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About the covers: *Atlantis II* and *Alvin* began a new partnership in ocean exploration when they departed Woods Hole in January 1984 for a 22-month voyage in the Pacific. The new lift system enabled the sub to make a record 178 dives in 1984. Jerry Dean of the Physical Oceanography Department captured the vessels hard at work on the East Pacific Rise in May.

The back cover features an aerial view of the Woods Hole scientific complex looking from Eel Pond toward the Elizabeth Islands, taken by James Staples.

Annual Report 1984:
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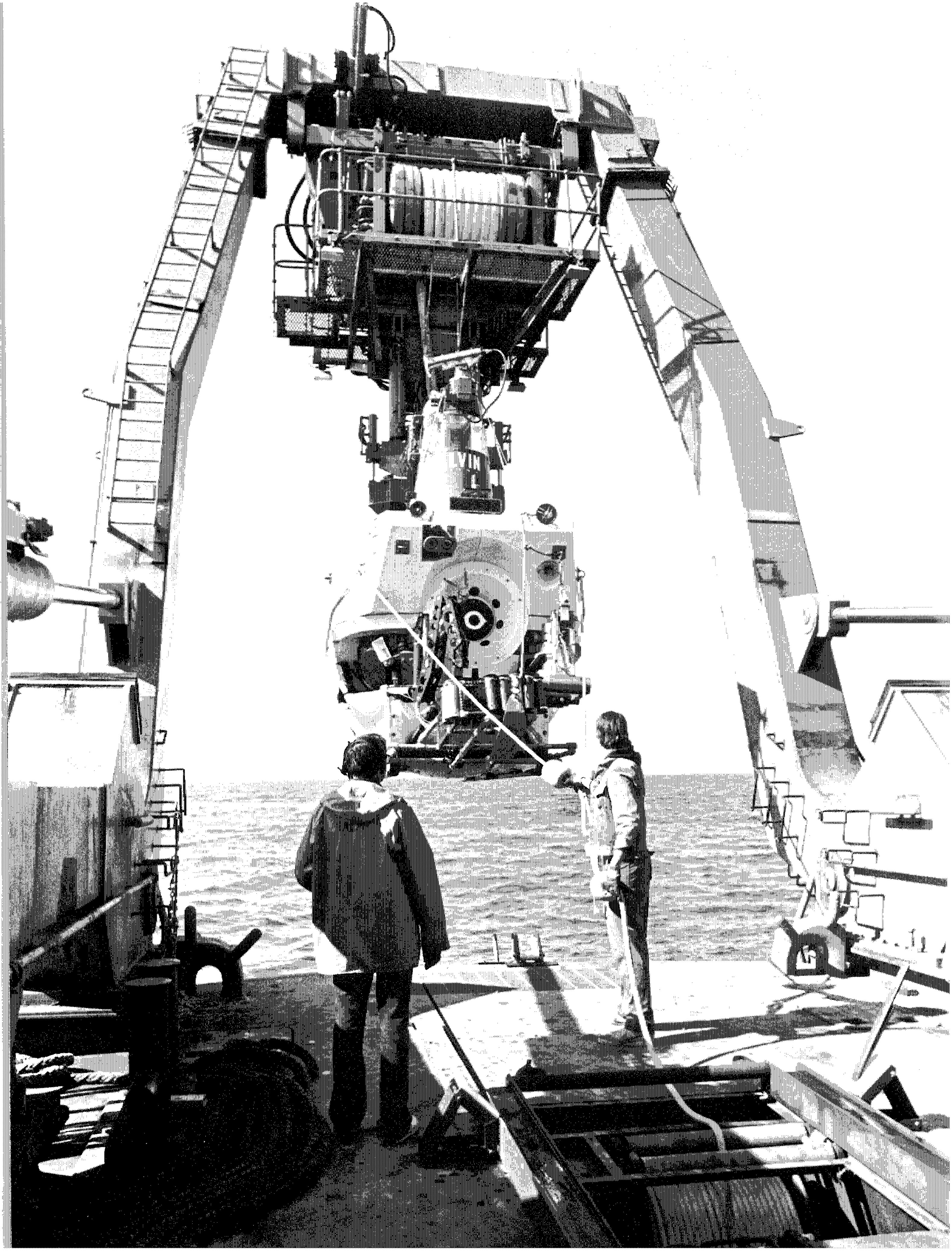
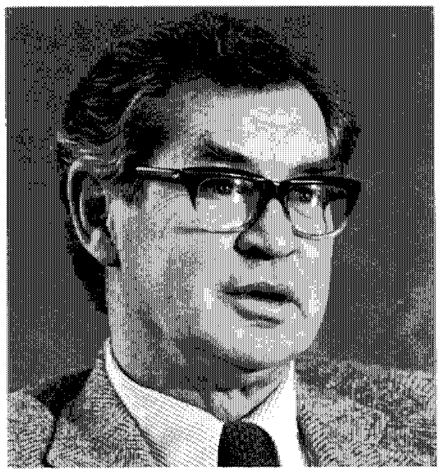


