Austin and in 1990 for the EDGE project headquartered at the Houston Area Research Center. We are further developing our OBH instrumentation to permit more flexible and rapid response opportunities to collect new data, and we are working with oil industry colleagues toward "piggy-backing" on certain well-chosen oil company reflection profiles.

By not recording the long-range wide-angle reflection and refraction energy generated by the huge airgun arrays that are in routine use today, we believe that tens of millions of dollars worth of superb broad-band seismic energy is being "wasted" every year. In taking some small steps towards correcting this situation, we will produce images of the deep structures beneath the continental edges that are the key to distinguishing the mechanisms of continental rifting.

Ambient Noise Beneath the Seafloor

Ralph A. Stephen,
Associate Scientist,
Geology &
Geophysics
Department

FOR more than 50 years, we have listened to ambient noises in the oceans generated by weather, animals, earthquakes, and shipping. Only in the last 10 to 15 years, however, have we been able to place sensors below the seafloor where the measurements will not be contaminated by fluid flow over the instruments or by poor coupling to true earth motion. The first borehole seismic measurements were made from the drill ships *Glomar Challenger* and *JOIDES Resolution*, but true ambient noise was rarely obtained because the drill ship was usually on station over the hole. Over the past three years, we have been developing a system to deploy a vertical array of seismic sensors into the seafloor without the drill ship and to record the signals autonomously using a seafloor package. This project was called the Low Frequency Acoustic Seismic Experiment (LFASE).

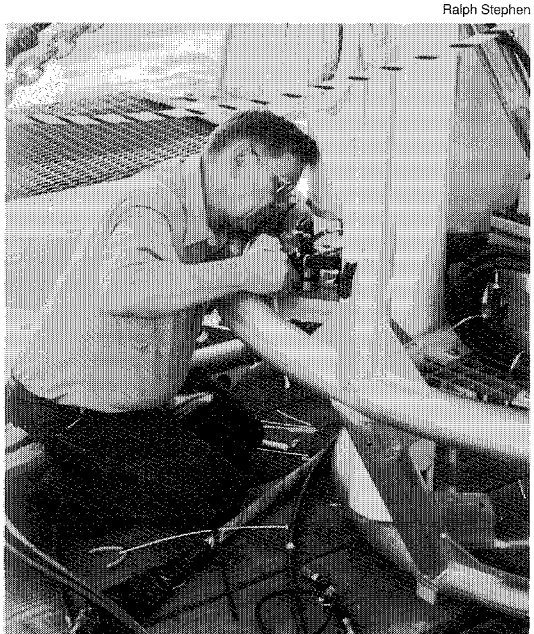
The objective of LFASE was to understand the physics of excitation (how noise is generated) and propagation (travel paths) of low frequency noise (2 to 50 hertz) immediately above, at, and below the seafloor.

The LFASE project was a multi-institutional effort with investigators from Johns Hopkins University, Applied Physics Laboratory (JHU/APL); the Naval Oceanographic and Atmospheric Research Laboratory (NOARL); the Massachusetts Institute of Technology (MIT); Science Applications International Corporation (SAIC); Scripps Institution of Oceanography Marine Physics Laboratory (SIO/MPL) and Institute of Geophysics and Planetary Physics (SIO/IGPP); and WHOI. JHU/APL managed the project, and project chief scientists were associated with SAIC and NOARL. The borehole re-entry operation was the responsibility of SIO/MPL. WHOI was responsible for the borehole array and its seafloor recording package. Senior Research Specialist Henri Berteaux led the group responsible for the mechanical aspects of the bottom-recording package including pressure housings and a backup release mechanism for the data recording unit. Research Specialist Don Koelsch and Research Associate Robert Goldborough designed, constructed, tested, and operated the electrical aspects of the system. Additional equipment deployed during the experiment included ocean bottom seismometers (from NOARL and SIO/IGPP) and a vertical hydrophone array (from NOARL).

The borehole seismic system consisted of four major components (see figure overleaf). At the bottom of the string is the borehole re-entry guide. It contains a slow scan television and hydrophone for locating the re-entry cone. It also contains two borehole calipers, a pressure transducer, and a thermister for measuring borehole diameter, tool depth, and borehole temperature, respectively, when the probe is in the hole.

Above the probe are four seismic sensors separated by 30-meter cable segments. Each sensor measures three components of ground velocity at frequencies between 2 and 50 hertz. On the top sensor there is also a borehole hydrophone for measuring pressure fluctuations in the hole. Each sensor is equipped with a spring-loaded clamping arm to fix the sonde (sound sensor) rigidly to the borehole wall. The seismic array is a

Ralph Stephen



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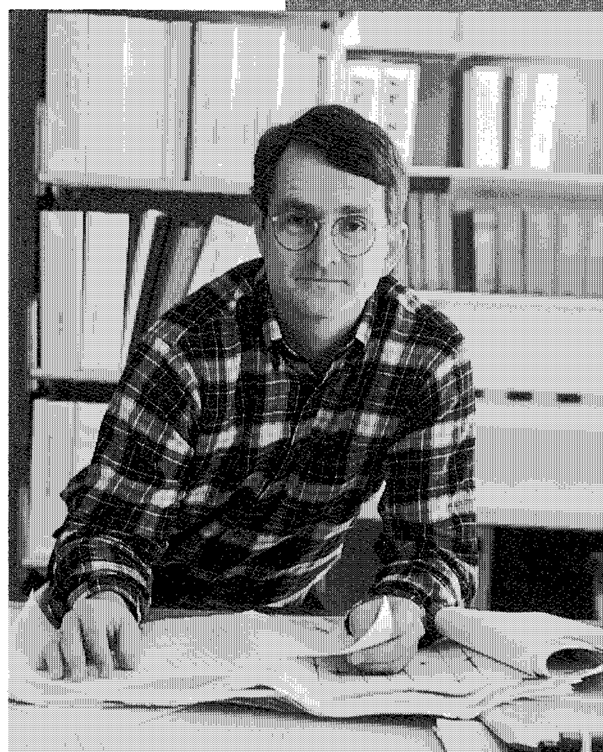


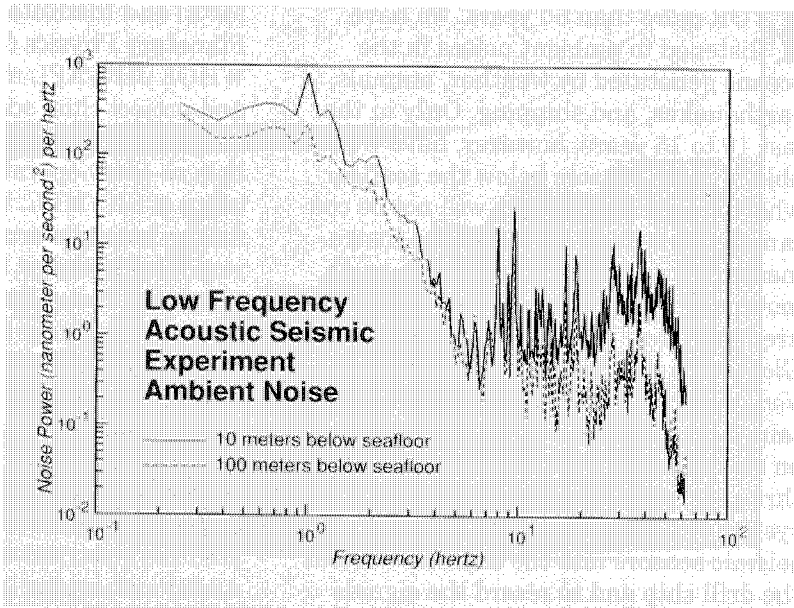
Above: Ralph Stephen is at work in his laboratory.
Left: Don Koelsh works on the LFASE bottom recording package aboard R/V *Melville*.

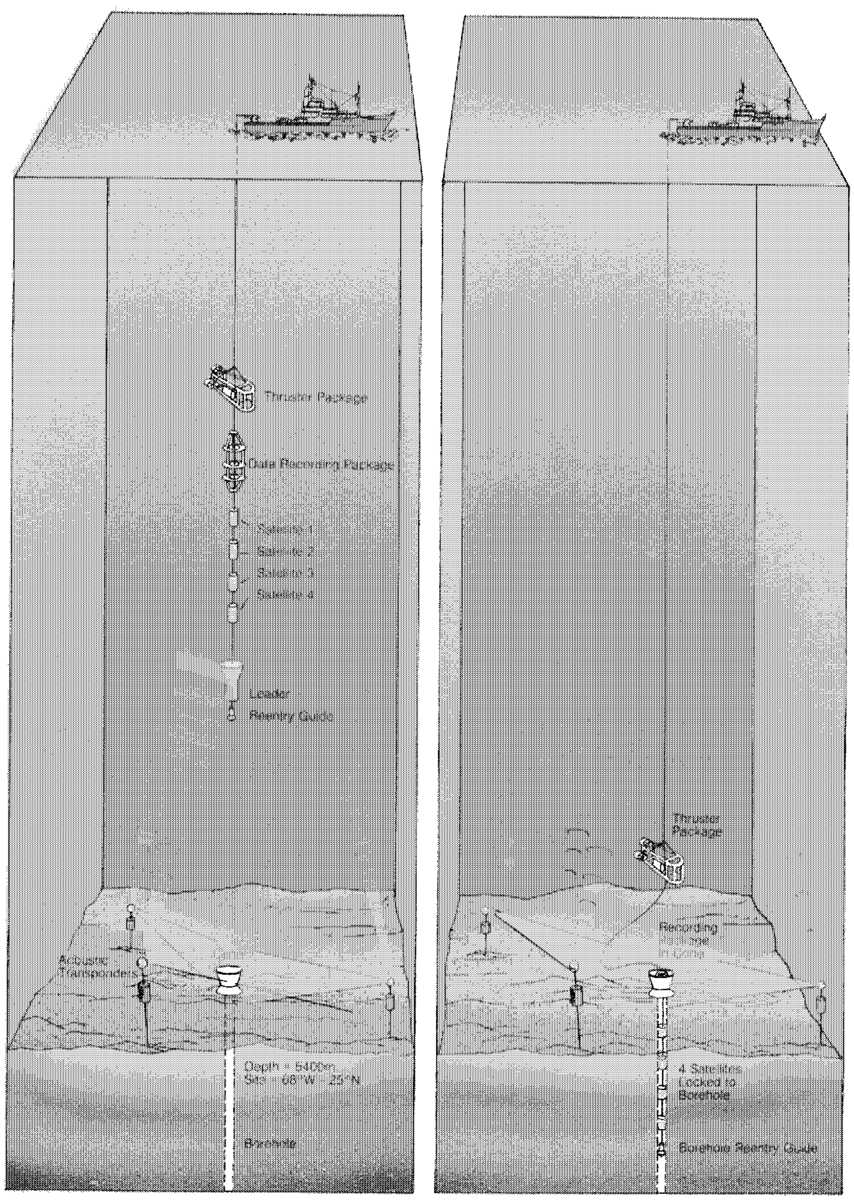
Ambient noise power spectra for vertical geophones at 10 meters and 100 meters below the seafloor show the decrease in noise with depth.

Schematic diagrams show the Low Frequency Acoustic Seismic Experiment instrument string before and after re-entry into the seafloor.

modified version of a commercially available array built by Compagnie Générale de Géophysique.

Above the seismic array is the docking system, which lands in the re-entry cone on the seafloor. This system contains the electronics for digitizing the seismic data and telemetering it over coax cable to the ship. It also has a





self-recording capability for more than 40 hours of data. This data can be acquired over a number of windows spanning up to one month on the seafloor. If necessary, the data package alone can be released from the docking system to float to the surface.

The thruster hovers above the docking system on about 250 meters of "soft tether." During re-entry, the thruster can be used to position the re-entry probe over the borehole. Once the docking system is in the cone, the thruster hovers nearby to decouple heave and horizontal motion of the surface ship from the docking system by the "slack tether." While the tether is attached to the docking system, data from the array can be acquired on board ship. The tether can also be released from the docking system to allow autonomous recording on the seafloor without the contaminating noises of the surface vessel.

This system was successfully deployed from R/V *Melville* operated by the Scripps Institution of Oceanography at Deep Sea Drilling Program Site 534 off the coast of Florida in August and September 1989. Data from the array was acquired on board ship for about two and a half days and on the seafloor system for an additional two weeks. During the shipboard recording phase, a second ship, USNS *Lynch*, fired airgun and explosive charges in radial lines and circles around the borehole array.

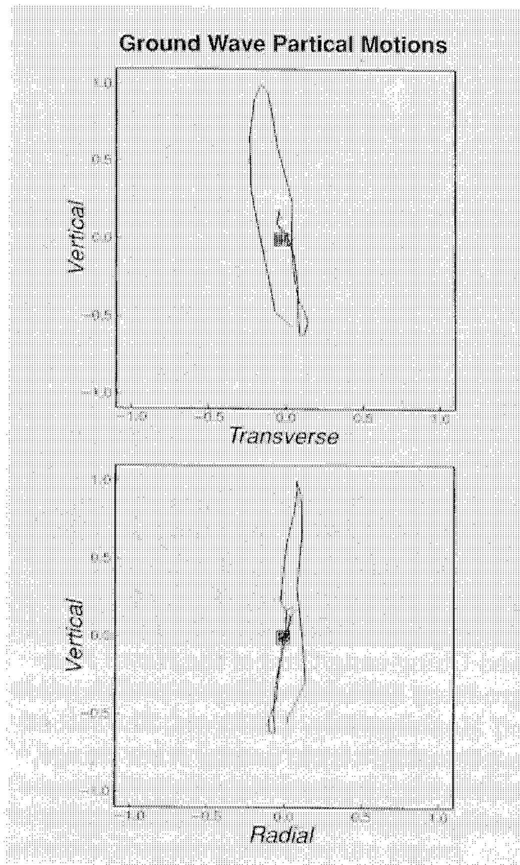
This is the first time that ambient noise was recorded as a function of depth in the seafloor. One exciting result is that

E. Paul Oberlander

the ambient noise level decreases 10 decibels (a factor of 3 in amplitude) between 10 meters and 100 meters downhole (figure at left). This suggests that the propagation mechanism for ambient noise is interface waves trapped at the seafloor. As the detector gets farther away from the seafloor, the ambient sound levels decrease.

Signal propagation across the array is consistent with theory (figure at right). For example, for a distant shot, the first arriving energy has travelled through the crust and mantle beneath the seafloor, which have a much higher velocity than the water column. This energy arrives at the array nearly vertically and the dominant particle motion should be on the vertical component rather than the horizontal components. This is observed in the data shown at right.

Preliminary conclusions are that borehole seismometers are excellent detectors of sound in the seafloor for two reasons: 1) they are located in a region where ambient noise is low, and 2) they are coupled well to true earth motion.



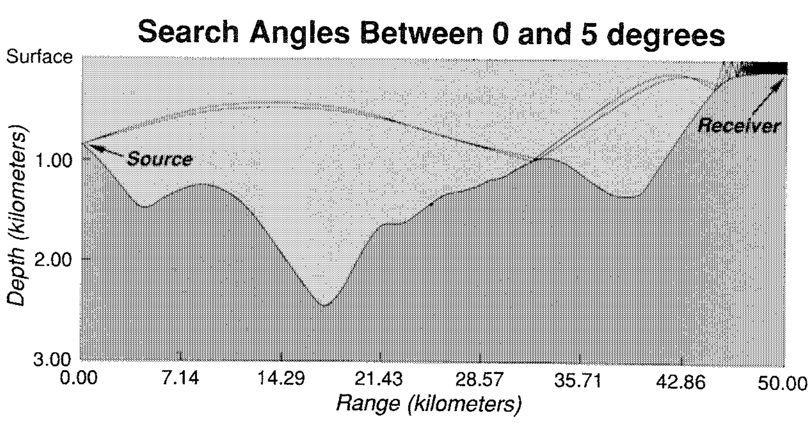
Polarization diagrams show the ground motion in the vertical-transverse and vertical-radical planes for a compressional wave that has traveled through the seafloor. The particle motion is predominantly vertical, indicating that the energy is arriving from directly below the receiver.

Surface Wave Tomography

James F. Lynch,
Associate Scientist,
Applied Ocean Physics & Engineering Department

WHEN sound travels from an underwater source to an underwater receiver, it can take a variety of physically allowed paths, called "ray multipaths." Sound pulses traveling along these paths take different amounts of time to reach the receivers, and they sample different parts of the water column, bottom, and surface (see figure below). The ocean features through which the sound passes affect the rays. "Fingerprints" left by ocean features along the paths consist of both a change in the time it takes the sound to travel from source to receiver and a change in the intensity of the sound. Using the former information, the so-called "travel time perturbation," Walter Munk of the Scripps Institution of Oceanography and Carl Wunsch of MIT formulated a method of three-dimensional mapping called "ocean acoustic tomography." Simply put, ocean acoustic tomography is the oceanographic analog of the CAT scan in medicine – indeed, the mathematical bases of the two techniques are very similar. However, while medical tomography uses the absorption of radiation by tissue to map its density, ocean tomography capitalizes on the fact that sound is *weakly* absorbed by water to make maps of ocean sound speed, temperature, and currents.

As originally conceived by Munk and Wunsch, tomography was meant to be a tool for mapping large scale ocean features such as fronts and eddies. Signals from smaller-scale oceanographic features like internal waves were filtered out as



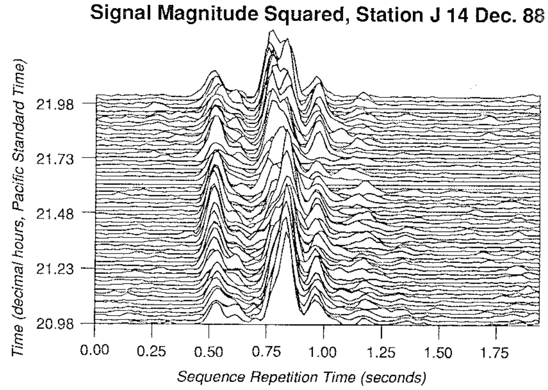
The trajectories of acoustic ray multipaths connecting source and receiver are shown in Monterey Bay, with launch angles between 0 and 5 degrees to the horizontal. The rays have considerable interaction with the surface and bottom as they "shoal" up to the receiver 50 kilometers from the sound source.