Director's Comments



Russ Kendall

In past reports, I have discussed the agenda for oceanography in the coming decade, such as the study of climate change where ocean dynamics are a central issue. I have described potential tools for such research, including satellites which can give us information about both the physical and biological processes we must understand for insight into global problems like ocean climate. Further, through the promulgation of the Exclusive Economic Zone (EEZ), the U.S. has acquired over 3 billion acres of the ocean. This more than doubles the area under our jurisdiction. The proper exploration of this new territory, in the spirit of Lewis and Clark, and its subsequent development and management are formidable tasks but exciting opportunities. Major undertakings such as these require strong, long-term national commitment. They need highly skilled professionals, laboratories and ships. The availability of these can never be guaranteed, and we are especially aware of this today. There is real cause for concern that we will not have the scientists, the facilities or the money for the work that lies ahead.

The funding of science is predominantly a federal process subject to year-to-year vagaries in policies. We have benefitted in the last four years from adequate funding of basic research. At the same time, however, there has been a decrease in support for the applications of results to issues, particularly in environmental concerns, which are regarded as appropriate for private and industrial funding. It is unclear whether the positive aspects of this funding pattern will be maintained in the face of mounting pressures on government to reduce deficits through cuts in all areas of federal spending. This uncertainty hampers our ability to plan the long-term advances in ocean science research where our involvement not only extends to large questions such as ocean climate dynamics, but also has applications to problems such as extended coastal management, waste disposal, and oil, hydrocarbon and other mineral resources in the deep ocean.

It would be unreasonable to expect complete predictability in funding, especially for science which is built on the search for new ideas and innovative techniques. This is especially true in the ocean where we continue to make startling discoveries in this still largely unknown realm. But, the scientific as well as the commerical exploitation of these discoveries requires some continuity. Within the tripartite structure of federal agencies, peer-reviewed grants, and research institutions, the first two are subject to the restrictions of year-to-year distribution of money. As funding gets tighter, they become more and more committed to a short-term, incremental approach to research. The continuity can be maintained only if the institutions themselves have some capability to plan longer-term strategies for the advance of the science. Yet, this strategic planning becomes increasingly difficult, partly because the programs are now on such a large scale and the facilities are so expensive, but also because the federal support for institution development is negligible. This problem is recognized, in principle, by agencies and by independent groups who have reviewed the structure of scientific research, but we do not see any steps to assure even a partial solution.

About half of our support at Woods Hole comes from one agency, the National Science Foundation. One quarter is provided by the U.S. Navy, and the remainder is mainly from non-federal sources – endowment, private foundations, corporations, and individual gifts. Only the last category has increased in the past decade. We have been fortunate to receive from the private sector the funds essential for new directions, including state-of-the-art chemical laboratories such as the Fye Laboratory, Innovative Research Awards, support for new ship designs. But, if this "seed" money is to bear fruit, it must be supplemented by federal resources. This is especially necessary for independent laboratories like the Woods Hole Oceanographic Institution. It is essential that we provide an environment in which our scientists can see the promise of a productive future for their research and for themselves. Without this element in the pattern of support, we shall soon face a crisis of confidence in the long-term development of ocean science.

John H. Steele
Director

Areas of Interest

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, planktonology, benthic biology, physiology, biogeochemistry, animal behavior, and aquaculture. Work on marine pollution includes research on the effects of PCB s and hydrocarbons and the biochemical responses of animals to these and other pollutants. The "patchy" distribution of many marine animals is under investigation as are the physiological adaptations of deep sea organisms to sparseness of food, low temperatures, high pressures, and deep sea thermal vents. Answers to questions about the food supply in the oceans are sought in studies of particles falling from the surface waters through the water column to the bottom of the sea, in studies of upwelling areas, through investigations of sulfur oxidizing organisms in the deep sea and shallow coastal ponds, and in laboratory experiments that complement field investigations. The uses of sound by marine mammals and the behavior of large marine animals followed by tagging are being studied. Other work concentrates on salt marsh ecology and conservation, nutrient cycling in coastal waters, and on aquaculture and waste water recycling. The symbiotic relationships between marine microbes and other organisms (including wood-borers) are a new focus. Gelatinous organisms of the plankton (salps, ctenophores, etc.) are being studied with new techniques that finally allow us to properly evaluate the roles of these organisms in the oceans.