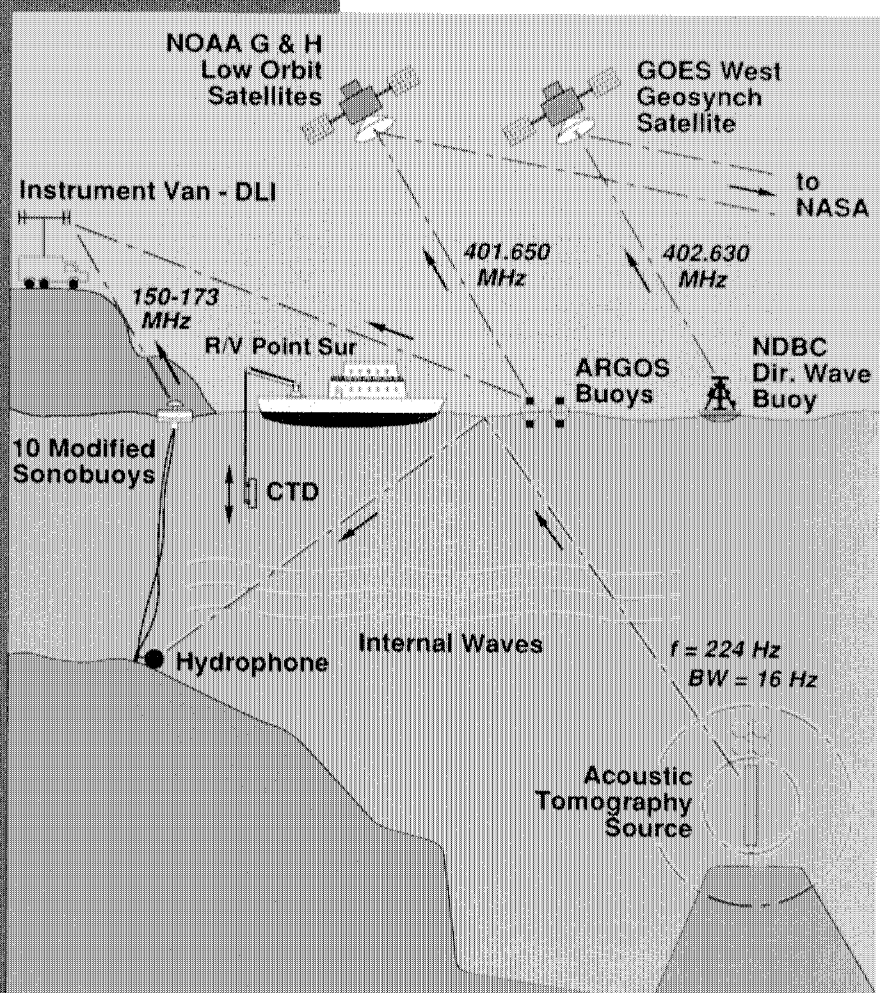
Right: Acoustic multipath arrival structure over one hour of transmissions is shown for December 14, 1988. The leftmost peak, a resolved multipath with eight surface interactions, was used to generate the frequency spectrum shown at left on the next page. The large peak is a group of unresolved multipaths, which cannot be used for spectrum generation. The small peak to the right of the large one is also a resolved single path.

Below: This is the configuration of the December 1988 Monterey Bay tomography experiment. Modified sonobuoys were used as receivers to provide real-time data from relatively inexpensive equipment. Bottom mounting of receivers and use of a very short mooring for the source eliminated travel time error that is caused by the sway of the mooring and that can ruin the internal wave measurements.

noise, and surface interacting raypaths, which would show effects of the surface wave field, were ignored altogether. During the 1980s, however, Stanley Flatte and his coworkers at the University of California, Santa Cruz, showed that tomography could, in fact, be used to obtain significant information about the internal wave field, and the WHOI tomography group successfully measured surface wave frequency spectra from a tomographic test transmission made off Spitsbergen, Norway.

In the past year or so, the WHOI tomography group has participated in two experiments designed both to ground truth (verify) and extend the theoretical developments of internal wave and surface wave tomography. In one experiment, we collaborated with James Miller and Ching-sang Chiu of the Naval Postgraduate School in a coastal transmission off Monterey Bay, California. The second experiment, which, among other things, will verify amplitude-based surface wave tomography, was a large, collaborative

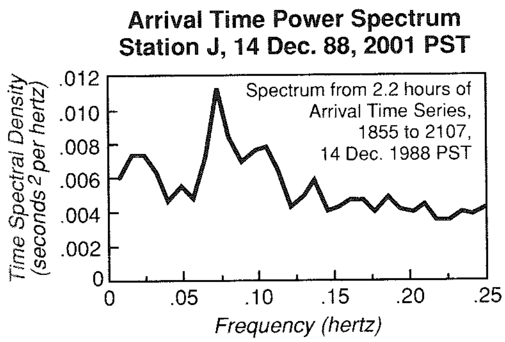




effort in the Greenland Sea involving WHOI, Scripps, the Applied Physics Laboratory at the University of Washington, and the University of Michigan. Both experiments produced exceptionally rich data sets, which should help to establish surface wave tomography as a well-understood, field-proven technique.

The basic principle of travel-time based surface wave tomography is rather simple. As the sea surface rises with a wave crest, a ray has farther to go to reflect off the surface and so requires an increase in travel time. A wave trough depresses the sea surface and causes a corresponding decrease in travel time. Thus, as waves cross the points where a sound ray hits the surface, the travel time for each ray wanders slightly to-and-fro. Relatively simple mathematics then relates the frequency spectrum of this travel time wander to the frequency spectrum of the surface waves. Surface wave tomography may also be used to detect the direction of the wave spectrum. Specifically, a single ray measures only the wave frequency spectrum, but a combination of many multipaths gives wave directional data, as well.

The Monterey Bay experiment (figure at left) covered a five-day period in December 1988. Rather fortunately, a storm producing waves of more than four meters passed through the area during the middle of the experiment, insuring good data! The figure above shows peaks corresponding to ray arrival times measured repeatedly over one hour during the experiment. The spectrum of the fluctuations of the first (leftmost) peak, which corresponds to eight surface interactions as a ray "shoals" near the receiver, produces the frequency spectrum shown in the figure at right above. The figure at far right shows this wave spectrum measured by a standard pitch-roll buoy, the "ground truth" against which we are checking our acoustic results. The agreement is clearly quite good. Moreover, our acoustic technique measures an additional, smaller peak at about 0.025 hertz, which corresponds to 40-second-period waves. This peak is actually due to wave groups, the embodiment of the surfer's rule of thumb that "every seventh wave is a big one." Going to even lower frequencies, our acoustic measurements in Monterey Bay have also detected packets of internal waves with 10-to-20 minute periods. The explanation of their origin and characteristics will be somewhat harder than for the surface waves, as: 1) our internal wave ground truthing

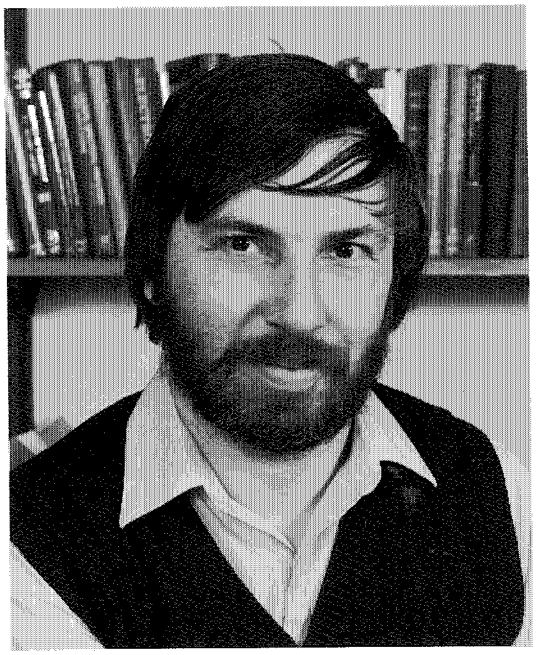


The acoustic travel time fluctuation spectrum calculated from the first arrival in the figure at the top of page 34 is plotted here. The frequency proportionality factor and "noise floor" have not been corrected here to emphasize "wave group" peak. When corrected, the spectrum agrees well with the conventional wave buoy measurement shown below.

measurements are less extensive, and 2) internal waves have many possible generation mechanisms, all of which could contribute to the observed signals. However, the fact that strong, structured internal wave signals were seen at all in this complicated coastal environment gives us confidence in the potential value of coastal internal wave tomography.

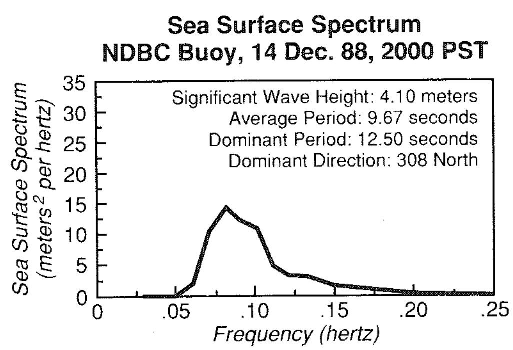
In more conventional tomography experiments, signals are transmitted not every two seconds (to sample surface waves) or even every 10 minutes (to sample internal waves), but rather every three or four hours (to sample larger ocean features). Thus, we *cannot* obtain the frequency spectra of either of these types of waves, but get, rather, a brief look every few hours. The look every few hours can give a glimmer of information about the average internal wave field energy, which changes over time scales of a day, but tells us little about the surface wave field, which can change dramatically over a few hours. To glean information on the surface wave field from only one look at the multipath structure, such as in the figure on page 33, we employ a different tactic, namely, a comparison of the relative sizes

Tom Kleindinst



Jim Lynch

of the different multipaths, that is, we use the sound *intensity* information. When sound reflects from a rough surface, its intensity is decreased by a simple function of the average wave height, the acoustic frequency used in the experiment, the surface interaction angles of the rays at the reflection points, and the number of surface interactions. Given that each ray has different surface interaction angles and numbers of bounces at a given frequency and average wave height, the rays will arrive at the receiver with different intensities. (This method requires that other known factors, such as geometric ray spreading and medium



This is the National Data Buoy Center wave buoy measurement in Monterey Bay. The low frequency wave group peak is missing because the instrument does not record very low frequencies.

attenuation be removed from the data.) Thus, one short transmission will give us an average wave height estimate. Using a number of noncollinear receivers (receivers not placed in a straight line) enables us to plot maps of a surface wave height field. A preliminary synthetic study on tomographically mapping a hurricane wave height field in the Gulf of Mexico yielded encouraging results from this technique – now we need to check the technique on real world, independently verified wave data.

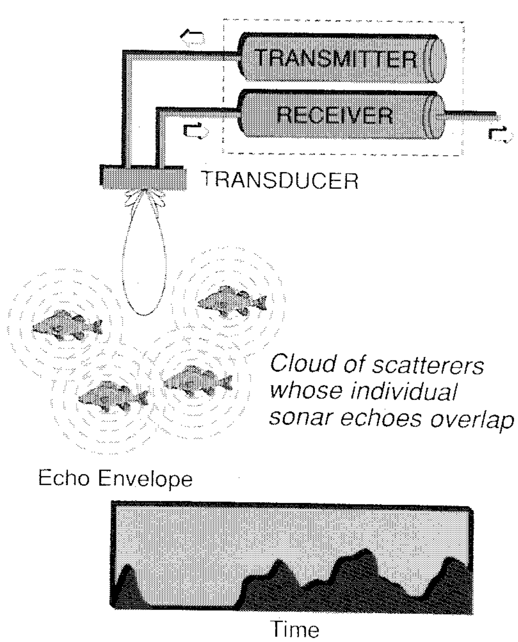
We expect the analysis of the Greenland Sea tomography experiment, conducted between September 1988 and September 1989, to help provide this check. One of its objectives was measurement of Greenland Sea gyre circulation forcing by surface wind stress. Tomography and other techniques are being employed to measure the ocean circulation for comparison with models employing wind stress maps supplied by the British Meteorological Office for every three-hour period during the entire year of the experiment. This wind stress data will be incorporated into a surface wave model by WHOI Assistant Scientist Hans Graber to generate "ground truth" maps of the wave field. (The intermittent ice cover in this region prevents use of a wave buoy for ground truth, and satellite altimetry, a better alternative, is not currently available. Thus, modeling, together with occasional cross-check measurements by ships and aircraft, offers the best estimate of the waves from conventional measurements.) The next step will be to generate equivalent wave maps tomographically and compare the results.

We believe there is a bright future for surface wave tomography. The travel-time based variant can potentially measure spatially and temporally varying frequency-directional spectra over large areas with adequate temporal sampling. The amplitude-based variant can be applied to "standard" tomography experiments and thus represents new information for researchers. It is the dream of today's tomography community eventually to populate large areas of the world's oceans with long-duration, real-time tomographic instruments. The ability to provide surface wave field information in real time, in addition to the large amount of other information tomography produces, would be of considerable importance to both navigation and oceanographic research.

Zooplankton Classification Using Sonar

Timothy K. Stanton, Associate Scientist, Applied Ocean Physics & Engineering Department

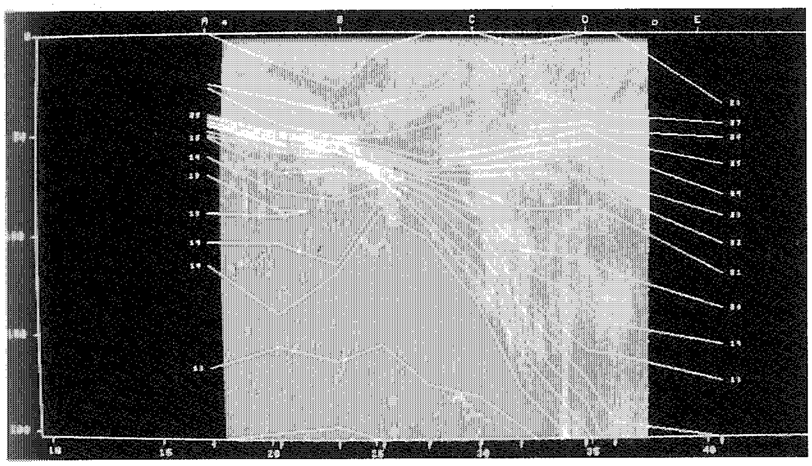
BECAUSE of the large expanse of the ocean and its complex spatial and temporal variabilities, it is essential to employ quantitative synoptic survey techniques that can rapidly and remotely sense the properties of large volumes of water in relatively short periods of time. Sonar techniques offer a solution to this requirement as sound can travel large distances through water with great speed. The variety of sonar techniques available includes active sonars that transmit their own signal and listen for the backscattered echoes (figure at right). Such devices can help direct the use of sampling methods, such as trawling, to capture organisms and coring to collect samples of the seafloor, and they can help provide for continuous interpolation of data between samples. Investigators using sonars in concert with these other techniques can produce large-scale acoustic "maps" of the area of interest as well as samples containing high quality morphological information at various locations within the map.



This figure shows an active sonar that transmits a short burst of sound and receives echoes from the marine organisms present.

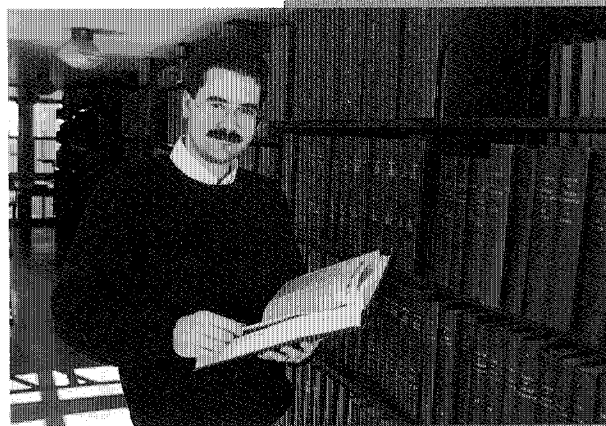
One of the greatest challenges in using sonars for remote sensing of the ocean is interpretation of the data. The physics of the interaction of sound with objects that are scattering the sound is usually a very complicated process, and analysis of backscattered echoes typically involves many ambiguities. Thus, it is important to understand the physical mechanisms causing the scattering in order to provide optimum interpretation of the echoes.

Much of my recent research has been motivated by field studies of macrozooplankton and micronekton at the Gulf Stream boundary northeast of Cape Hatteras, North Carolina. Our sonar measurements showed correlation between the presence of the organisms and the temperature structure of the boundary (figure below). However, we had difficulty making accurate comparisons between observed sonar data and trawl catch. Some of the discrepancies were due to the fact that many of the larger organisms detected by the sonar avoided the trawl, hence giving a larger sonar return than predicted from the trawl data. The remainder of the errors were attributed to the inadequacy of the scattering models. In particular, the organisms that were, for the most part, elongated (euphausiids and shrimp) were treated as spheres in the mathematical scattering models (there were no better models available at the time). Needless to say, predictions based on the trawl catch as well as independent laboratory studies demonstrated the need for more sophisticated models.



In this sonar transect of the Gulf Stream boundary northeast of Cape Hatteras, NC, the colors represent various levels of acoustic intensity ranging from blue for the weakest echoes to red for the strongest. White lines of constant temperature are also shown. The 200-meter-deep by 20-kilometer-long map illustrates correlation between the spatial distribution of the biological sound scatterers and the temperature structure. The horizontal axis is distance in kilometers, and the vertical axis is depth in meters.

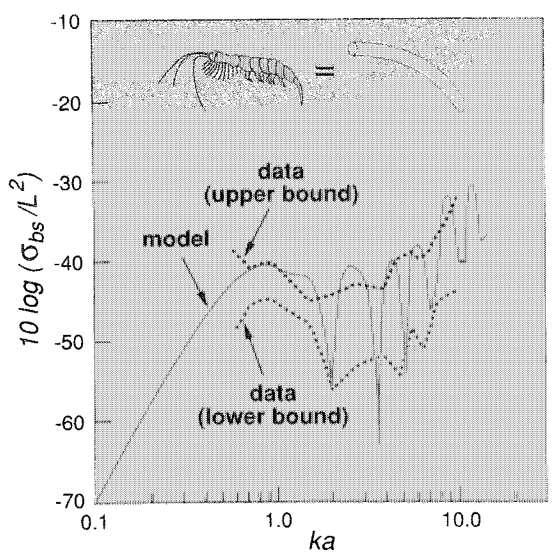
As zooplankton play a major role in the ocean food chain, it is important to have accurate estimates of their abundance. I, therefore, developed a general mathematical model that takes into account the elongation, deformation, and material properties of the many zooplankton that are shrimplike in shape. Although the solution usually involves use of a computer, simple convenient expressions can be derived from it under certain limiting conditions. After trying a variety of simple trial shapes in modeling the scattering, the bent fluid cylinder model has proven to be the most successful "first approximation" to euphausiids, while short, straight cylinders whose length is comparable to the length of the thorax has best fit data involving shrimp. The promise of the theory is illustrated in the figure at the bottom of this column, a comparison between the bent cylinder model and laboratory backscatter data from euphausiids.



Tom Kleindinst

Tim Stanton is shown in the stacks of the MBL/WHOI library.

At this point in the research, the theory can describe scattering processes at a level more complex than can be tested by existing data. I have therefore embarked upon a laboratory investigation using a wide range of closely-spaced sonar frequencies and careful recording of organism behavior. The experiments will provide an empirical basis for parameters of the model, including the elastic properties of the shells, the fluid properties of the interior, and the statistical nature of the behavior (distributions of shape and orientation and



In this bent cylinder scattering model of a euphausiid, the vertical axis is a logarithmic measure of the backscattered intensity, while the horizontal axis is related to the product of acoustic frequency and size of organism.

their influence on the scattering).

Further development of the model is also underway. The shape of the organisms has so far been treated as smooth, but simple visual inspection of the animals as well as the characteristics of the scattering indicates that the texture of the organisms is important. I have therefore directed my most recent theoretical and numerical efforts toward the description of rough elongated objects. Predictions based on these new models indicate profound effects of roughness on scattering. In particular, the various wavelets that scatter from the organisms, including circumferential waves that first travel around the objects before returning to the sonar receiver, are attenuated by the texture when the dimensions of the texture reach the order of one-tenth of the acoustic wavelength or greater.