Chemistry

Chemical oceanographers are concerned with the composition of the ocean environment. They seek to understand the processes that have brought seawater and sediments to their present composition and that contribute to the observed variability. They also seek understanding of the extent to which the environment may be changed by both natural and man-made phenomena operating on a variety of time scales. Input from rivers and reactions at the air-sea, seawater-sediment boundaries and seawater-volcanic rock interaction at spreading centers are under investigation as chemists consider the processes taking place at major ocean boundaries. Some critical questions in chemical oceanography revolve around the vertical transport and transformations in particles as they fall from the surface waters to the bottom of the water column. The photochemistry of the surface ocean and the marine atmosphere is critical to our understanding of the global sources and sinks for many gases. The genesis and composition of the oceanic crust and its interaction with seawater is important to a general understanding of the oceanic system. Studies concerning the interstitial water chemistry of deep sea sediments help us to better understand the diffusive flux of ions between sediments and the oceans. Work on the fluxes of organic carbon includes determination of the amount of organic carbon produced in surface waters, the distribution, nature, and biogeochemistry of specific organic compounds in the marine environment, and studies of processes responsible for formation and diagenesis of organic matter in sediments. While studying radioactive isotopes in the ocean, whether as a natural occurrence or as a form of pollution, chemists are also finding the known decay rates of the isotopes useful as indicators for studying rates of water circulation, the in situ rates of chemical processes in the sea, and rates of biological and chemical processes that change the composition of seawater. Stable isotopic studies in rocks can be used as geochemical and petrological indicators of large scale terrestrial mantle processes.

Geology and Geophysics

Marine geologists and geophysicists study the processes which form and affect the earth beneath the sea, as reflected in its underlying structure and composition. The sedimentary and volcanic material of the seabed is investigated by direct sampling and remote observation. Coring, dredging, or drilling techniques are commonly used to obtain samples, which are further classified in the laboratory by petrological descriptions, geochemical analyses, and measurement of physical properties. Geophysical methods include the fields of seismology, gravity, magnetism, and geothermics. The establishment of plate tectonics as the primary kinetic process creating and shaping ocean basins has focused attention at the boundaries where plates interact. At divergent plate boundaries, or mid-ocean ridges, the processes which bring up hot materials to create ocean crust and lithosphere are studied in detail. Investigations of rifted continental margins of different geological ages are important to understand how continental plates initially break apart. Finally, subduction of oceanic lithosphere beneath either continental or other oceanic lithosphere is a process which is ultimately associated with the creation of deep sea trenches and back-arc basins, accompanied by the important geological phenomena of earthquake belts and volcanic island arcs. In such geological processes, earth materials sometimes behave like viscous fluids, which can be modelled in the laboratory. Research is actively pursued on processes of particulate flux in the ocean ('marine snow'), carbonate and silicate dissolution, and other phenomena relevant to the transport of biogenic material to the sea floor. The results are essential to a better understanding of the fossil record, which in combination with studies of its oxygen isotopic variation reveal changes in climate and ocean environment over periods of thousands to millions of years. The study of the dynamics of sediment distribution on the ocean floor is important to deciphering the fossil record and interpreting sea floor morphology. Marine geologists also study near-shore and shallower regions such as continental shelves and coasts where earth, ocean, and atmosphere dynamically interact to produce complex and rapidly-changing morphology.

Ocean Engineering

The field of ocean engineering is a complex hybrid of many of the classical engineering disciplines such as electrical, mechanical, civil, chemical, and marine engineering. Its purview is broad and inter-disciplinary. Ocean engineers conduct research and design instrumentation in almost every field of oceanography. Mechanical, electrical, acoustical, chemical, optical, civil, marine, and ocean engineering talents are used to develop techniques for measuring oceanic processes and for answering basic scientific questions about the marine environment. Measurement programs span ocean time scales of years to milliseconds and ocean space scales of kilometers to millimeters. Electronic data handling and processing circuits using microprocessors are developed for these programs. Instrument housings and anchoring and mooring systems are designed, fabricated, and deployed at sea. Acoustic techniques are applied to measurement problems. Manned and unmanned deep submersible systems are engineered for search and discovery. Techniques for using the earth orbiting satellite as an observational tool are being developed together with image enhancement and image processing algorithms. Information processing, whether applied to acoustic systems, satellite images, geophysical time series or general data reduction is the primary concern of a large segment of the department. Research is conducted in hydrodynamics, signal processing theory, applied mathematics, acoustic tomography and propagation, deep submergence engineering, arctic acoustics, coastal processes and benthic currents, and instrumentation techniques. Programs in mooring materials and design, electronic and microprocessor applications, optical measurement, and remote observation and sampling support these and other scientific projects throughout the Institution. The technological sophistication of modern ocean science demands the application of special engineering knowledge and skills. The solution of challenging problems requires creative combinations of wide ranging ocean engineering principles.

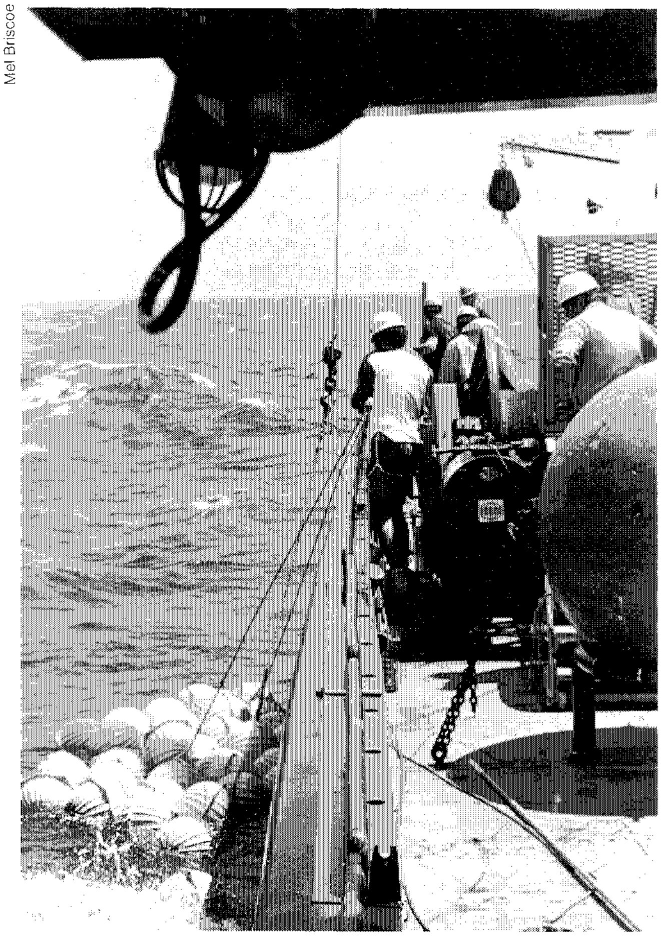
Physical Oceanography

Physical oceanography is the study of the physics of the ocean. Its central goal is to describe and explain the composite of oceanic motions, which occurs in a wide range of scales from millimeters to megameters, and seconds to centuries. On a large scale, the sun heats equatorial waters and the ocean transports this heat toward the poles, so as to smooth out the climate of the planet and make large parts of the earth habitable. Variations of the temperature and salinity, the driving effects of the winds, the rotation of the earth, and the pull of the sun and the moon all contribute to these motions. There are grand persistent currents like the Gulf Stream, and there are transient waves and eddies of almost all sizes and speeds, from high frequency acoustic and surface gravity waves, to slower internal gravity waves beneath the sea surface. Large regions of the oceans are dominated by the mesoscale eddying vortical patterns of flow that display visual and dynamic similarity to atmospheric weather patterns. As in the atmosphere, relatively intense frontal systems exist. Important mixing and stirring of the ocean is accomplished by a variety of physical processes, some of great subtlety like the phenomenon of "salt fingers" whose sizes are on the centimeter scale. Important scientific questions also arise in considering the interaction of the ocean with the atmosphere. The ocean and the atmosphere drive each other in an as yet poorly understood way: exchanges of energy between the air and sea are important in determining the climate of both the atmosphere and the oceans. Physical processes in coastal regions are strongly affected by atmospheric forcing and bottom topography, and the current and wave systems in this complicated region are of vast importance to the local climate and ecology. Physical oceanography staff members are involved in experimental, theoretical, laboratory, and numerical investigations of many parts of the system of oceanic motions. Small programs and large international projects are underway, and multidisciplinary efforts are increasing. All of these studies have the ultimate goal of understanding the structure and movement of the world's oceans, the interaction of the sea with its boundaries, and the physical role of the ocean in relation to other branches of oceanography. Physical oceanographers come to the subject with a variety of backgrounds: mathematics, physics, engineering, computers, and chemistry. The mix of interests provides a broad approach to the equally broad range of problems in the ocean.