Once the scattering by the organisms has been fully understood from laboratory and theoretical investigations, we can then provide accurate and robust sonar interpretation methods for remote detection and classification of organisms. The research is applicable to all types of sonar technology, ranging from multibeam, single frequency sonars to single beam, multifrequency sonars.

Do Young Dolphins Learn to Imitate Sounds from Their Mothers?

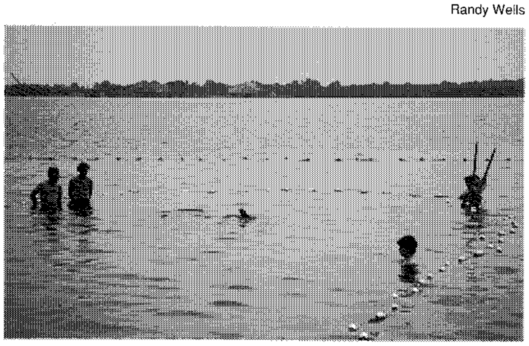
Laela S. Sayigh, Joint Program Student, & Peter L. Tyack, Associate Scientist, Biology Department

BOTTLENOSE dolphins, *Tursiops truncatus,* produce individually distinctive vocalizations called signature whistles. These whistles appear to function both to broadcast individual identity and to maintain contact between individuals such as mothers and calves.

In a long-term field project organized by Randy Wells, WHOI Guest Investigator and Behavioral Ecologist at the Chicago Zoological Society, researchers have found that free-ranging bottlenose dolphin mothers and calves remain closely associated for up to 10 years, averaging 3 to 6. (Male bottlenose dolphins do not play a role in raising the offspring.) Clearly, the mother's whistle must be a dominant component of a young calf's acoustic environment in the wild. Do calves learn their signature whistles from their mothers?

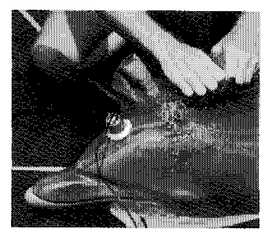
Learning has not yet been found to play a role in natural vocal development of any mammal other than humans. Even our closest primate relatives do not seem to modify their vocal repertoire as a result of what they hear. This is surprising since we require this skill to develop our natural communication system, language.

Randy Wells



A great deal has been learned about dolphins from a temporary capture and release program that employs this large net corral in Sarasota, Florida.

Observational data gathered by Randy Wells and his coworkers over the past 20 years have provided information on matrilineal relationships among most of approximately 100 individuals in a resident coastal community of free-ranging bottlenose dolphins in waters near Sarasota, Florida. A capture and release program, where dolphins are temporarily held in a large net corral in shallow water to be measured, sampled, and marked, has provided information on age, sex, and life history. During these temporary captures, we record vocalizations from each known individual by placing a suction cup hydrophone directly on the head of the animal. It is otherwise difficult, if not impossible, to determine which dolphin is vocalizing. To date, we have obtained recordings from a total of 110 individuals, including 38 calves and their mothers, over a period of 15 years (recordings from 1975-76 were made by Michael Scott and Paul Graycar, who were working with Marineland of Florida).



Peter Tyack

During temporary capture, researchers use a suction cup hydrophone to record individual dolphin whistles.

When we examine dolphin whistles visually using spectrograms (plots of frequency versus time), we find that they tend to vary between 5 and 25 kilohertz, and to last about one second. The contour, or pattern of frequency changes over time, is distinctive for each dolphin's whistle. We asked independent judges, Nancy Haley

Left: Peter Tyack and Laela Sayigh are aboard *Abel-J* on a sperm whale acoustics cruise off the coast of Dominica.

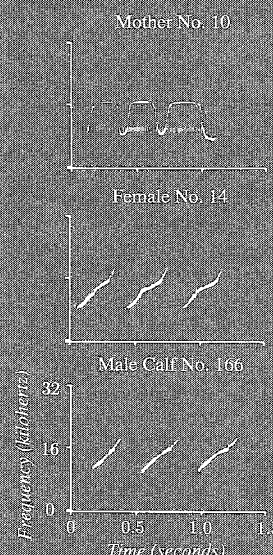
who had no knowledge of the 38 mother-calf relationships included in the study, to compare spectrograms of whistles of mothers and calves. They rated the similarity of these whistles on a scale of 1 to 5 (with 1 being not similar and 5 being very similar).

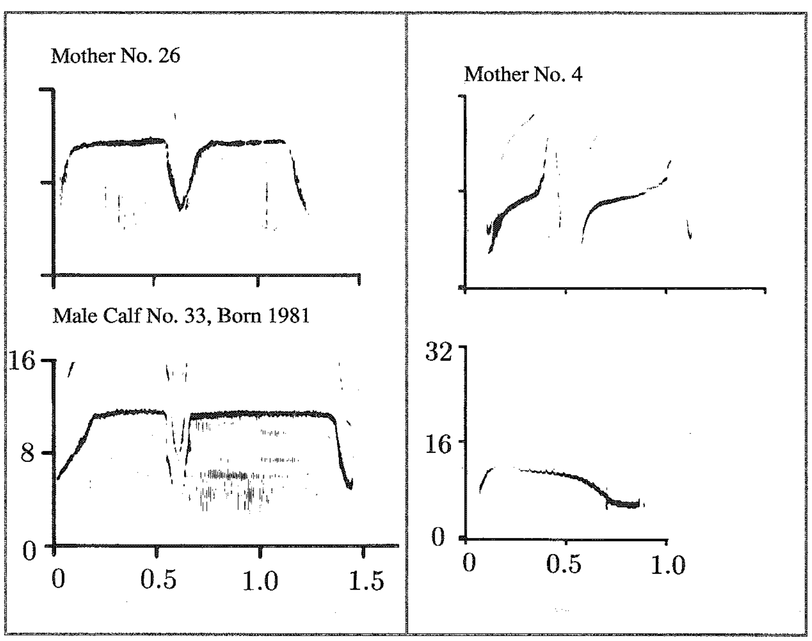
As it turned out, 65 percent (11 of 17) of the whistles of male calves received mean ratings of similarity to their mother's whistles of 3.0 or greater (figure at left below). However, only 14 percent (3 of 21) of the whistles of female calves received mean ratings of similarity to their mother of 3.0 or greater (figure at right below). Apparently there is a sex difference in the propensity of calves to learn their signature whistles from their mothers.

Why might such a sex difference exist? We speculate that it may relate to the different roles males and females play in the social structure of the community. Randy Wells and his coworkers have found that Sarasota females tend to remain in their matrilineal groups, while the males tend to disperse into the community. If female calves were to produce whistles similar to those of their mothers, then several females in a matrilineal group would be producing similar whistles. It could thus be difficult for a young calf to maintain contact with his or her mother. On the other hand, it could be advantageous for males to retain characteristics of their mothers' whistles, perhaps to maintain contact with kin or to avoid inbreeding.

We are currently testing the validity of these ideas through careful observations of undisturbed mother-calf pairs along with simultaneous acoustic recordings. These observations may also help us to understand precisely how the acoustic environment and the mother's behavior affect the development of the signature whistle. For example, does a calf who does not develop a signature whistle like its mother's learn its whistle from another individual? There are preliminary indications that this may be the case (see figure at right). We hope that a better understanding of the factors governing vocal development in this species may provide new insights into the individually specific social relationships of these marine mammals.

Below: These spectrograms represent signature whistles of male calf no. 166, his mother (no. 10), and a close female associate of his mother (no. 14). Note the similarity in whistle contour between male calf no. 166 and female no. 14. The authors speculate that this male calf may have learned his whistle not from his mother but from female no. 14.





Left: Spectrograms of signature whistles of male calf no. 33 and his mother, no. 26, are shown here. These two whistles received a mean rating of similarity from the judges of 5.0, the highest possible score. Time (seconds) is on the horizontal axis, and frequency (kilohertz) is on the vertical axis.

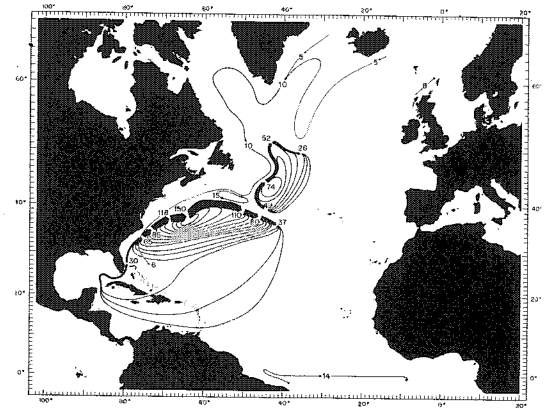
Right: These are spectrograms of signature whistles of female calf no. 20 and her mother, no. 4. These two whistles received a mean rating of similarity from the judges of 1.0, the lowest possible score. Axes are as in figure at left.

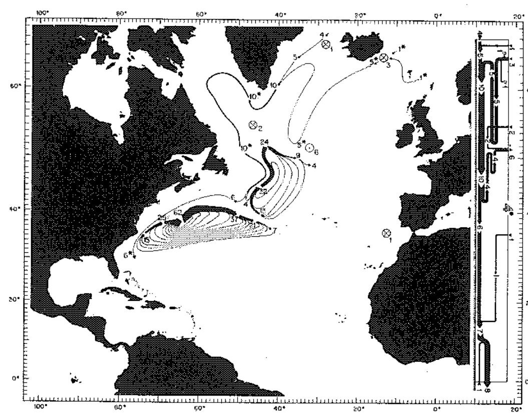
The Gulf Stream Recirculation

Nelson G. Hogg,
Senior Scientist,
Physical Oceanography Department

AFTER the Gulf Stream leaves the coast at Cape Hatteras and begins its vigorous meandering, large recirculation gyres develop and enhance the downstream transport. Valentine Worthington, WHOI Scientist Emeritus, first described this circulation in 1976. The figures at right show his scheme for the total transport as well as for water colder than 4°C. The eastward transport in the Stream more than doubles from about 60 million cubic meters a second at Cape Hatteras to 150 million south of Nova Scotia, with half the addition coming from water colder than 4°C (for comparison, the Amazon carries less than 1 million cubic meters per second). Since the size of this recirculation is much smaller than that inferred from classical wind driven models, some other process is at work.

Worthington deduced this picture largely from water property analysis supplemented by intuition and a modest amount of direct velocity measurement. Hydrographic measurements have been the principal source of our knowledge about global ocean circulation over the past 100 years. Unfortunately, the hydrographic suite (salinity, temperature, depth) lacks any direct measure of velocity, so inferences about the actual circulation depend on some rather arbitrary assumptions about the circulation at a particular level – the so-called geostrophic method allows determination of relative velocities only. Advances in moored current meter technology, especially in the last 15 years, now provide us with real velocity data. The current meter has evolved into an extremely reliable ocean "wind recorder," which can be deployed and left for periods greater than two years. Much of the development of this technology has taken place at WHOI, and, over the years, use has spread from our back door in the northwest Atlantic to practically every ocean basin.





Worthington's 1976 circulation scheme for (above) the total, top-to-bottom, transport and (below) water colder than 4°C.

Various investigators have made a large number of measurements in the Gulf Stream recirculation region (figure at right). Although the WHOI Buoy Group is responsible for the majority, scientists from the University of Rhode Island, the University of North Carolina, Oregon State University, Florida State University, and the Bedford Institute of Oceanography have also been active in the region. These measurements range from about three months to more than two years in duration, and they were taken at different times as part of experiments with differing specific objectives.

We separated the ensemble into three groups to determine the large scale structure of the deep circulation. Most noticeable is the consistently westward flow along isobaths of those vectors inshore of the 4,000 meter isobath. This is part of the so-called Deep Western Boundary Current of polar origins. Like the Gulf Stream, it flows along the western boundary, but unlike the Stream, it flows southward and transports its northern waters

Susan Tarbell

New mooring technology has permitted long-term measurements in strong currents such as the Gulf Stream. The large syntactic foam sphere shown here provided most of the buoyancy for a single mooring. It has a lifting force of about 900 kilos when submerged. This sphere has just returned from two years in the water, and close inspection reveals some fouling, even though the sphere was generally below 500 meters depth.

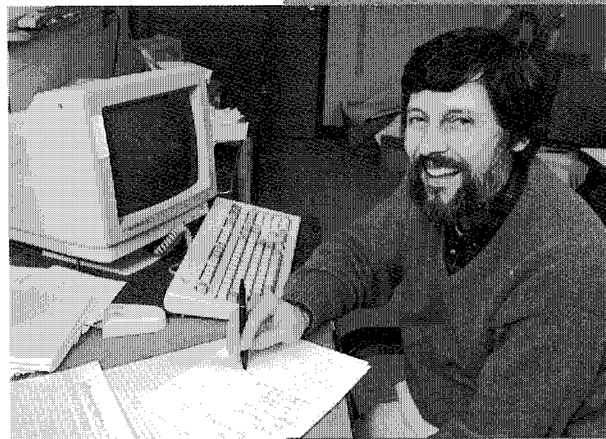
ich in oxygen and man-made tracers ıch as freons and tritium) into the outhern Hemisphere and eventually on ıto the Indian and Pacific oceans.

Directly offshore of this "thermohal- ıe" flow and between the Grand Banks ıd the New England Seamounts, water also moving westward on average. urrent meter measurements from shal- ›wer depths indicate that this westward ow fills most of the water column. How- ver, this does not appear to be a part of large, global scale circulation. Instead, ıis water turns eastward near the New ngland Seamounts where the isobaths ›rce intersection with the Stream. It ıen essentially becomes the deep Gulf tream, which eventually peels off and ırns back westward where the Stream ıns into the southern edge of the Grand anks. This circulation, absent in Worth- ıgton's analysis, transports on the order f 30 million cubic meters a second or as ıuch as the Stream carries through the traits of Florida. We have called this the Iorthern Recirculation Gyre.

South of this gyre there is little vidence for the clockwise Worthington Gyre in the deep water. The only direct confirmation is near 55°W, 36°N where velocity vectors change from strongly eastward to strongly westward moving south. However, this is just the sense to expect if a broader flow were forced to navigate the low seamount found at this location (identified by the single contour on the figure below). The Worthington Gyre would appear to be more of a shallow, thermocline feature.

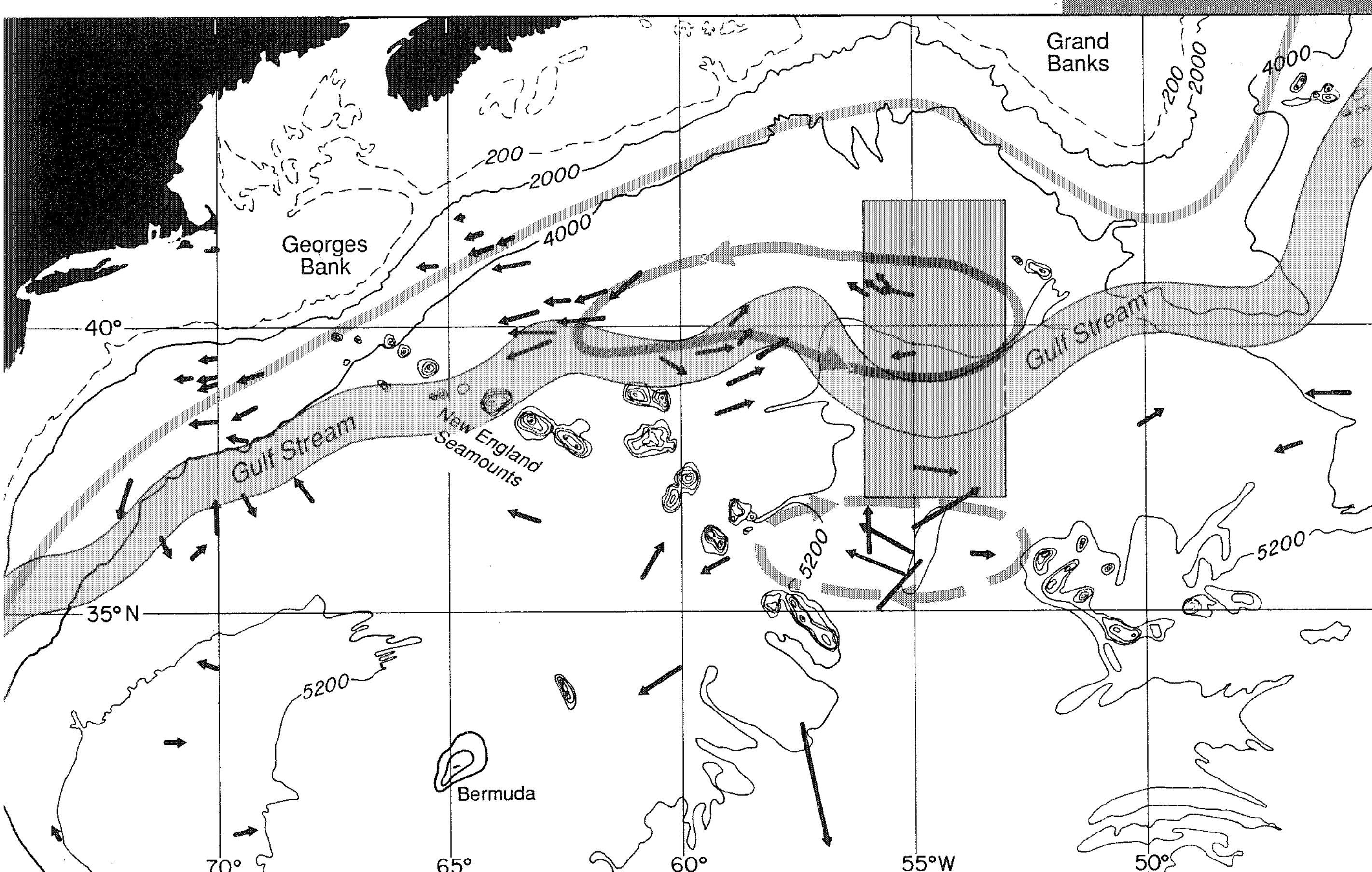
Little is known about the reason for these recirculations. In order to gain insight into what physical processes may be relevant, in 1987 the WHOI Buoy Group deployed the first current meter array designed to measure a cross section of the Stream from top to bottom. Part of the Synoptic Ocean Prediction program sponsored by the Office of Naval Research and

Tom Kleindinst



Nelson Hogg

This compilation of long-term, deep current meter measurements in the western North Atlantic can be divided into three different regimes as shown. New measurements covering the whole water column and venturing into both recirculation zones were made in the shaded area near 55°W.



A major advance in mooring technology is the use of plastic fairing to streamline the wire. It is installed on the upper portion of the mooring, piece by piece, as the wire is played out.