Marine Policy & Ocean Management

The Marine Policy and Ocean Management Center provides an opportunity for scholars to conduct interdisciplinary research regarding the problems and opportunities generated by our increasing use of the ocean. Evaluating and suggesting appropriate policies and management strategies to deal with the issues of marine resource development, utilization, and protection are complex tasks, often requiring the data and skills of both natural or physical scientists and social scientists. The three main objectives of the Marine Policy Center are: to provide opportunities for interdisciplinary application of natural science, technology, and social science to marine policy problems; to research, evaluate, and convey the information necessary for the development or modification of local, national, and international ocean policy; and to provide support and experience to Research Fellows interested in marine policy issues. The professional research staff of the Center conducts studies on a wide range of policy issues, aided by a competent support staff. In addition, the Center sponsors seminars, conferences, and lectures on marine policy issues. Within the broad field of marine policy and the wide range of research interests pursued by the Center's staff, a coherent research program has emerged around, but is not limited to, the following thematic areas: Law of the Sea issues, implication, and opportunities for domestic and international marine policy including broader future U.S. ocean policy in light of the Law of the Sea Treaty and the U.S. declaration of an Exclusive Economic Zone (EEZ); Marine Mineral and Mining studies consider the domestic and international policy problems of developing potential resources contained in seafloor nodules, polymetallic sulfide deposits, and other marine minerals; Coastal and Fisheries Management issues include assessments of the use of scientific and technical information in the management of coastal zones, including techniques in integrating social, economic, and biological information into fisheries management planning, and analyzing the effectiveness and distributional aspects of fisheries management policies; Studies of the Interaction of Science and Policy observe ocean science and policy from two perspectives: 1) how marine science and technology are affected by public policy, and 2) how scientific information is used in the formulation of decisions for coastal and ocean resources policy; Cooperative International Marine Affairs projects have been initiated to assist developing countries which are interested in addressing informational and policy needs stemming from the extension of their national jurisdictions over vast marine territories, i.e., their 200-mile EEZs. The Marine Policy Center offers Research Fellowships to professionals in the social sciences, law, or natural sciences to apply their training to these research areas. Thus far, more than 90 Fellows trained in such fields as law, economics, anthropology, political science, engineering, marine science, mathematics, and geography have participated in the program.

Mel Briscoe



Mooring recovery aboard *Oceanus*.

Reports on Research

The constituents that make up seawater and ocean sediments, as we see and experience them today, have resulted from a melange of complex interacting processes operating both within the ocean and at its boundaries. These processes are active over a very wide range of spatial and time scales, from seconds and centimeters to thousands of years and kilometers. All contribute to the dynamic and changing perspective of the ocean as a chemical system. Evaporation and precipitation, the growth, settling and decay of organisms, sediment-water exchanges, seawater-hot lava reactions, riverine and atmospheric materials fluxes, and the stirring and mixing created by winds and the rotation of the earth are examples of some of the processes that are effective in modifying the composition of the ocean environment and whose study is one of the principal occupations of many ocean scientists. In recent years, principally due to advances in analytical technology, it has been possible to deduce and follow many of the processes by studying chemical tracers. In this report we have concentrated on the highlights of such studies underway in the Chemistry Department.

Radioactive isotopes are added to the ocean both artificially and naturally. Manmade radioactivity from weapons tests and from nuclear reprocessing wastes can provide a very valuable tracer of the rate of formation of the world's deep ocean water, as is illustrated for the North Atlantic and Arctic Oceans in the article by Livingston and Sholkovitz. Knowledge of the rate at which the ocean water column "turns over" will be essential for our future understanding of the role of the ocean in modifying weather and climate. Given the variety of chemical forms involved and the fact that the input rates are reasonably well known, the distributions of manmade as well as natural radioactive isotopes as discussed by Bacon are revealing information on the rates at which reactive chemicals are removed from the ocean. Such information is important for the prediction of pollutant behavior in the marine environment.

It has been known for many years that the world's rivers contribute both solid particles and dissolved chemicals to the ocean. Only in recent years, however, has the importance of an atmospheric path been documented. Programs such as SEAREX (Sea-Air Exchange Program), described by Gagosian and Peltzer, are major contributors to this knowledge. Exchange of gas at the air/sea interface is involved in modifying the composition of both ocean and atmosphere. The importance of this exchange in terms of the carbon dioxide level and the resulting "greenhouse effect," or global atmospheric warming, as well as some of the problems involved in its assessment are treated in the article by Brewer.