Susan Tarbell

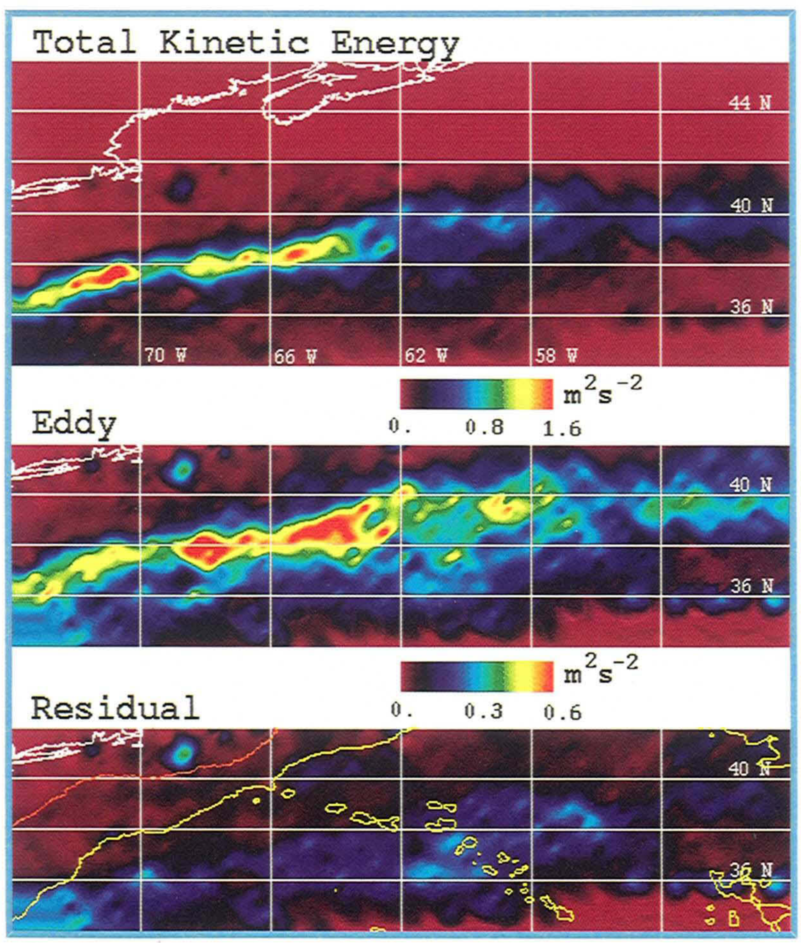
the National Science Foundation, these were set at the locations shown in the figure at the bottom of page 41 for a period of two years and recovered in the fall of 1989 from the British ship, RRS *Darwin*. Traditionally, moorings extending from top to bottom in the Gulf Stream were considered too risky. In this case, we employed two important developments to reduce strong-current drag on the mooring. A single, large syntactic sphere provided flotation at the top of the mooring in place of the more traditional group of smaller spheres, and clip-on fairing reduced drag on the wire by streamlining water motion around it. We were rewarded with outstanding instrument and mooring performance and have begun analysis of the collected information toward a better understanding of the Gulf Stream system.

Rapid Gulf Stream Variability

Kathryn A. Kelly, Assistant Scientist, & Terrence M. Joyce, Senior Scientist, Physical Oceanography Department

DOWNSTREAM of Cape Hatteras, the Gulf Stream often shows large, rapid fluctuations in location, transport, and structure so that hydrographic surveys of different regions separated by a few months may offer very different pictures. A long time series of Gulf Stream measurements would help us to understand its dynamics, but it is difficult to obtain the needed temporal and spatial resolution with measurements currently available. We can infer Gulf Stream location and surface currents using data from the U.S. Navy's GEOSAT satellite altimeter, but it would be more useful to have three-dimensional series of measurements so that we could, for example, compute volume transports. Therefore, we are working on ways to combine the altimeter data with ship-based observations.

Gulf Stream volume transport within the upper 800 meters can be calculated reasonably accurately using only expendable bathythermograph (XBT) measurements made while the ship is underway rather than traditional hydrographic measurements (salinity, temperature, and depth), which require the ship to hold its station. This decreases the time needed to make the

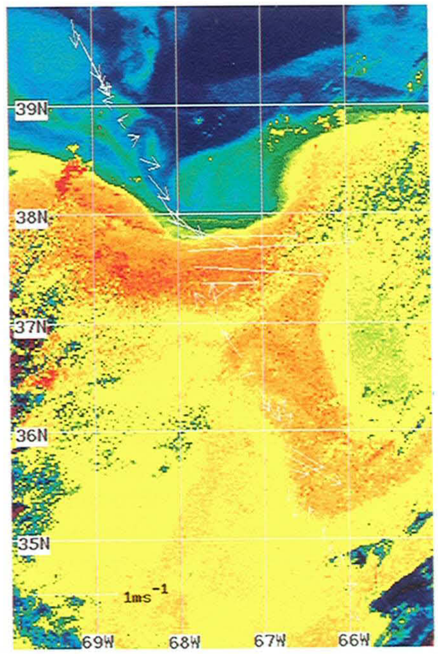


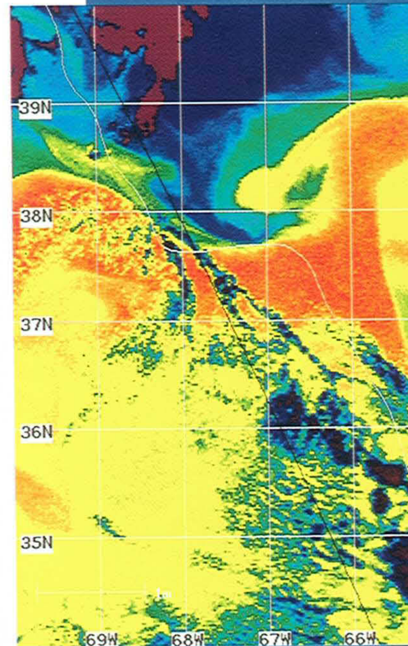
The total kinetic energy of the cross-track velocity, the "eddy" kinetic energy or velocity variance, and the residual kinetic energy are shown with the simple model velocity removed. The upper scale is for the top figure, and the lower scale is for the middle and bottom figures. The total kinetic energy decreases dramatically downstream of the New England Seamount chain at 64°-60°W, which can be seen in the 4,000 meter isobaths overlaid on the lower plot (yellow lines). Most of the velocity variance (middle) is due to the meandering of the Gulf Stream rather than to eddies, because little variance remains (bottom) after the simple model velocity is removed.

ıuired measurements between, for ample, Bermuda and Cape Cod from ır days to about two and a half days. It uld also enable measurements by ships- opportunity rather than expensive search vessels. One critical instrument t available on most ships-of-opportunity the acoustic Doppler current profiler DCP) that provides the reference-level locity needed to convert the inferred locity profile into an absolute velocity. ıerefore, we need a way to obtain the locity with the altimeter, using the adients of sea surface height to infer the locity at the ocean surface.

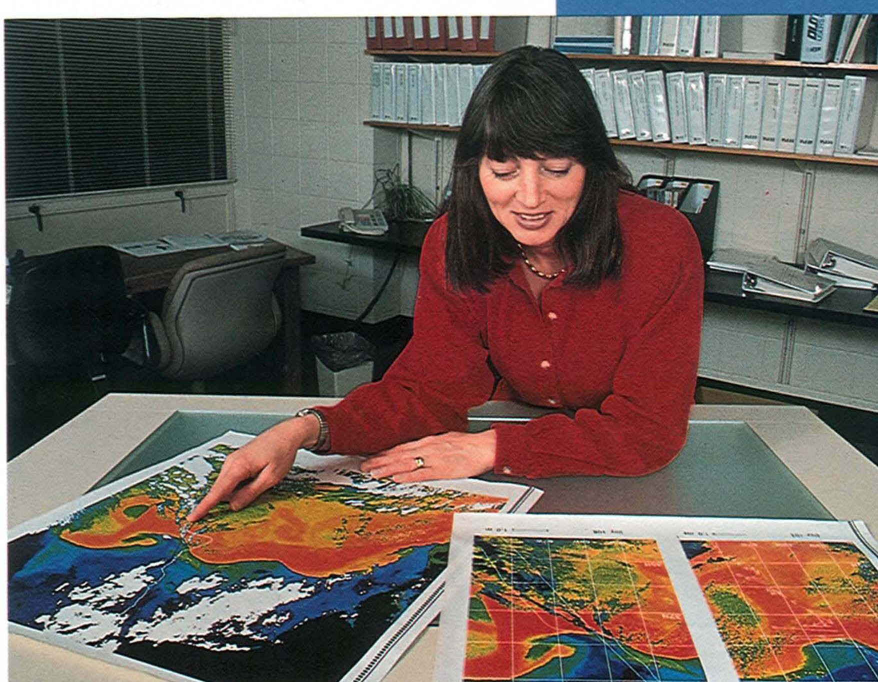
The problem with using the altimetric easurements is that the measured sea rface height includes the Earth's gravi- tional geoid as well as the dynamic to- graphy needed to compute currents. ommonly, the mean height profile over me long time period is removed to elimi- ıte the geoid, but this also removes the ean dynamic topography (and therefore e mean currents), so that only relative ıriations in currents can be studied. If e geoid were known, we could subtract it rectly; however, the current geoid is only liable on scales of thousands of kilome- rs and the Gulf Stream is about 100 lometers across. If we could measure the ınamic height along a satellite subtrack ıd subtract it from the altimetric height, ıe remainder would be the alongtrack ˌoid, and it would then be available for ture analyses. Alternatively, if we could timate the mean height profile, it could added back into the relative height ofiles to obtain the absolute dynamic eight. We investigated both methods.

A simple model of the velocity profile the Gulf Stream and synthetic data ere used to estimate the mean dynamic eight for two and a half years of EOSAT data. This mean sea surface was ɪded back to the residual sea surface eight to produce a time series of absolute ynamic height profiles. Along with the ıean dynamic height field, this analysis roduced time series of parameters to escribe the Gulf Stream meandering and ructure, time series of velocity profiles, ıd maps of kinetic energy (figure at left). oth the mean and temporally varying de- criptions of the Gulf Stream showed two ifferent flow regimes separated by a elatively narrow transition region coin- ding with the New England Seamount Chain. West of about 64° W, the Gulf Stream has a predominately eastward direction with a narrow mean current profile, relatively smooth paths with eastward propagating meanders, and long time scales. East of about 58°W the mean current broadens by a factor of two because of increased meandering, time scales drop by a factor of three, and peak velocities and surface transport drop by 25 percent. An analysis of the correlation between Gulf Stream position and surface transport suggests that larger transports are correlated with more northerly positions.





Above: Current vectors and the GEOSAT dynamic height profiles are overlaid on thermal infrared images. The plot at left shows acoustic Doppler current profiler vectors at a depth of 100 meters taken along a GEOSAT subtrack on day 103 of 1989, and the plot at right shows the sea surface height profile (positive to the right), relative to the geoid, using synthetic data for the mean dynamic topography for day 108 of 1989. The rapid change in height corresponds to the large velocities in the Gulf Stream itself.
Below: Kathie Kelly



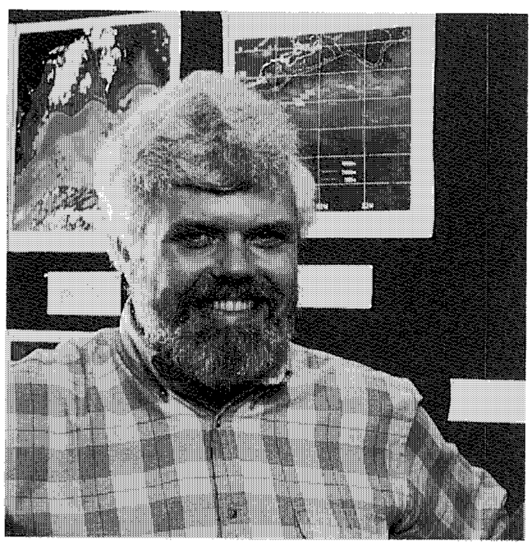
Al Bradley

The fast hydrographic profiler developed by Al Bradley and colleagues in the Applied Ocean Physics and Engineering Department faces heavy seas on a 1988 R/V *Oceanus* research voyage.

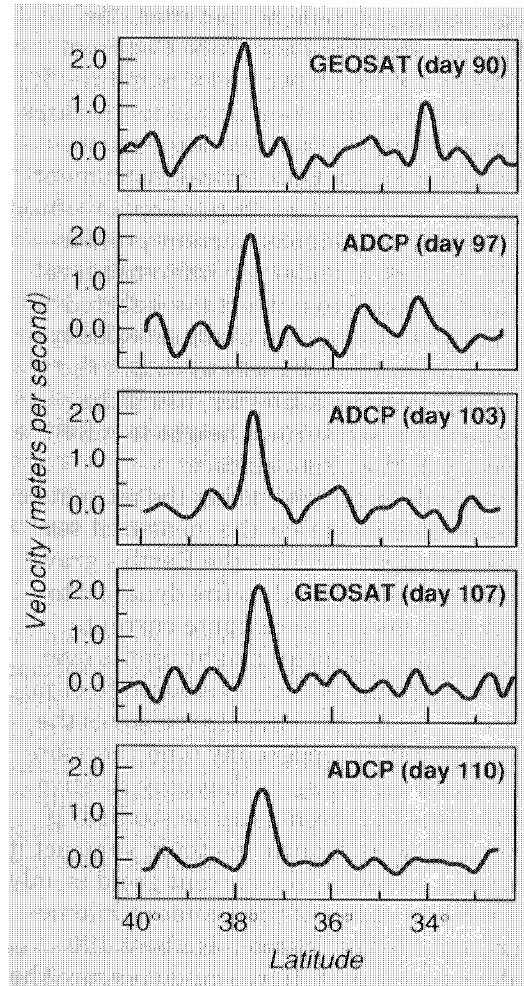
Time series of the velocity at right angles to the GEOSAT subtrack are plotted for April 1989. Two of the profiles are from the altimeter and three from the acoustic Doppler current profiler. The steady southward shift in the Gulf Stream location is apparent in this series. The reduced peak velocity on day 110 is due to a rotation of the Gulf Stream so that it no longer crossed the subtrack at right angles.

Terry Joyce

In separate surveys in April and December of 1989, XBT and ADCP measurements were repeated several times along a GEOSAT subtrack between Bermuda and Cape Cod (figure on page 43). In a period of only 14 days on the first survey, the Gulf Stream shifted southward by about 30 kilometers and rotated by about 30 degrees due to a meander. Velocity measurements from the ADCP were extrapolated to the surface to give peak values of about 2.0 meters per second. These agreed with the velocities calculated from GEOSAT using the synthetic mean within about 0.2 meters per second, which could be attributed to temporal variability (figure at right) or small departures from the geostrophic balance (balance between pressure gradient and velocity) at the ocean surface. This suggests that the synthetic method, which has been applied to the entire Gulf Stream region, gives a reasonably accurate mean. To reduce the measurement error, we made the December survey of the Gulf Stream on the same day as the GEOSAT overflight. (Unfortunately, the GEOSAT altimeter had begun to fail as



early as the spring of 1989 and data were not available for the December survey.) In a comparison of the two surveys, the April transport was significantly larger than that in December, consistent with a relative maximum in the surface velocities from the GEOSAT analysis for the Gulf Stream region.



In the future, we plan to use the synthetic data method on the Kuroshio Extension and hope to make similar comparisons using the new Navy altimeter scheduled for launch in 1990 and ship-based measurements of dynamic topography.

Large Photo: Keith von der Heydt. Inset: Henrik Schmidt.

WHOI researchers ranged from the Arctic to the Antarctic in 1989. The top photo shows part of the evacuation from the CEAREX acoustics ice camp to a waiting ship when the camp drifted perilously close to open water. CEAREX is an acronym for Coordinated Eastern ARctic EXperiment. The camp was located at 81°30' N, 5° W. In the inset photo, Keith von der Heydt tends a remote hydrophone transmitter located several kilometers from the ice camp.

At the other end of the Earth, Mark Kurz samples a Taylor Glacier boulder for cosmogenic helium. The inset shows one of the camps in the antarctic dry valleys set up by Mark's research party – complete with a WHOI flag.

Large Photo: Ed Brook. Inset: Mark Kurz.

External Affairs Report

WHOI now has a Directorate for External Affairs, which brings together Communications, Development, and Industrial and International Affairs. This reorganization will focus and coordinate all of the Institution's outreach efforts in order to broaden the base of support for the scientific staff. It is essential that we maintain our competitive position as oceanography's most prestigious institution, the one most able and free to do science "from within." We are committed, therefore, to increasing significantly our endowment. With a strong base of endowment for salary support, or "hard money," we can attract and sustain the best and brightest staff while ensuring that WHOI remains the place where world-class oceanographers are collectively challenged to unravel how two-thirds of our planet works.

In the coming year, the External Affairs group will work closely together to articulate to the broadest possible audience our need to diversify the funding base at WHOI. The reason for this is clear and simple, but not widely understood by those outside our realm. In order for WHOI scientists to continue to pursue the research at which they excel and to take the risks they must, we cannot rely exclusively on the restrictive support of the federal government. Independent and unattached sources of income that can be used at the discretion of the Institution to support scientist's salaries and research must be available. Through increasing independence, we intend to take control of our future. Team building has been our focus this year, and we are aggressively seeking those who will commit themselves to a future of the best and most exciting years in the context of financial independence.

How do people learn about our cause? How do they get excited? How do we get them involved and invested in WHOI's future? And, how do we market oceanography?

First, we must articulate who we are, why we are unique and why our work is so essential. This message, whether through *Oceanus*, *Ocean Views*, newsletters, *WHOI in the News*, the annual report, videotapes, congressional testimony, or personal presentations and visitations, must be communicated very convincingly. The position of the Director of Communications, who will oversee publications and public information, is still open, but we are well along in that search.

Jacqueline M. Suitor, the new Director of Development, is assembling a staff ready and able to manage a major endowment initiative. Those on board are excited by the challenge we face. WHOI does not have undergraduate alumni, key to fundraising at colleges. However, by not having a built-in constituency, we also are not limited by a well-defined group. We seek to interest the many people who will want to make a real difference in oceanography by becoming more involved in this Institution, and we plan to reach this global constituency by conveying our message in a clear and compelling fashion.

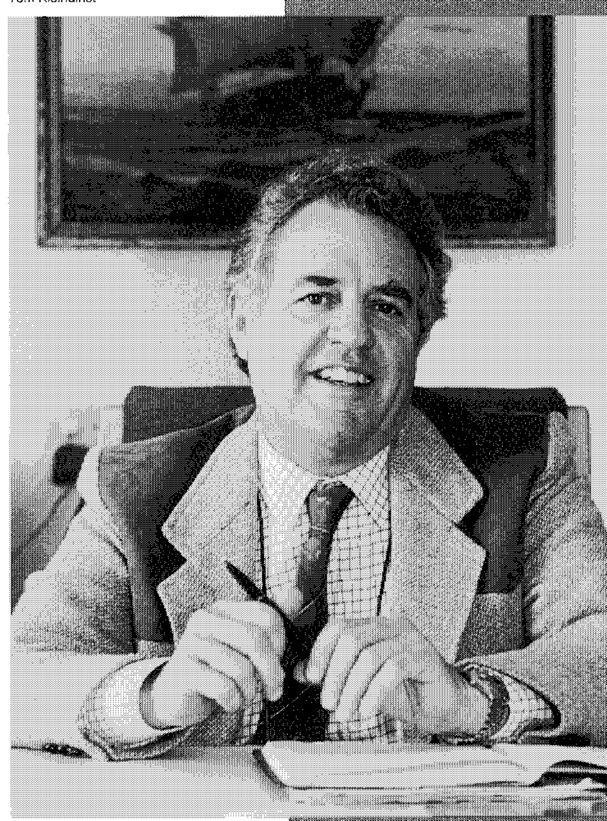
Our Development office provides committed donors with opportunities for personal involvement in the Oceanographic. It encourages substantial support from those who have both the resources and the interest to underwrite institutional initiatives.

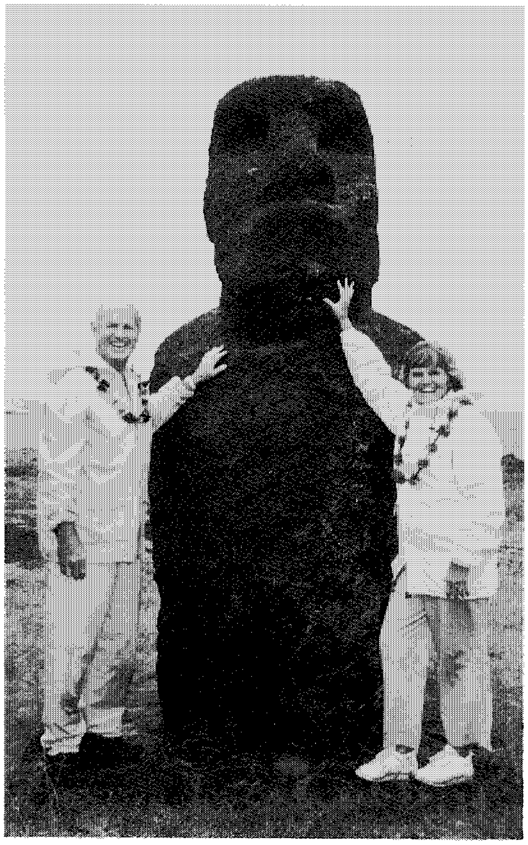
In order to reach our fundraising goals, we recognize the critical need to expand our donor base. We are mounting a major effort to expand and strengthen our Associates Program under the able leadership of the President of the Associates, Charlie Dana, who with an ad hoc committee has made several recommendations for restructuring the membership. These will be implemented in June 1990.

A new office for industrial and international affairs was established this year. Its director, Paul Dudley Hart, is pursuing exciting initiatives with our counterparts in the Soviet Union and Japan with the aim of increasing financial support for and opening new territory to our scientists. We are also engaged in dia-

Charley Hollister

Tom Kleindinst





Development Committee Chairman Walter Smith and his wife Hope visit an Easter Island statue during a 1989 trip to the South Pacific that was sponsored by the WHOI Associates Program.

logues with CEOs of major chemical companies concerning the role of the oceans in the management of hazardous waste and sludge. In addition, talks are underway with oil company executives to provide them with scientific information in order for them to handle disasters in an environmentally sound fashion.

All the above equates to a new and vigorous plan to educate, excite, and motivate those who will dramatically increase our chances of scientific discovery by providing opportunity. Our message, even as we organize to articulate it more effectively, already must be reaching some as evidenced by the marked increase in the 1989 total of private support – 35 percent higher than 1988, nearly four million dollars! We are confident this is only the beginning of a real success story. To those of you who have made this such a banner year, my sincerest thanks and appreciation.

Charles D. Hollister
Vice President and
Associate Director for External Affairs

Acting Dean's Comments

I NOTE with some amusement in reviewing last year's report that one "RADM Craig Dorman (Joint Program Graduate, Ph.D., 1972)" was listed among the "other speakers" at the Joint Program's 20th anniversary celebration. It reminds me of both how much we've changed, and yet how stable and successful the MIT/WHOI Joint Program, our major education program, has been.

During 1989, the education program witnessed:

- Charley Hollister's move from Dean to Vice President of the Corporation and Associate Director of External Affairs, my succession as (self-appointed) Acting Dean, and the search for a new, fully-salaried Associate Director of Education and Dean of Graduate Studies.
- An Advisory Committee review of the Joint Program, headed by Professor Owen Phillips of Johns Hopkins University, and a Navy Curriculum review by RADM Richard Pittenger, Oceanographer of the Navy.
- The second successful College Faculty Workshop, this time run concurrently with workshops at the Scripps Institution of Oceanography and the University of Washington as we attempt to promote our field to those who can most directly affect college students' career decisions.
- Continuation of our strong acceptance rate of over 65 percent in the graduate program; a record high of Summer Student Fellows, 32 with the addition of nine National Science Foundation REUs (Research Experience for Undergraduates), and the sustained private support of associates, alumni, and friends; a very strong group of 10 new Postdoctoral Scholars; the 31st summer of the Geophysical Fluid Dynamics Program; and continuation of our ongoing Guest Student Program for volunteer students who want hands-on laboratory experience (see insert for enrollments).
- Promotion of A. Lawrence "Jake" Peirson III to Associate Dean.

I deliberately stepped into Charley's shoes early in my tenure as Director so that I could acquaint myself in detail with our program and ensure that education had become and would remain an intrinsic and thoroughly integrated part of our research and life at WHOI. This gave me the opportunity to receive directly the report of the MIT/WHOI Joint Advisory Committee, from which I quote:
"In overall quality it is, in the minds of the committee, clearly among the best in the country, probably the best. It is of national importance in the education of scientists in ocean sciences and engineer-

1989 Enrollment

Postdoctoral Scholar Awardees	10
Marine Policy & Ocean Management Fellows	4
MIT/WHOI Joint Program–Fall 1989	117
Summer Geophysical Fluid Dynamics Fellows	10
Summer Student Fellows	32
Guest Students	34

Karen Rauss

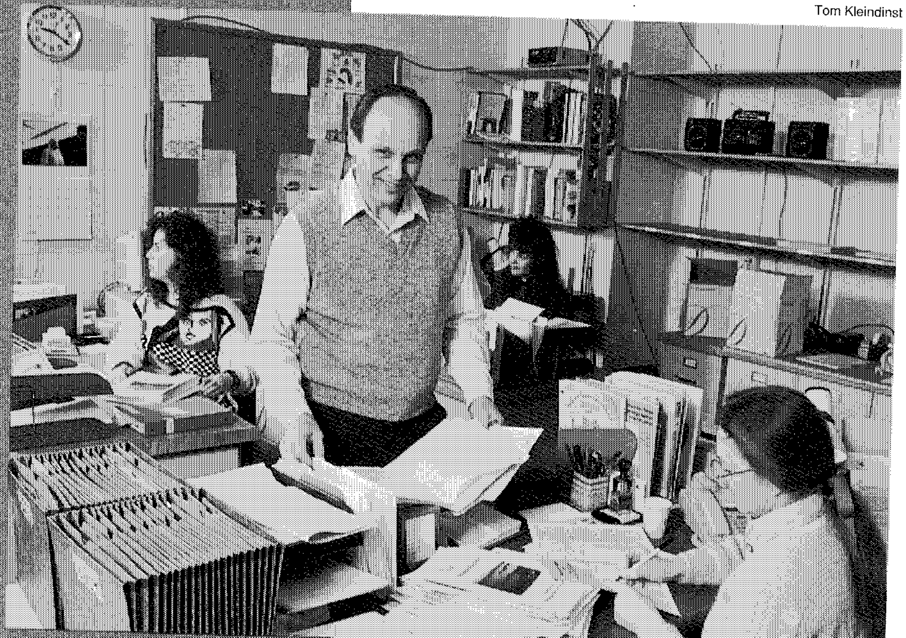
The annual student summer meeting in August of 1989 included a Craig Dorman look-alike conspiracy – students and education office staff sported heavy eyebrows, cigars (or breadsticks), and red shirts similar to one the Acting Dean was known to be fond of wearing.

ing and has already, in the twenty years or so of its formal existence, contributed massively to the preparation of a generation of ocean scientists and engineers who are now at the forefronts of their fields.... The Joint Program [is] of cardinal importance to oceanography and a shared jewel in the crowns of two institutions."

Coming from highly respected scientists such as Owen Phillips, Frank Press, Robert Frosch, Frank Richter, James Holton, William Kemperer, Kenneth Macdonald, and our own Executive Committee members Mildred Dresselhaus and Keith Thomson, this is no small praise. Of course they also had a few critiques and suggestions, the most significant of which was to undertake a national search for a new WHOI Dean of "high scientific stature, academic experience and administrative ability, with the responsibility and authority to ensure that the highest academic standards be maintained, to serve as an advocate for the Joint Program and an interface with MIT." We took advantage of this charge to reconsider the role of education at WHOI. Given the national dilemma in science and engineering education, the excellence and excitement of our scientists and field, and the interest of a broad cross section of our staff and students in education, we decided that we should make a major commitment to increasing our educational outreach. To this end, we created a new Associate Director position and started an intensive national search under the leadership of Joe Pedlosky. (As this report went to press, we were pleased to announce the selection of former WHOI staff member John W. Farrington for this position. He will be leaving his post as Michael P. Walsh Professor of Environmental Science at the University of Massachusetts, Boston, to come to Woods Hole in August 1990.)

Jake Peirson is shown in the Education Office with Barbara Ewing-Deremer (foreground), Sara Wheeler (upper left), and Pam Goulart (upper right).

Tom Kleindinst



Graduate Degrees Awarded

		1989	1968-89
WHOI	Ph.D	—	3
MIT/WHOI	Ph.D	18	202
MIT/WHOI	Sc.D.	0	25
MIT/WHOI	Engineers	4	30
MIT/WHOI	Masters	8	17
		30	277
Total Degree Recipients*		27	273

*Some receive more than one degree.

A few other less critical but still significant changes are:

• We are at long last constructing a Student Center in the attic of Clark extension.

• Thanks to the generosity of the Horace W. Goldsmith Foundation, we are starting a new tradition of offering entering students an opportunity to sail for a week on Sea Education Association's 125-foot schooner *Westward*. The intent is to introduce them to practical oceanography while they get to know each other in one of the best ways possible, on a tall ship in the North Atlantic. This should also help us forge stronger ties with our neighbors at SEA.

• Thanks to help from MIT Joint Program Director, Sallie W. "Penny" Chisholm, we are renting an apartment at 100 Memorial Drive, Cambridge, for WHOI scientists to spend time more conveniently with their colleagues at MIT. We also expect to upgrade our microwave link between WHOI and MIT and, through the link, to introduce the Athena cluster concept so successfully developed by MIT to improve the use of computers in education.

The Navy curriculum review was equally successful. We timed an internal reassessment of the Master's Degree Program to coincide with it, and we have decided to consolidate our M.S. efforts in the Oceanographic Engineering Program, with continued participation by Geology and Geophysics.

On a somewhat peripheral note, I was appointed by Governor Dukakis as a Trustee of Massachusetts Maritime Academy, to fill the seat left vacant by the death of Paul Fye. Readers from this state will recognize that this placed me directly in state education issues, since the Academy had been in the public eye and was under threat of merger or clo-sure. A recent state decision to retain its autonomy now poses the challenge of strengthening its position and improving its posture in the state higher education system.

Our local outreach is also increasing. Together with the Marine Biological Laboratory, U.S. Geological Survey, National Marine Fisheries Service, and the local school systems, we have formed a partnership to improve the quality of science education on the Cape. This is just getting geared up but promises to be an exciting enhancement of our tradition of support for secondary school education through science fairs, scholarships, and laboratory assistance. And although we cover it in detail in another article, it would not do to bypass mention here of our Education Office's role in coordinating Cape school participation in the JASON Project's activities. This initiative of Bob Ballard's has helped generate excitement in science education throughout our community, and the logistic hassles of getting several thousand school kids into and out of town are more than repaid by the resulting increase in their interest in the oceans and science education.

Education at WHOI has started to take on a new dimension during 1989. Building on the solid base that Charley and Jake and the Education Office have established, we intend to keep the Joint Program the best in the world, to make opportunities to participate in education more readily available to a larger segment of our staff, and to increase our outreach activities, while strengthening our ongoing fellowship programs.

Craig E. Dorman
Acting Dean

1989 Ocean Ventures Fund Awardees

Carol Arnosti
"Effect of Structure on Bacterial Degradation of Carbohydrates"

Debra Colodner
"Geochemistry of the Element Iridium"

Linda King
"Chlorophyll Diagenesis in Recent Sediments"

John Kokinos
"Modern and Fossil Dinoflagellate Cysts: New Techniques to Link the Present with the Distant Past"

Christopher Scholin
"A New Approach to the Study of New England's Toxic Algal Blooms"

Paul Snelgrove
"The Importance of Food Quality in the Maintenance of Deep-Sea Species Diversity"

Nathalie Waser
"Application of ^{32}p and ^{33}p to the Study of Phosphorus Cycling in the Upper Ocean"

1989 J. Seward Johnson Chairs in Oceanography

Biology
Judith E. McDowell

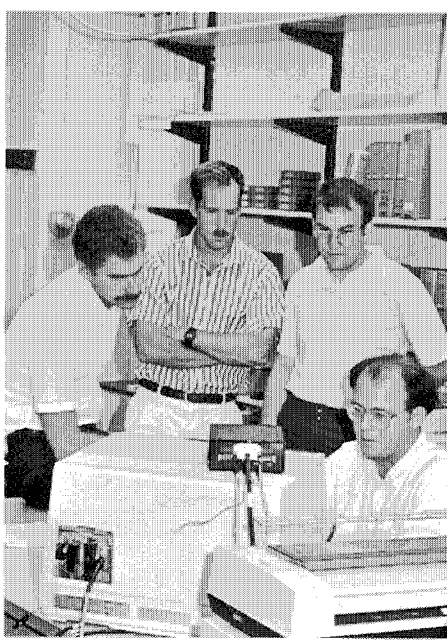
Chemistry
Edward R. Sholkovitz

Geology & Geophysics
Elazar Uchupi

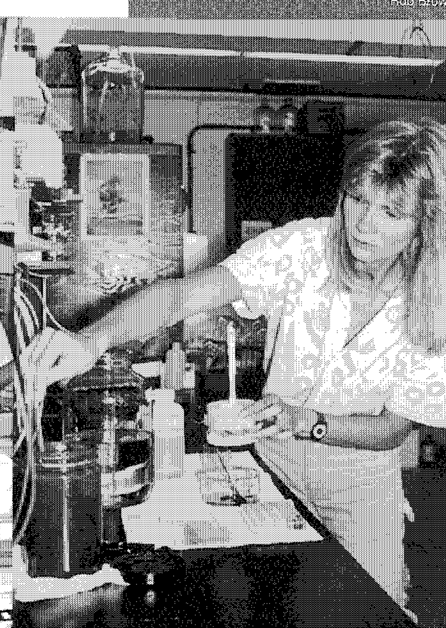
Applied Ocean Physics & Engineering
James F. Lynch

Physical Oceanography
Nick P. Fofonoff

David Gray



Rob Brown



Left: From left, Bruce Miller, John Ferguson, and Randall Richards look over Eddie Scheer's shoulder.
Right: Kimberly Warner, a 1988 Summer Student Fellow, works in a WHOI laboratory.

Right: The remotely operated vehicle *Jason* inspects an ancient shipwreck on the Mediterranean seafloor off Sicily during Project JASON.

Below right: Cape Cod schoolchildren arrive at Redfield Auditorium for one of the JASON Project shows.

© Quest Group, Ltd.

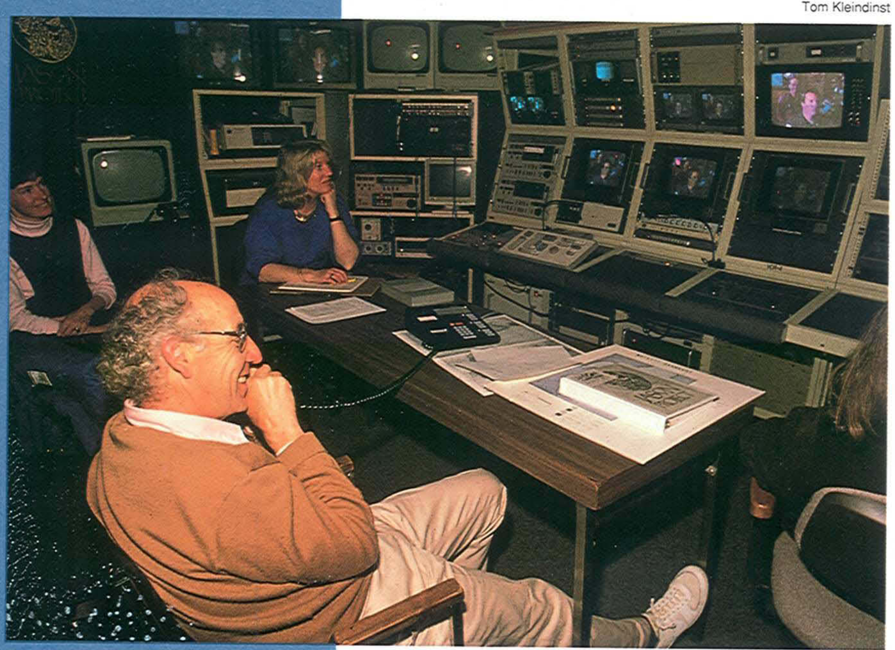
George F. Mobley
© National Geographic Society

Above: Bob Ballard reached nearly a quarter of a million schoolchildren through Project JASON.

Tom Kleindinst

Below: Geochemist Geoff Thompson, in Woods Hole, experiences telepresence as he "visits" an interesting site on the Mediterranean seafloor and guides *Jason's* movements by telephone to its operator aboard *Star Hercules*.

Tom Kleindinst



In response to the deepening science education crisis in the United States, Dr. Robert D. Ballard, Senior Scientist in the Applied Ocean Physics and Engineering Department and Director of WHOI's Center for Marine Exploration, conceived and executed the JASON Project. Named after the most advanced and versatile of the WHOI Deep Submergence Laboratory's unmanned underwater vehicles (in turn named after the mythological Greek hero), in its first year the JASON Project brought over 225,000 school children into 12 museum sites around the country (and WHOI's Redfield Auditorium) to experience underwater exploration in the Mediterranean Sea as it occurred.

JASON combined the undersea technology of WHOI with the communications expertise of Electronic Data Systems Corporation and the programming and broadcasting skills of the National Geographic Society and Turner Broadcasting System to create what Bob calls "telepresence." After studying a curriculum developed by the National Science Teacher's Association, the students visited a museum to join Bob and his team on board *Star Hercules* as they conducted geological studies on the Marsili Seamount or undertook an archaeological investigation of a fourth century shipwreck. Through telepresence, the students could watch the activities both in the control room and on the seafloor, and ask Bob questions. Some 84 live programs were broadcast during the 14-day expedition.

The JASON Project vividly demonstrated the excitement and joy of ocean sciences to nearly a quarter million school children, motivating them to study science and mathematics and focusing on science as an important intercultural bridge to the basic dynamics of human behavior. Scientists at WHOI had the added opportunity to receive data from instruments on the robot as well as the pictures, as they viewed the first discovery of hydrothermal vents in the Mediterranean and explored the surrounding geology and biology from half the world away in the comfort of the "Black Room" on the first floor of the Blake Building.