Perhaps the most obvious but least understood processes involved in the modification of the ocean's composition are the growth, death and decay of marine organisms, particularly as they affect the nature and distribution of organic chemicals. Some recent advances in this area are described by Lee and Wakeham. The growth of organisms in the surface ocean and their subsequent settling into the deep ocean has been shown to be of primary importance for modifying not only the surface ocean but also the deep ocean and the sediments underneath. While this settling flux and its effects have been known for many years, the article by Deuser shows that it is much more rapid than was supposed. This work, together with other studies, show that the deep ocean floor can respond to changes in the ocean surface in periods as short as weeks to months. The settling of small organisms into sediments with subsequent burial and alteration are believed to be the precursor steps in the genesis of crude oil and natural gas. The nature of the transformation processes that convert dead organisms to petroleum hydrocarbons is the subject of the article by Whelan, Farrington and Hunt.

One of the principal actions of sunlight on the surface ocean is to stimulate the growth of microscopic plants that form the basis of the food web. These plants are the ultimate source of the downard "rain" of biological particles discussed in previously mentioned articles. Zafiriou notes that plant growth is not the only important result of the absorption of the sun's energy; an extensive suite of chemical changes occur directly via photochemistry without the intervention of life processes.

The recent discovery of hydrothermal hot springs on mid-ocean ridges has sparked tremendous scientific and popular interest. These areas are among the few places on earth where material from the mantle beneath the earth's crust is erupted to the surface to form new crust. Processes occurring within the mantle are responsible for sea floor spreading at these mid-ocean ridges and for the formation of the continents and ocean basins as we know them today. The article by Kurz describes some of our efforts to understand the nature of this inaccessible part of our world. The hot water that issues from these vents was once cold deep seawater that has penetrated into cracks on the ocean floor to zones of hot lava and rocks in the mantle. Thompson and Mottl describe the chemical alterations involved in this process and their effects on the composition of seawater worldwide.

Derek W. Spencer
Associate Director for Research

Radiochemistry: Artificial Radionuclides in the Marine Environment

Hugh D. Livingston and Edward R. Sholkovitz

There is considerable interest in the fate and behavior of artificial (man-made) radioactivity in the world's oceans. This man-made radioactivity has been largely provided by two sources: 1) global fallout of atmospheric nuclear weapons testing and 2) radioactive waste discharges following the reprocessing of spent nuclear fuel.

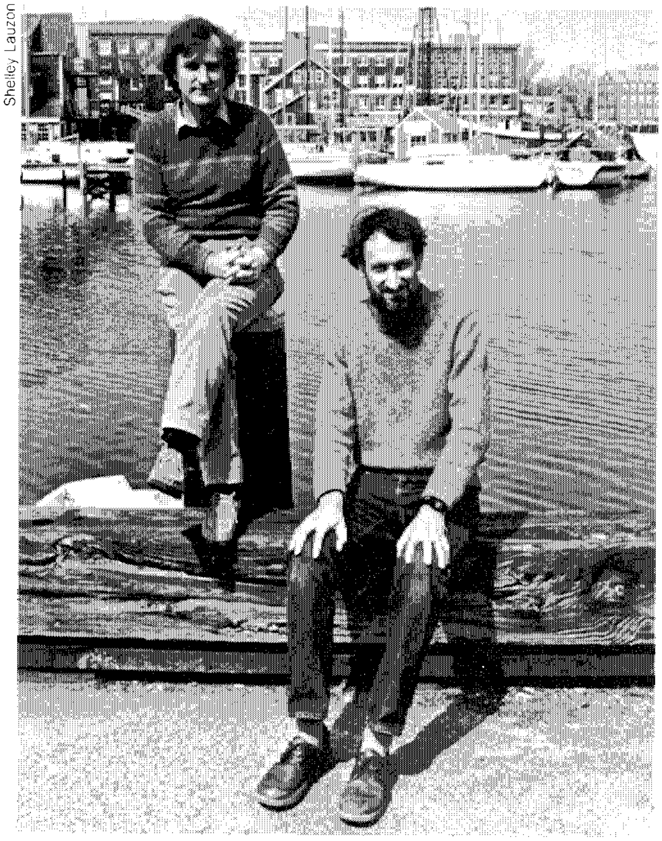
The arrival of artificial radioactivity in the ocean from atmospheric nuclear weapons tests took place primarily in the 1950s and early 1960s. Since most of the tests took place in the Northern Hemisphere, it received a larger proportion of the atmospheric fallout. In contrast to the global nature of fallout, radioactivity from nuclear fuel reprocessing waste is introduced to coastal zones at point sources. Although such waste discharges to the ocean have been made by the United Kingdom (U.K.), France and India, only the U.K. releases have been quantitatively large enough to represent other than minor local inputs. The U.K. releases from the Sellafield plant (formerly called Windscale) in northwest England were especially large during the 1970s but are currently declining and are expected to become insignificant in the near future. This radioactive waste is discharged into the Irish Sea and, depending on the chemical reactivity of the component radioisotopes, is either deposited in the sediments of the Irish Sea or flushed northward along the European shelf through the shallow European seas and into the Arctic Ocean.