WHOI supported Bob in coordinating the entire prototype JASON Project in 1989. The results were sufficiently promising, with enough enthusiasm from the schools and museums (and sufficient strain on the participants) that it was decided to form an independent not-for-profit organization to continue and expand the effort. Consequently, the JASON Foundation for Education was incorporated in Washington, DC, “1) to conduct and support educational activities using the technology of telepresence across the spectrum of physical sciences, and in support thereof; 2) to foster, stimulate, and support scientific research in oceanographic and marine topics and other physical and social sciences; and 3) to aid, assist, and contribute to the support of corporations, associations, and institutions which are organized and operated exclusively for such purposes and which are described in Section 501(c) 3 of the Code.”

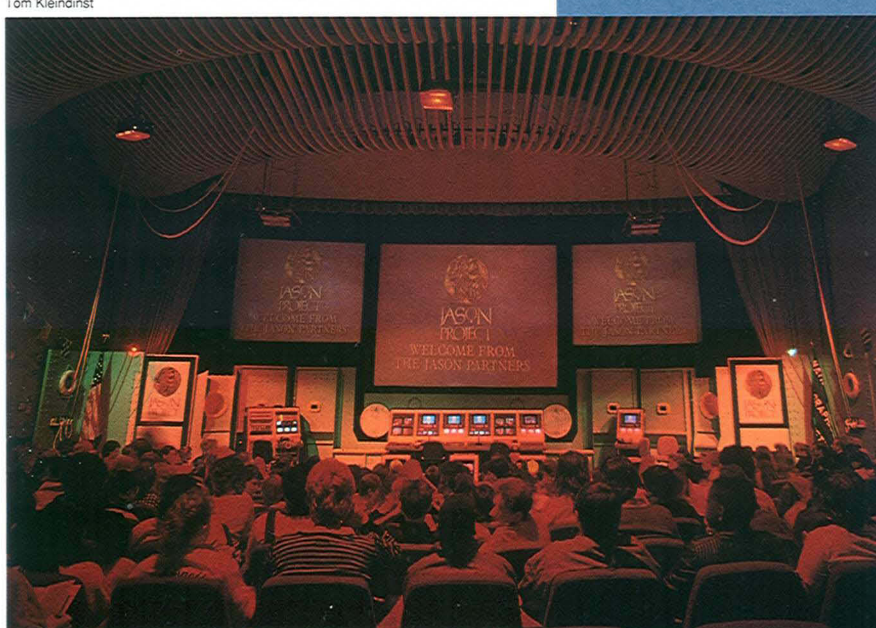
WHOI retains its close ties to the JASON Foundation for Education not just through Bob, who is Chairman of the Board, but through our own Chairman, Guy Nichols, and Director, Craig Dorman, who are also Directors (along with Les Aberthal, President and Chairman of the Board of Electronic Data Systems; Gilbert Grosvenor, President and Chairman of the Board of National Geographic Society; and Michael T. Gustafson, President of Wesco Resources). WHOI will contract annually to the Foundation to supply the services of the DSL team, vehicles, and production van for the field programs, and will continue to act as a downlink “museum” site for Cape schoolchildren’s participation.

The early May 1990 program was designed to take students to the depths of Lake Ontario to study the U.S. Navy vessels *Hamilton* and *Scourge*, which sank in a squall after taking part in all the major Naval battles fought on Lake Ontario in the War of 1812. In addition to history, the curriculum will feature the technology and control of the robot vehicles, the limnology of the lakes, the state of the ships, and ecology. Future expeditions are planned for the Galapagos Islands and the waters off Spain and Japan.

Terri Corbett

George F. Mobley, © National Geographic Society

Tom Kleindinst



Jason Project & Jason Foundation for Education

JASON PROJECT™

Top: Archaeologist Anna McCann works with one of the amphorae recovered during the 1989 JASON Project.

Middle: Bob Ballard and one of the JASON Project students explore the Mediterranean seafloor during the discovery phase of the JASON Project.

Bottom: The JASON Project show begins at the National Geographic Society Explorers' Hall in Washington, DC.

WHOI Awards & Honors

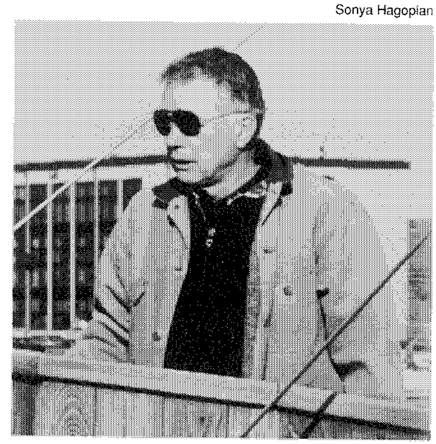
Some 270 WHOI employees with 10 or more years of service received awards at the first Employee Recognition Celebration. The October festivities, held in a tent on the Fenno House lawn, included music and refreshments. For 10-year service award is a lapel pin, the 20 a Seth Thomas clock, and the 30 choice of a Nichols & Stone WHOI armchair or rocker.

The Penzance and Vetlesen awards were established in 1989 by Director Craig Dorman with funds from the Penzance Foundation and the Vetlesen Foundation. The winners were chosen from staff nominations.

Vetlesen Awards are given for "selfless dedication of a major portion of . . . time and talents to the entire WHOI community over a long period of time," and the Penzance Award honors a WHOI group for exceptional contributions to the Institution and its staff.

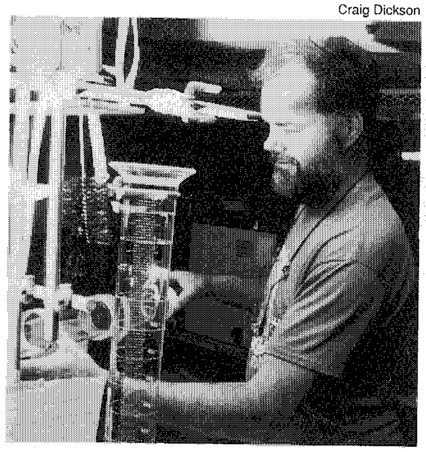
Tom Kleindinst

Sonya Hagopian



In the photo at top left, Personnel Manager Barbara Wickenden shows the 20-year service award, a Seth Thomas clock, to Marv Stalcup, left, and George Power.

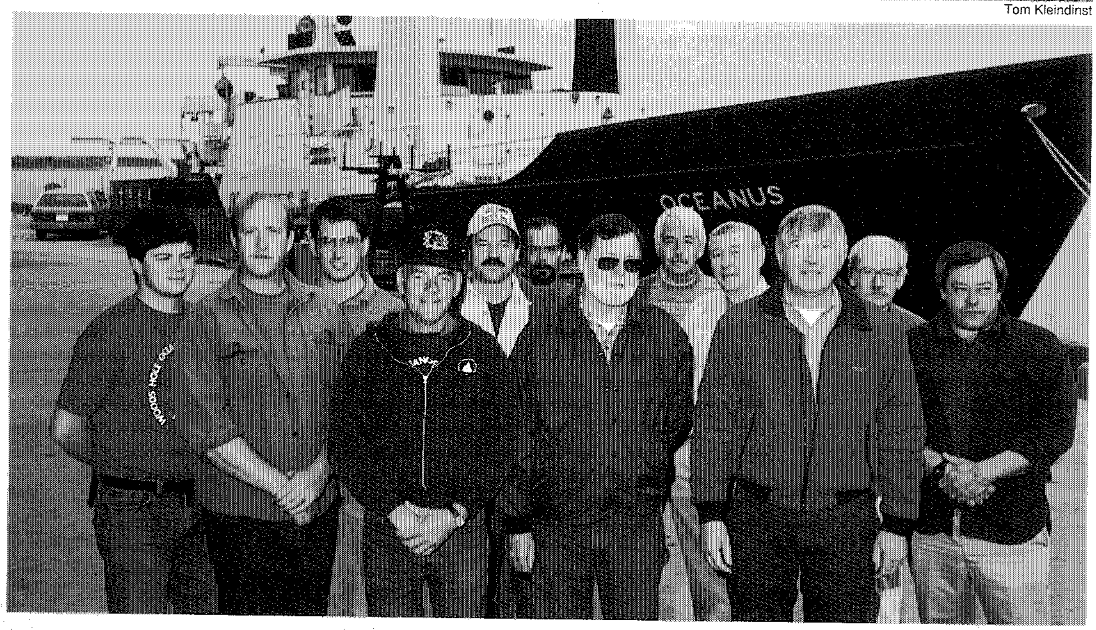
Craig Dickson



Tom Kleindinst

The 1989 Vetlesen Award winners, for "selfless dedication of a major portion of their time and talents to the entire WHOI community over a long period of time," are Dick Colburn (top right photo), Hovey Clifford (left center), and Judy McDowell (right center).

Tom Kleindinst



The crew of R/V *Oceanus* received the 1989 Penzance Award for exceptional contributions to the Institution and its staff. Those serving on the vessel in April of 1990 are pictured at right. From left, they are Pat Mone, Steve Murphy, Greg LeBlanc, Rick Simpkin, Doug Mayer, Kevin Kay, Mike Palmieri, Jeff Stolp, Buzzy McLaughlin, Paul Howland, Hugh Dakers, and Larry Bearse.

Alvin's 25th Anniversary

EVERAL events during the year cele- brated the 25th anniversary of the ımissioning of DSV *Alvin*. More than 00 employees and guests gathered ler a tent on the Iselin Mall June 5 for sic, refreshments, *Alvin* sea stories, l presentation of several awards. Allyn ıe, Harold Froelich, Charles Momsen, and, posthumously, Paul Fye were ıored for their contributions to making l keeping *Alvin* a special national ility. Numerous greetings, citations, l awards lauded*Alvin* and the *Alvin* up, including the National Science ındation's Distinguished Public Service ard, a National Oceanic and Atmos- ›ric Administration citation for 25 years ıutstanding operations and safe service he marine science comunity, and the M International (formerly American ɔiety of Metallurgy) designation as an toric landmark. WHOI Associates ıed the 25th anniversary celebration en their June 16 Woods Hole dinner tured an *Alvin* lecture and exhibits.

A Silver Jubilee Symposium in Redfield Auditorium October 16-18 drew some 125 scientific users of *Alvin*. Their discussions ranged over *Alvin's* many contributions to marine science in such areas as studies of hydrothermal vents, deep-sea fishes, marine snow, geophysics and seafloor structures at mid-ocean ridges, and deep-sea microbiology.

On November 17, the 1989 Elmer A. Sperry Award for "the invention, development and deployment of the deep-diving submarine *Alvin*" was presented to *Alvin* designers and visionaries Harold Froehlich, Charles Momsen, Jr., and Allyn Vine The occasion was the annual meeting of the Society of Naval Architects and Marine Engineers. Director Craig Dorman was the principal banquet speaker with a presentation focusing on underwater challenges of the present and future. The Sperry Award was established in 1955 to honor the inventions of Elmer Sperry and to encourage progress in transporation engineering.

Paul Oberlander delivers balloons to the celebration.

Photos by Terri Corbett

Top left: Craig Dorman, center, and Barrie Walden, right, enjoy Larry Clark's description of organizing the NSF Distinguished Public Service Award for a nonperson.

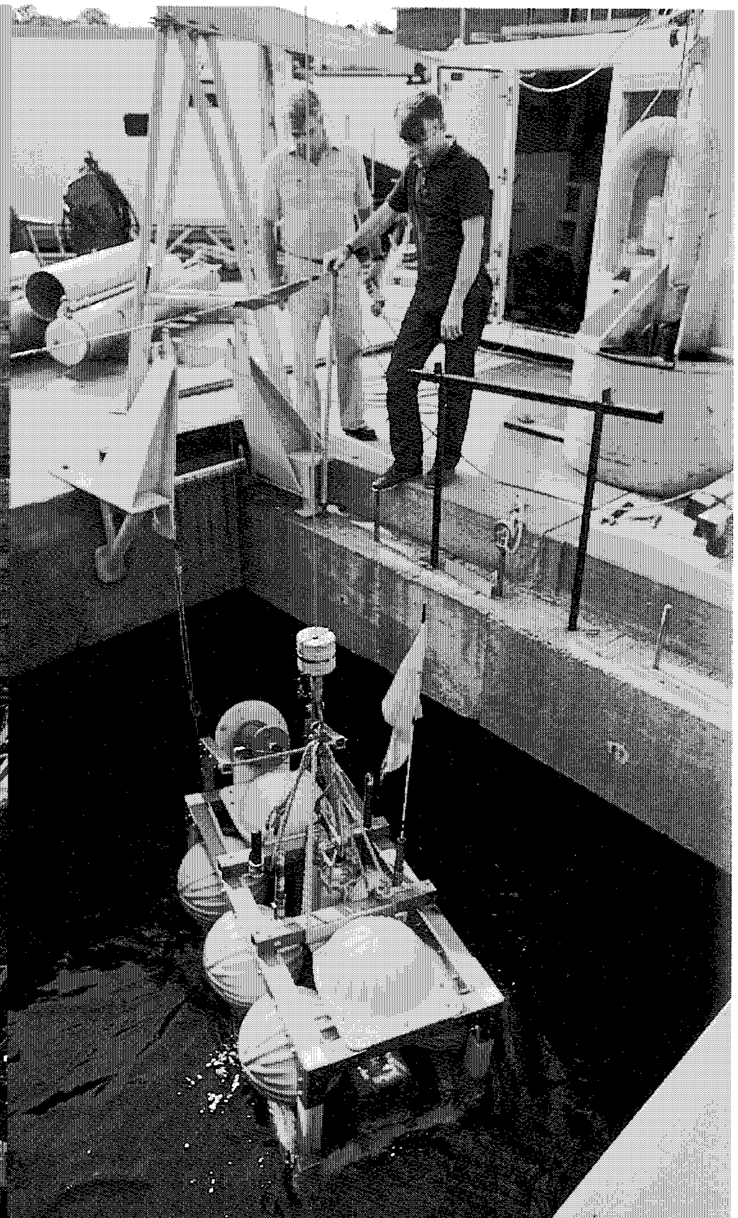
Top right: Victoria Kaharl, whose history of *Alvin* is scheduled for 1990 publication, reviews the sub's career for those attending the 25th anniversary celebration in the Iselin Mall tent.

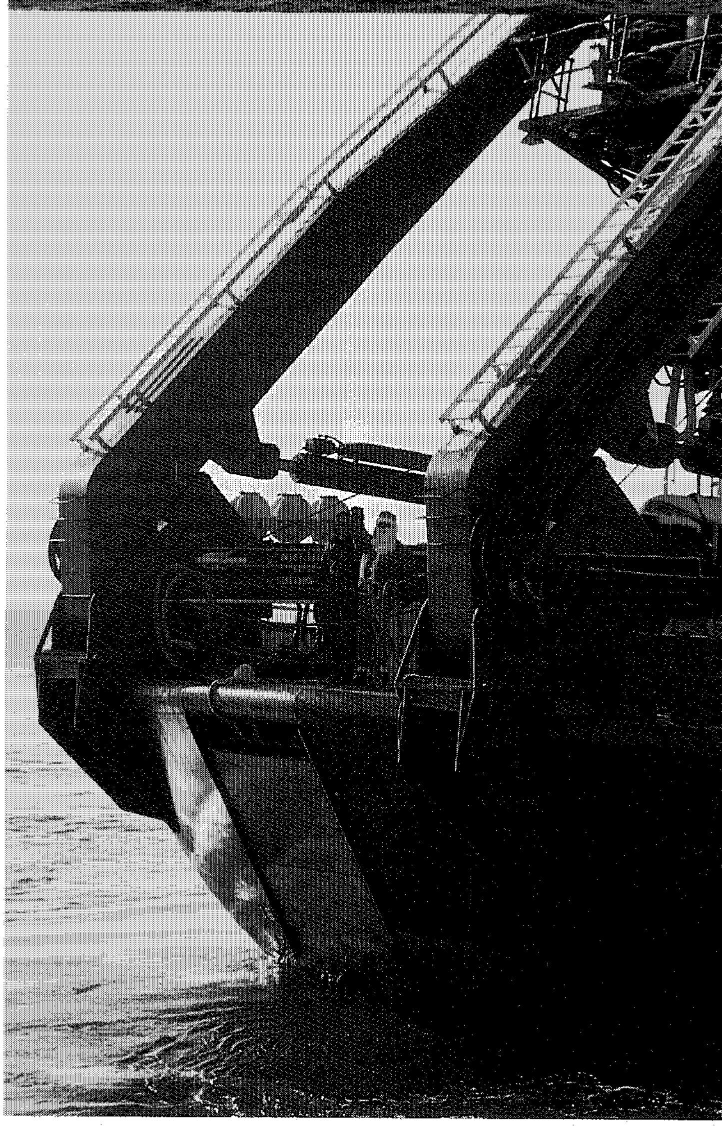
Lower left: *Alvin*, undergoing overhaul in the Iselin high bay, received visitors during the anniversary celebration.

Lower right: Those receiving awards for their contributions to making and keeping *Alvin* a special national facility were, from left, Charles Momsen, Ruth Fye (on behalf of her husband, Paul Fye), Allyn Vine, and Harold Froehlich.

Upper Photo: David Hosom. Lower Photo: Terri Corbett.

Upper Photo: Tom Kleindinst. Lower Photo: Tom Kleindinst.





Top left: Asterias tows a new meteorological buoy to a mooring test site. *Top right:* Rob Handy, left, and Beecher Wooding test a new ONR ocean bottom seismometer in the WHOI pier basin. *Lower left: Atlantis II* steamed into Woods Hole carrying an unusual red-suited passenger in December. *Lower right:* A second Clark Laboratory addition that will house part of the Physical Oceanography Department was well underway in December 1989.