The introduction to the ocean of artificial radioisotopes from these two sources has been widely used by oceanographers to study a variety of geochemical and oceanographic problems, including water circulation, reactive element removal and cycling, and issues related to the use of the ocean for the disposal of radioactive waste. We summarize below three topics under investigation in our laboratories.

Arctic Ocean Ventilation and Circulation

Because of their inaccessibility, the Arctic Ocean and contiguous seas have not been studied as extensively as the other oceans. Yet, as the major region of deep water formation in the Northern Hemisphere, it is a critical point of connection between the atmosphere and the world oceans. A variety of man-made chemical tracers have recently been employed as tools to learn more about Arctic Ocean circulation. Hugh Livingston and his colleagues have been studying the dispersion of the radioelement cesium-137 as a tracer of Arctic processes; cesium-137 is a major component of the Windscale (U.K.) discharges and is extremely soluble and well suited for tracing water circulation.

Shelley Lauzon



Hugh Livingston and Ed Sholkovitz

Figure 1 shows its surface distribution pattern in the Norwegian and Greenland Seas in 1981-1982. The high levels along the eastern margin of the region result from its transport from U.K. coastal waters. Although cesium-137 is present in the oceans from bomb fallout, the cesium-137 signal from Windscale dominates in this region. In the North Atlantic, south of Iceland, the observed levels result only from fallout and represent the regional baseline prior to the arrival of the Windscale cesium-137. The Windscale-derived tracer has two properties which are particularly relevant to Arctic circulation. Firstly, it has labelled the warm and saline Atlantic water flowing into the Arctic Ocean through Fram Strait with a well-characterized time-marker. The invasion of this signal throughout the upper layers of the Arctic should trace the routes and rates of Atlantic water circulation in the Arctic. Secondly, dense water forming on the Arctic shelves and moving offshelf into the Arctic Ocean interior should carry a strong Windscale cesium-137 signal. In 1979, a strong Windscale cesium-137 signal believed to be of shelf origin was found at a depth of 1500 meters (nearly 5,000 ft.) underneath the North Pole.

Geochemical Cycling of Fallout Transuranics

Researchers in Hugh Livingston's laboratory have also been studying the oceanic behavior of the group of radionuclides called the transuranics. Named for elements heavier than uranium, transuranics such a neptunium, plutonium and americium were widely distributed in the ocean from fallout produced by atmospheric nuclear weapons tests. Since many of the isotopes of these radioelements remain radioactive for hundreds and thousands of years and are major components of nuclear waste, knowledge of their oceanic behavior is critical to the development of a predictive capability of their fate following accidental or planned release to the ocean.

Figure 2A illustrates the depth distributions of fallout plutonium and americium at about 30°N in the central North Pacific. These profiles represent the distributions which have developed approximately two decades following their input to the surface. The most outstanding features are the large maxima in concentrations at about 500 meters. Both elements have chemistries favoring association with particles. Their distributions are a result of a variety of processes, including horizontal and vertical advection and diffusion of soluble and suspended particulate phases, and vertical transport and cycling in association with sinking particles. Figure 2B illustrates a model currently believed reponsible for the vertical transport of reactive substances on particles. Large particles produced in the upper ocean by various biological processes sink rapidly and interact with the fine particles in suspension. They both add to the fine particle phase by disintegration and subtract from it by coalescence of fine particles with which they come in contact. The particle phase is in dynamic equilibrium with the soluble phase fraction of the substance in question. This type of mechanism is believed responsible for the particle transport of fallout transuranics