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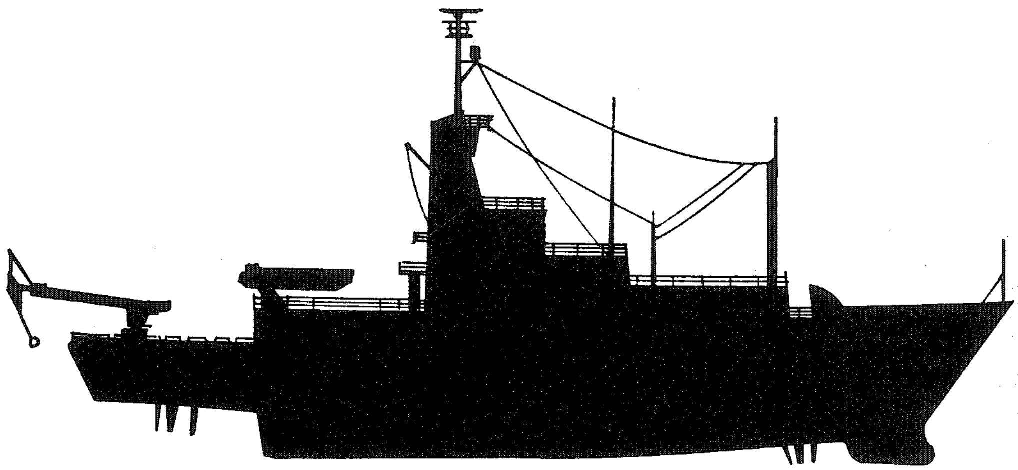
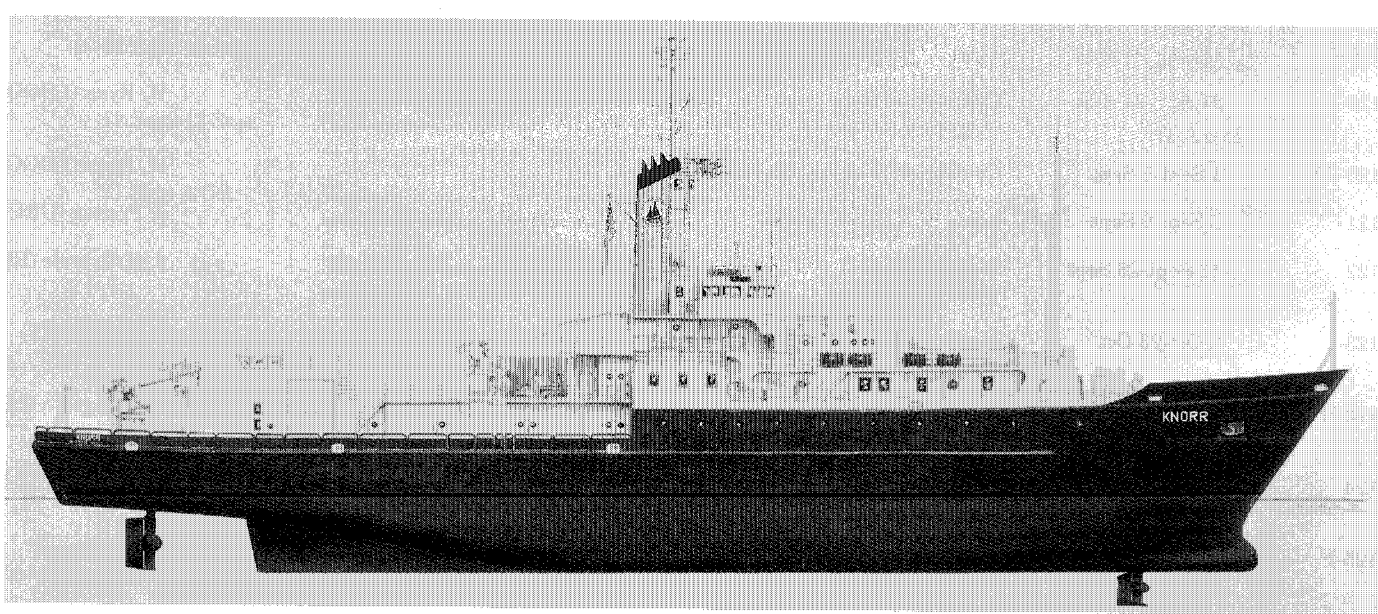


Voyage Statistics

R/V *Knorr* spent the year at McDermott Shipyard in Amelia, Louisiana, for a refit that included lengthening the ship and a variety of other improvements. The old profile is shown at the top of the page, the new at the bottom, and the ship cut in half in the middle.



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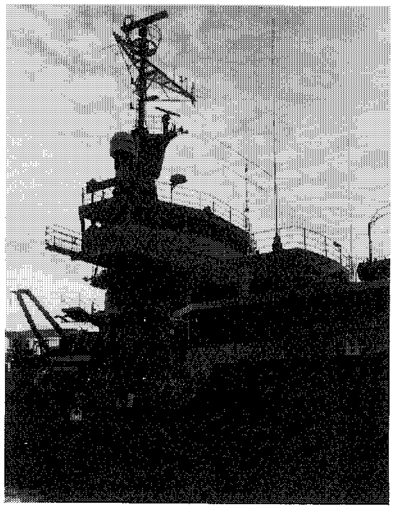

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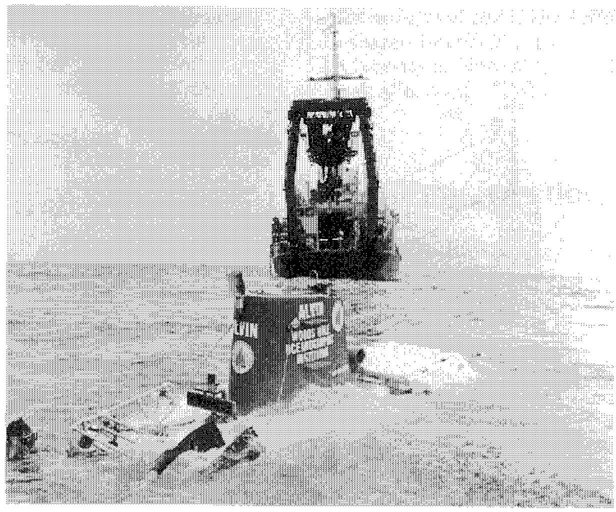

Terri Corbett

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

Total Nautical Miles for 1989 - 23,344
Total Days at Sea - 202

Total Dives - 26

Voyage	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
	1 Jan-13 Mar	Maintenance at WHOI Pier	Woods Hole	
119-I	14 Mar-24 Mar	Transit to Joint Global Ocean Flux Study area, 20°W (JGOFS)	Funchal, Madeira	
119-II	28 Mar-7 Apr	Eastern North Atlantic, bottom tethered sediment trap array experiment (JGOFS)	Reykjavik, Iceland	S. Honjo
119-III	10 Apr-13 Apr	South of Iceland, marine luminescence in the mixed-layer pilot program	Reykjavik, Iceland	L. Sullivan (LDGO)
119-IV	18 Apr-11 May	Eastern North Atlantic, primary production measurements (JGOFS)	Ponta Delgada, Azores	J. Marra (LDGO)
119-V	15 May-8 June	Eastern North Atlantic, North Atlantic Bloom Study (JGOFS)	Reykjavik, Iceland	H. Ducklow (UMD)
119-VI	13 June-27 June	Central North Atlantic, ALS recovery/ transit to Woods Hole	Woods Hole	W. B. Owens
	28 June-9 Aug	Refit *Atlantis II* for *Alvin* following biannual *Alvin* overhaul	Woods Hole	
120-I	10 Aug-20 Aug	*Alvin* trials and certification, 9 dives	St. George, Bermuda	B. Walden
120-II	21 Aug-31 Aug	Continental slope, anatomy, age, and origin of passive margin unconformities, 1 dive	Woods Hole	W. Ryan (LDGO)
120-III	1 Sept-5 Sept	Continuation of Voyage 120-II	Woods Hole	W. Ryan (LDGO)
121	8 Sept-9 Sept	Local SEA BEAM trials	Woods Hole	J. Freitag (URI)
122	16 Sept-26 Sept	Western North Atlantic, 7 dives, effects of deep-water sludge disposal at Deep Water Dumpsite 106	Woods Hole	J. F. Grassle (RU)
123-I	2 Oct-23 Oct	North Atlantic, temporal variability of lead in the Atlantic	Ponta Delgada, Azores	E. Boyle (MIT)
123-II	29 Oct-29 Nov	Mid-Atlantic Ridge, hydrothermal circulation on sediment starved mid-ocean ridges	Woods Hole	M. Langseth (LDGO)
124	5 Dec-20 Dec	Continental slope, anatomy, age and origin of passive margin conformities, 9 dives	Woods Hole	W. Ryan (LDGO)
125-I	29 Dec-31 Jan '90	Mid-Atlantic Ridge, investigation of hydrothermal processes	Woods Hole to Jacksonville, Florida	G. Thompson P. Rona (NOAA)

R/V *Knorr*

Total Nautical Miles for 1989 - 1,932
Total Days at Sea - 10

Voyage	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
	6 Feb- 15 Feb	Transit to Shipyard in Morgan City, Louisiana, for refit. Out of service		

R/V *Oceanus*

Total Nautical Miles for 1989 - 36,583
Total Days at Sea - 231

Voyage	Cruise Period	Principal Objective, Area of Operations	Ports of Call	Chief Scientist
205-IV	5 Jan-27 Jan	Tropical Atlantic, SOFAR Float Study of deep boundary currents	Fortaleza, Brazil	P. Richardson
205-V	2 Feb-20 Feb	Continuation of Voyage 205 IV	Las Palmas, Canary Islands	P. Richardson
205-VI	25 Feb-21 Mar	Tropical Atlantic, trans-Atlantic CTD and doppler profiling section	Bridgetown, Barbados	D. Roemmich (SIO)
205-VII	28 Mar-1 Apr	Transit Barbados-Bermuda, Gulf Stream upper ocean studies	St. George, Bermuda	T. Joyce
205-VIII	4 Apr-21 Apr	Western North Atlantic, Gulf Stream upper ocean studies	Woods Hole	T. Joyce
206-I	5 May-12 May	Sargasso Sea, biochemistry of nitric oxide	St. George, Bermuda	O. Zafiriou
206-II	13 May-20 May	Continuation of Voyage 206-I	Woods Hole	O. Zafiriou
207	26 May-21 June	Gulf Stream, SYNOP (Synoptic Ocean Prediction) experiment mooring deployment	Woods Hole	D. R. Watts (URI)
208	26 June-28 June	North Atlantic, test SeaSoar system	Woods Hole	J. Luyten
209	5 July-29 July	Shipyard maintenance work	Brooklyn, New York	
210-I	8 Aug-19 Aug	Gulf Stream, SYNOP experiment mooring recovery	Woods Hole	D. R. Watts (URI)
210-II	22 Aug-1 Sept	Continuation of Voyage 210-I	Woods Hole	D. R. Watts (URI)
211	6 Sept-7 Sept	NSF inspection	Woods Hole	
212-I	11 Sept-11 Sept	Local waters, test of improved meteorological system	Woods Hole	K. Prada
212-II	12 Sept-13 Sept	Stellwagen Bank, sediment collection at long-term monitoring site	Woods Hole	G. Jones
213-I	21 Sept-4 Oct	Western North Atlantic, microelectrode studies of benthic carbonate fluxes	St. George, Bermuda	S. Emerson (UWA)
213-II	5 Oct-10 Oct	Bermuda-Woods Hole, flying fish profiler test, SYNOP buoy recovery	Woods Hole	A. Bradley
214-I	14 Oct-19 Oct	Sargasso Sea, flow cytometry studies of marine microbial ecology	St. George, Bermuda	R. Olson
214-II	20 Oct-29 Oct	Continuation of Voyage 214-I	Woods Hole	R. Olson
215-I	3 Nov-9 Nov	Continental slope, acoustic telemetry experiments with large fish	Woods Hole	F. Carey
215-II	9 Nov-21 Nov	Continuation of Voyage 215-I	Woods Hole	F. Carey
216	30 Nov-13 Dec	Western North Atlantic, Gulf Stream upper ocean studies	Woods Hole	T. Joyce

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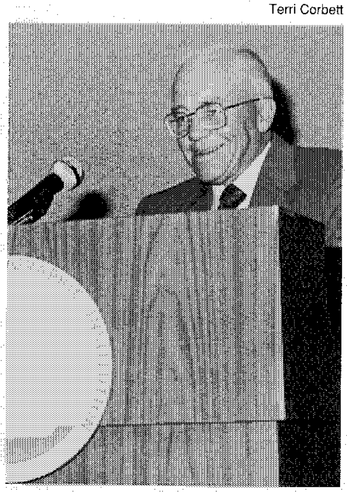

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In Memoriam

The Institution gratefully acknowledges the service and support of Robert M. Akin, Jr., John M. Alden, John A. Gifford, George Nichols, Jr., Howard Simons, and Alfred M. Wilson, who passed away in 1989, and Harold E. Edgerton, who passed away in early 1990.

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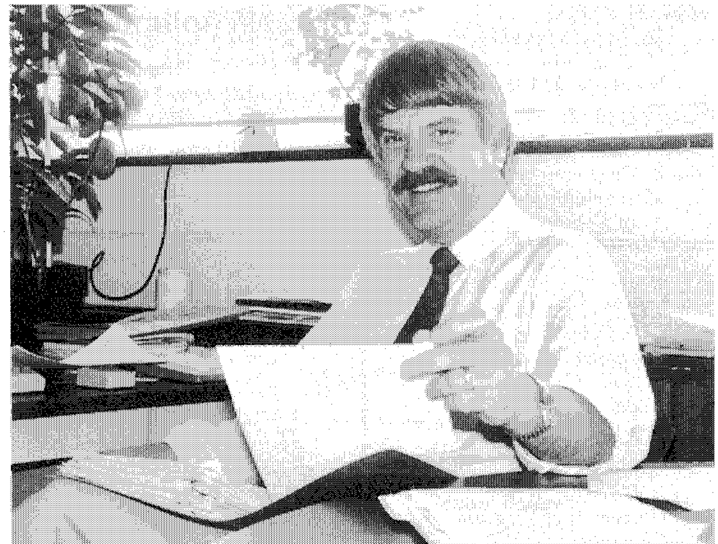

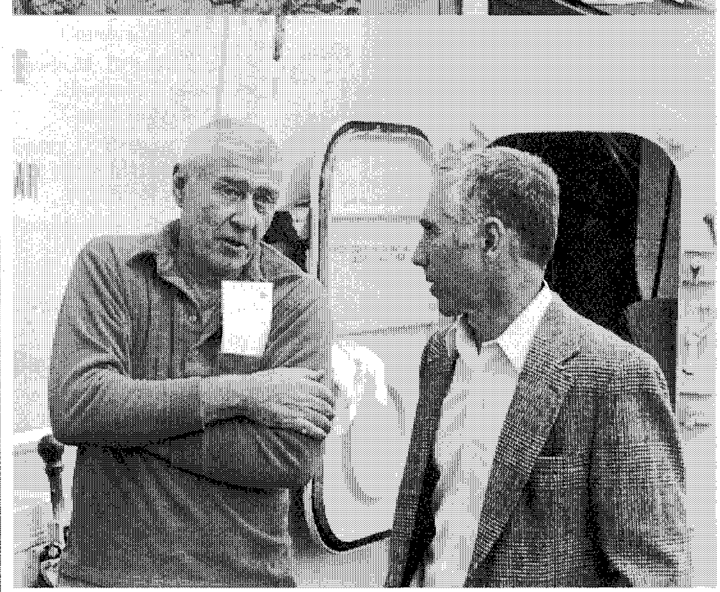

Top: Bill McKeon. *Center left:* Rose Petrecca and dumpsite mud. *Center right:* Kim Fahnley. *Bottom:* Buzzy McLaughlin, left, and Craig Dorman.

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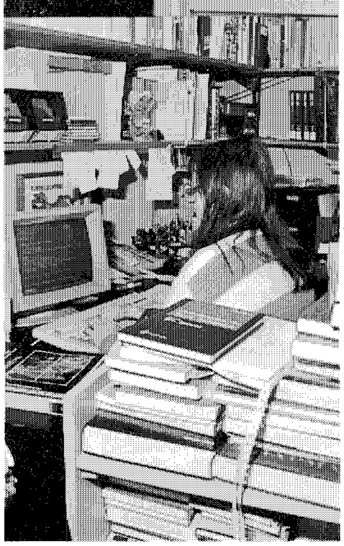

Top: Mike Toner
Bottom: Maggie Rioux (and books)

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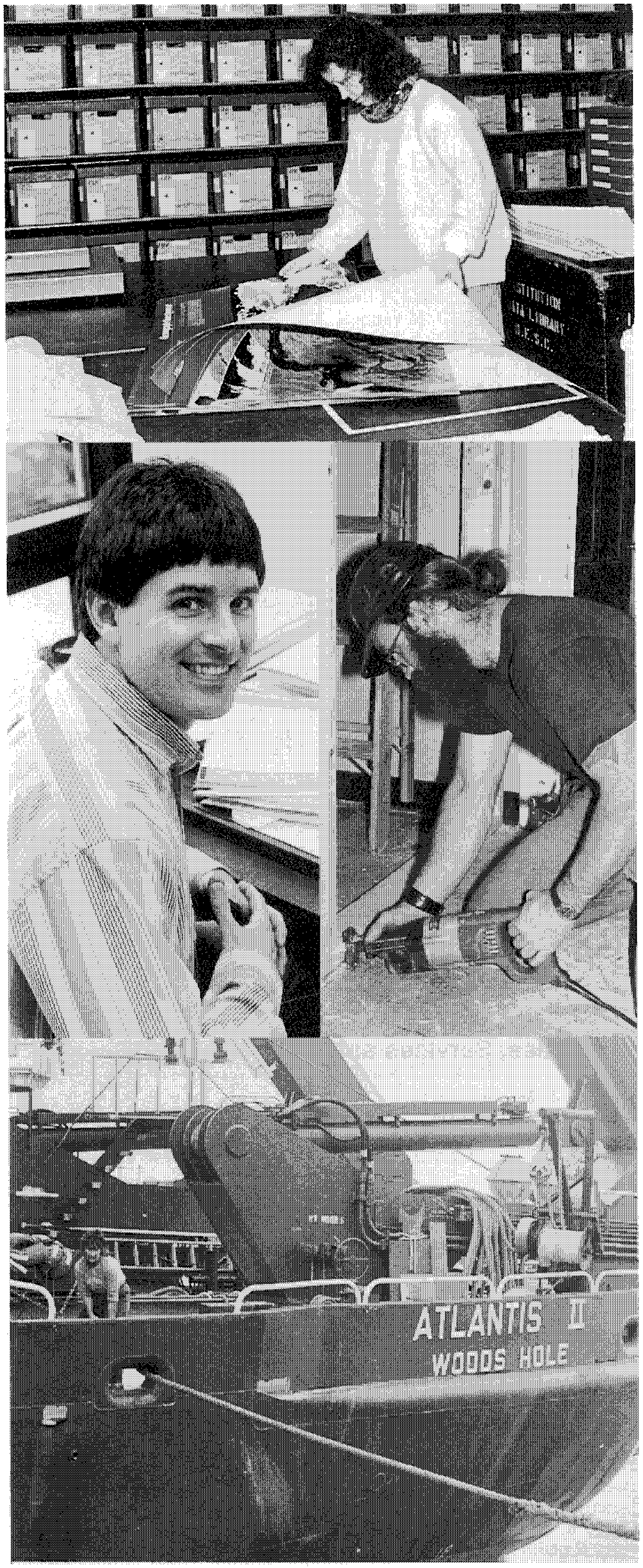

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Center right: Chris Kennedy. *Bottom:* Cecile Hall.

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Joseph Ribeiro

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Massachusetts Institute of Technology/ Woods Hole Oceanographic Institution Joint Program in Oceanography/ Oceanographic Engineering

Doctor of Philosophy

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B.Sc. University College, Cork
M.Sc. University College, Wales
Special Field: Marine Geology & Geophysics
Dissertation: A Search for Layering in the Oceanic Crust

Peter H. Dahl
B.S. University of Washington
M.S. University of Washington
Special Field: Oceanographic Engineering
Dissertation: Acoustic Diffraction from a Semi-infinite Elastic Plate under Arbitrary Fluid Loading with Application to Scattering from Arctic Ice Leads

David M. Delonga
B.S.M.E. United States Naval Academy
M.B.A. University of Maryland
S.M.M.E. Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: A Control System Design Technique for Nonlinear Discrete Time Systems

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B.S. Winona State University
Special Field: Marine Geology & Geophysics
Dissertation: Ocean Bottom Seismic Scattering

Kelly K. Falkner
B.A. Reed College
Special Field: Chemical Oceanography
Dissertation: An Investigation of the Marine Geochemistry of Gold

Ichiro Fukumori
B.S. University of Tokyo
Special Field: Physical Oceanography
Dissertation: Efficient Representation of the Hydrographic Structure of the North Atlantic Ocean and Aspects of the Circulation from Objective Methods

Tanya H. Furman
B.S.E. Princeton University
Special Field: Marine Geology & Geophysics
Dissertation: Evolution of Icelandic Central Volcanoes: Evidence from the Austurhorn Plutonic and Vestmanneayjar Volcanic Complexes

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B.S. University of Michigan
S.M.C.E. Massachusetts Institute of Technology
Special Field: Oceanographic Engineering
Dissertation: Modelling Bottom Stress in Depth-Averaged Flows

Pamela J. Kloepper-Sams
B.S. University of California, Irvine
Special Field: Biological Oceanography
Dissertation: Molecular Regulation of the Induction of Cytochrome P-450E in the Estuarine Fish *Fundulus heteroclitus*

Brian P. Palenik
B.S.E. Princeton University
Special Field: Chemical Oceanography
Dissertation: Dissolved Organic Nitrogen Utilization by Phytoplankton: the Role of Cell-Surface Deaminases

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B.S. Michigan Technical University
Special Field: Biological Oceanography
Dissertation: Swimming Behavior and Energetics of Sharks

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B.S. University of Maryland
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Special Field: Marine Geology & Geophysics
Dissertation: Inference of Ecology from the Ontogeny of Microfossils

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Dissertation: The Trace Metal Geochemistry of Suspended Oceanic Particulate Matter

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Dissertation: Tidal Dynamics and Dispersion around Coastal Headlands

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Dissertation: Rates of Vertical Mixing, Gas Exchange, and New Production: Estimates from Seasonal Gas Cycles in the Upper Ocean Near Bermuda

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Dissertation: Diffusion of Helium Isotopes in Silicate Glasses and Minerals: Implications for Petrogenesis and Geochronology

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Dissertation: Chemosynthetic Communities in the Deep Sea: Ecological Studies

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Dissertation: Trace Metal Sources for the Atlantic Inflow to the Mediterranean Sea

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Dissertation: An Application of Ocean Wave-Current Refraction to the Gulf Stream Using SEASAT SAR Data

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Dissertation: A Code-Division, Multiple Beam Sonar Imaging System

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Dissertation: The Structure of the Kuroshio West of Kyushu

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Dissertation: Acoustic Tomography in the Straits of Florida

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Dissertation: Deeply-Towed Underwater Vehicle Systems: A Verified Analytical Procedure for Creating Parameterized Dynamic Models

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Scripps Institution of Oceanography

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LuAnne Thompson
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Irene G. Yushina
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Columbia Preparatory High School

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Japan Marine Science and Technology Center

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Massachusetts Institute of Technology

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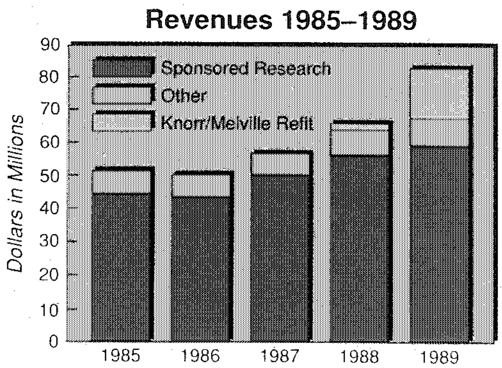
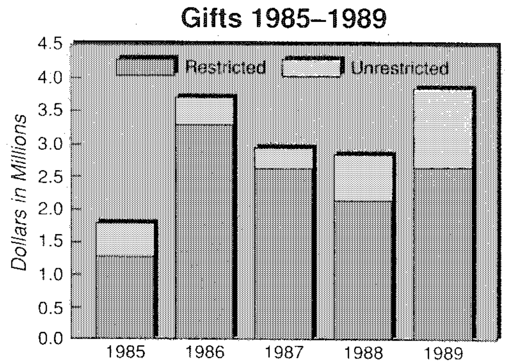
The June Associates dinner celebrated *Alvin's* 25th anniversary with colorful balloons and good company.

Financial Statements





THE Institution's financial results depict a successful year. In 1989, total revenues increased by 26% to $82,293,250 from $65,356,152, an increase of $16,937,098 of which $12,363,543 was for the *Knorr/Melville* refit.

Excluding the *Knorr/Melville* refit, increases in government and nongovernment sponsored research income of $2,508,527 and $825,293, respectively, accounted for $3,333,820 of the $4,573,355 yearly change and represented increases of 5% and 10% respectively over the previous year. This increase occurred principally in Physical Oceanography and Geology and Geophysics. For government research, the National Science Foundation showed a $537,596 decrease, down 2% due to reduced ship operation support as a result of the *Knorr* refit. Research funding from the United States Navy increased by $2,590,372, up 17%, due primarily to new programs in tactical oceanography. Other government funding advanced by $455,751, an increase of 12%. The increase of $825,293 from nongovernment sources was principally revenues from the Jason Program in the Mediterranean. The backlog at year end of sponsored research excluding the vessel refit decreased by $1,191,750 to $27,754,606. Increases for other income of $1,036,619 and $203,116 for the education program accounted for the remainder of the total increase.

The five year trend for total revenues, shown in the graph above, reflects an increase of 61% for this period. Sponsored research, excluding the *Knorr/Melville* refit, increased 33% during this same period.

Total expenses increased $16,910,289 to $79,782,345 from $62,872,056, an increase of 27% from 1988. Costs of sponsored research, excluding the *Knorr/Melville* refit, increased by $3,333,820, up 6%. Education expenses increased 8% while other expenses increased by 46%, principally in the unsponsored research and external affairs areas.

Current unrestricted funds, totalling $2,923,395, were allocated as follows: $1,900,000 to unexpended plant funds, $500,000 to replenish the Director's Innovative Fund, $250,000 to Director's Discretionary Fund, and $273,395 in other transfers.

In 1989, gifts and grants from private sources increased by $1,010,353 to $3,814,776 from $2,804,423. A graph depicting gifts for the last five years is shown above.

The market value of the endowment including new gifts of $630,172 increased by $12,001,241 to $101,650,113 from $89,648,872.

Capital expenditures totalled $6,185,240 in 1989, an increase of $4,165,842 over 1988. Total expenditures include $2,727,996 for the Clark and $939,676 for the Fye laboratory additions and $994,586 for student housing. Funds for capital expenditures were provided from depreciation recovery, unrestricted income, and grants from government agencies.

The number of employees at year end increased by 56 to 867 principally as a result of additional positions on the scientific and technical staffs.

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

Gary B. Walker
Assistant Director for Finance & Administration

Kenneth S. Safe, Jr.
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George A. Smith
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Balance Sheets December 31, 1989 and 1988

ASSETS	1989	1988
Current fund (Note A):		
Cash	$ 9,652,026	$ 6,620,237
Short-term investments, at cost which approximates market	15,356,620	18,196,388
Accrued interest and dividends	982,221	872,880
Reimbursable costs and fees:		
Billed	1,388,283	1,436,724
Unbilled	941,050	1,489,989
Other receivables	472,708	357,194
Inventories	425,090	326,154
Deferred charges and prepaid expenses	691,380	190,938
Deferred fixed rate variances	1,823,828	470,768
Due to other funds	(7,148,192)	(9,885,113)
	24,585,014	**20,076,159**
Endowment fund (Notes A and B):		
Investments, at market	88,954,391	52,624,756
Cash and equivalents	12,309,750	35,560,206
Pooled income investments, at market	194,629	163,803
Due from current fund	29,316	1,158,348
	101,488,086	89,507,113
Annuity investments, at market	162,027	141,759
	101,650,113	**89,648,872**
Plant fund (Note A):		
Land, buildings, and improvements	30,757,821	25,685,973
Vessels and dock facilities	7,395,774	7,410,793
Laboratory and other equipment	5,412,765	4,836,566
Work in process	218,196	1,008,389
	43,784,556	38,941,721
Less: accumulated depreciation	(19,383,653)	(17,700,548)
	24,400,903	21,241,173
Due from current fund	7,118,876	8,726,765
	31,519,779	**29,967,938**
Total all funds	**$157,754,906**	**$139,692,969**

LIABILITIES AND FUND BALANCES	1989	1988
Current Fund:		
Liabilities:		
Accounts payable and other liabilities	$4,405,299	$2,325,353
Accrued payroll and related liabilities	3,513,783	4,517,497
	7,919,082	6,842,850
Fund balances:		
Restricted-unexpended:		
Sponsored research	9,516,160	8,602,677
Education program	3,154,468	1,235,334
Designated	1,954,563	942,067
Unrestricted	2,040,741	2,453,231
	16,665,932	13,233,309
	24,585,014	**20,076,159**
Endowment Fund:		
Endowment:		
Income restricted	59,380,215	53,060,909
Income unrestricted	1,149,546	1,016,244
Quasi-endowment:		
Income designated	14,842,974	11,829,734
Income unrestricted	26,115,351	23,600,226
	101,488,086	89,507,113
Annuity	162,027	141,759
	101,650,113	**89,648,872**
Plant Fund:		
Invested in plant	24,400,903	21,241,173
Unexpended:		
Restricted	102,852	10,207
Unrestricted	7,016,024	8,716,558
	31,519,779	**29,967,938**
Total all funds	**$157,754,906**	**$139,692,969**

Statements of Current Fund Revenues, Expenses and Transfers for the years ended December 31, 1989 and 1988

	1989	1988
Revenues:		
Sponsored research:		
Government	$49,699,822	$47,191,295
Nongovernment	9,296,649	8,471,356
	58,996,471	55,662,651
Knorr/Melville refit	14,628,534	2,264,991
Education funds availed of	2,441,787	2,238,671
Total restricted	76,066,792	60,166,313
Unrestricted:		
Fees	488,004	497,682
Endowment income	1,498,396	1,260,688
Gifts	1,177,655	670,392
Tuition	1,150,474	1,111,089
Investment income	1,273,869	1,113,560
Oceanus subscriptions	289,104	238,165
Other	348,956	298,263
Total unrestricted	6,226,458	5,189,839
Total revenues	**82,293,250**	**65,356,152**
Expenses:		
Sponsored research:		
Salaries and fringe benefits	17,178,058	15,690,678
Ships and submersibles	6,943,470	8,947,175
Material and equipment	10,127,523	9,267,937
Subcontracts	4,609,922	4,065,538
Laboratory overhead	5,472,190	4,734,575
General and administrative	5,346,493	5,243,207
Other	9,318,815	7,713,541
	58,996,471	55,662,651
Knorr/Melville refit	14,628,534	2,264,991
Education:		
Faculty expense	1,359,440	1,147,741
Student expense	985,430	1,018,212
Postdoctoral programs	405,609	328,845
Other	266,545	299,417
	3,017,024	2,794,215
Unsponsored research	1,256,896	798,037
External affairs	1,519,841	899,177
Other activities	363,579	452,985
Total expenses	**79,782,345**	**62,872,056**
Net increase before transfers	**2,510,905**	**2.484,096**
Transfers – (to) from:		
Designated reserves	(1,012,496)	(173,223)
Endowment fund	–	(581,979)
Plant fund	(1,900,000)	(800,000)
Other	(10,899)	–
Total	**(2,923,395)**	**(1,555,202)**
Net increase (decrease) – unrestricted current funds	**$ (412,490)**	**$ 928,894**

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

Statement of Changes in Fund Balances for the year ended December 31, 1989

	Current Funds					Plant Fund		Total All Funds	
	Restricted	Designated	Unrestricted	Total	Endowment Fund	Invested in Plant	Unexpended	1989	1988
Increases:									
Gifts, grants and contracts:									
Government	$66,024,295			$66,024,295				$66,024,295	$54,271,651
Nongovernment	8,629,051		$1,177,655	9,806,706	$ 630,172		$ 102,500	10,539,378	10,629,408
Endowment and similar funds	3,992,615		1,498,396	5,491,011				5,491,011	4,493,754
Net increase (decrease) in realized and unrealized appreciation					9,724,601			9,724,601	3,370,896
Supplemental retirement plan					1,640,000			1,640,000	–
Other	149,170		3,550,407	3,699,577	6,468		94,198	3,800,243	3,309,870
Total increases	78,795,131		6,226,458	85,021,589	12,001,241		196,698	97,219,528	76,075,579
Decreases:									
Expenditures	(76,066,792)		(3,715,553)	(79,782,345)				(79,782,345)	(62,872,056)
Depreciation (Note A)						$(1,868,894)	1,607,080	(261,814)	(261,814)
Plant asset addition						5,218,288	(5,218,288)	–	–
Other						(189,664)		(189,664)	–
Total (decrease) increase	(76,066,792)		(3,715,553)	(79,782,345)		3,159,730	(3,611,208)	(80,233,823)	(63,133,870)
Net change before transfers	2,728,339		2,510,905	5,239,244	12,001,241	3,159,730	(3,414,510)	16,985,705	12,941,709
Transfers – additions/(deductions):									
Current revenues to:									
Plant funds			(1,900,000)	(1,900,000)			1,900,000	–	–
Designated reserves		$1,012,496	(1,012,496)	–				–	–
Other	10,899		(10,899)					–	–
	10,899	1,012,496	(2,923,395)	(1,900,000)	–	–	1,900,000	–	–
Other	93,379			93,379			(93,379)	–	–
Total transfers	104,278	1,012,496	(2,923,395)	(1,806,621)	–	–	1,806,621	–	–
Change in fund balances for year	2,832,617	1,012,496	(412,490)	3,432,623	12,001,241	3,159,730	(1,607,889)	16,985,705	12,941,709
Fund balance, December 31, 1988	9,838,011	942,067	2,453,231	13,233,309	89,648,872	21,241,173	8,726,765	132,850,119	119,908,410
Fund balance, December 31, 1989	**$12,670,628**	**$1,954,563**	**$2,040,741**	**$16,665,932**	**$101,650,113**	**$24,400,903**	**$7,118,876**	**$149,835,824**	**$132,850,119**

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

Report of Independent Accountants

To the Board of Trustees of Woods Hole Oceanographic Institution:

We have audited the accompanying balance sheet of Woods Hole Oceanographic Institution as of December 31, 1989 and the related statements of changes in fund balances, and of current fund revenues, expenses and transfers for the year then ended. We previously audited and reported upon the financial statements of the Institution for the year ended December 31, 1988; totals for that year are shown for comparative purposes. These financial statements are the responsibility of the Institution's management. Our responsibility is to express an opinion on these 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, 1989, the changes in its fund balances, and its current fund revenues, expenses and transfers for the year then ended, in conformity with generally accepted accounting principles.

Boston, Massachusetts
March 30, 1990

Coopers & Lybrand

Notes to Financial Statements

A. Summary of Significant Accounting Policies:

Fund Accounting

The accompanying financial statements have been prepared on the accrual basis. In order to comply with the internal designations and external restrictions placed on the use of the resources available to the Institution, the accounts are maintained in accordance with the principles of fund accounting. This procedure classifies resources into various funds in accordance with their specified activities or objectives.

Cash

Included in cash at December 31, 1989 and 1988 is $9,807,506 and $5,061,364, respectively, representing advances received from the United States Navy. Such amounts are restricted in use to certain vessel refit and other research programs. Interest earned on unspent funds reverts to the federal government.

Investments

Investment securities held by the Endowment Fund 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. Realized and unrealized gains and losses are recognized on a specific fund basis.

Contracts and Grants

Revenues earned on contracts and grants are recognized as related costs are incurred. The Institution has negotiated with the federal government fixed rates for the recovery of certain indirect costs. 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 account represents the cumulative amount owed to or from the federal government.

Gifts

Unrestricted gifts are recognized as revenue when received and restricted gifts are recognized as revenue as they are expended for their stated purposes.

Noncash gifts are generally recorded at market value on the date of gift, 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.

Plant

Plant 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 equipment. Depreciation expense on plant assets purchased by the Institution amounting to $1,607,080 in 1989 and $1,534,200 in 1988, has been charged to operating expenses. Depreciation on certain government funded facilities (Atlantis II, the Laboratory for Marine Science and the dock facility, amounting to $261,814 in each year) is accounted for as a direct reduction of the plant asset and invested in plant fund. Title to the research vessel *Atlantis II* is contingent upon its continued use for oceanographic research.

The Institution consolidates available cash from the plant fund with other cash in the current fund for investment purposes.

Reclassifications

Certain amounts in the 1988 presentation have been reclassified to conform with the 1989 presentation.

B. Endowment Fund Investments:

The cost and market value of investments held at December 31, 1989 and 1988 are as follows:

	1989		1988	
	Cost	Market	Cost	Market
Government and government agencies	$22,229,145	$22,269,101	$19,305,864	$19,188,872
Convertible bonds	256,808	256,500	337,795	278,438
Corporate bonds	10,116,249	10,570,631	8,907,202	8,745,226
Other bonds	333,982	345,092	–	–
Common stock	47,457,881	53,876,864	19,869,737	23,079,219
Other	1,685,719	1,636,203	1,357,733	1,333,001
Total investments	**$82,079,784**	**$88,954,391**	**$49,778,331**	**$52,624,756**

C. Investment Units:

The value of an investment unit at December 31, 1989 and 1988 was $1.9471 and $1.7596, respectively. The investment income per unit for 1989 and 1988 was $.1073 and $.0901, respectively.

	1989	1988
Unit value, beginning of year	$1.7596	$1.6900
Unit value, end of year	1.9471	1.7596
Net change for the year	.1875	.0696
Investment income per unit for the year	.1073	.0901
Total return per unit	**$ .2948**	**$ .1597**

D. Endowment Income:

Endowment income consisted of the following:

	1989	1988
Interest and dividends	$5,920,374	$4,845,424
Investment management costs	(429,363)	(351,670)
Net endowment income	**$5,491,011**	**$4,493,754**

E. Retirement Plans:

The Institution maintains two noncontributory defined benefit pension plans covering substantially all employees of the Institution. Pension benefits are earned based on years of service and compensation received. The Institution's policy is to fund pension cost accrued.

Combined net pension expense for two plans consisted of the following for 1989:

Service cost	$ 2,638,284
Interest cost	4,228,429
Actual return on plan assets	(10,629,992)
Net amortization and deferral	5,538,959
Net pension expense	**$ 1,775,680**

Below is a reconciliation of the combined funded status of the plans at December 31, 1989:

Accumulated benefit obligation:	
Vested benefits	$40,121,980
Nonvested benefits	4,314,553
Total accumulated benefit obligation	**44,436,533**
Projected benefit obligation	62,593,200
Market value of plan assets	69,162,602
Plan assets in excess of the projected benefit obligation	(6,569,402)
Unrecognized net transition asset	6,213,473
Unrecognized prior service costs	(713,018)
Unrecognized net gain	2,573,273
Accrued pension cost	**$1,504,326**

In addition to the $69,162,602 of plan assets listed above, the Institution has approximately $1,640,000 available at December 31, 1989 to fund certain benefits.

The discount rate and rate of increase in future compensation used to determine the projected benefit obligation as of December 31, 1989 were 7.25% and 7.06%, respectively. The expected return on plan assets was 8.00%.

F. Postretirement Health Care 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 cost of retiree health care is recognized as an expense when paid. These costs amounted to $240,912 in 1989 and $193,301 in 1988.