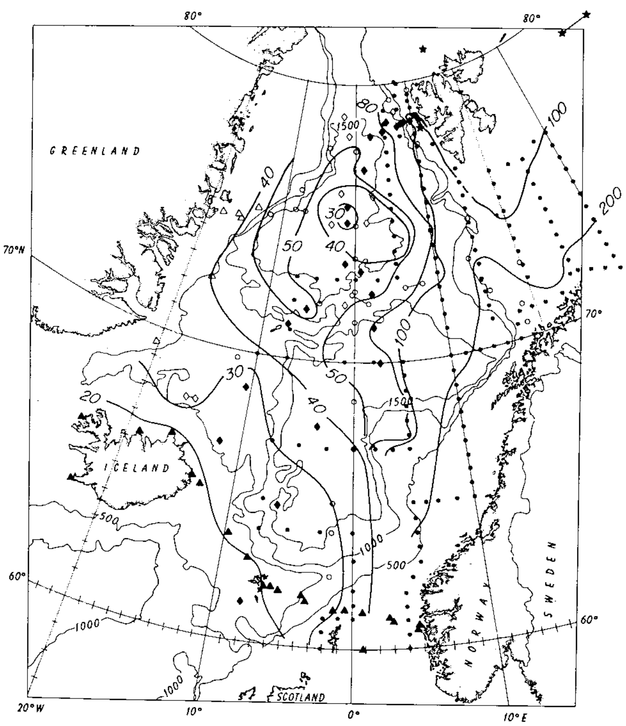
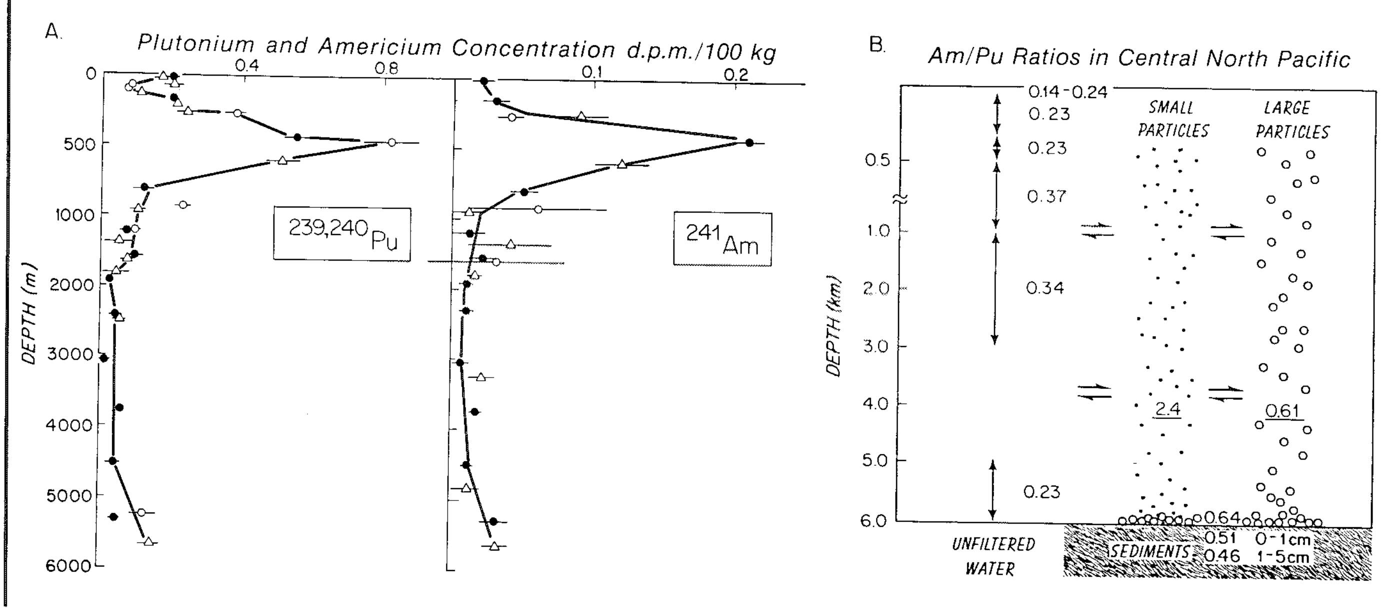


Figure 1
Dispersal pattern of Windscale cesium-137 in sub-Arctic surface waters (1981-1982).
Symbols indicate different ships and cruises.

Figure 2
A. Vertical profiles of plutonium (^{239,240}Pu) and americium (^{241}Am) from the Central North Pacific Ocean water column.
B. Schematic model showing relationship of particle transport to Am/Pu ratios in the North Pole.



through and below the main thermocline to the deep ocean. This transport occurs at rates set by the different particle reactivities of the various transuranics. Some idea of this difference can be derived from the different proportions of plutonium and americium in the various phases depicted in Figure 2B. The particulate phases, especially the fine particulates, are americium rich (or plutonium poor) as compared to their soluble phase composition. As a result of the greater affinity of americium for particles, it is transported to depth and delivered to the seafloor at rates substantially faster than those for plutonium.

Plutonium Chemistry in the Coastal Environment

Edward Sholkovitz and co-workers have been studying the marine chemistry of plutonium in the coastal environment. Sampling has been done in the estuaries of the Delaware and Connecticut Rivers and on the continental shelf and slope of the northeast United States. Water depths range from 10 to 3000 meters (30 to 3,900 ft.) while the salinity varies from 0 (freshwater) to 36 parts per thousand. The purpose of the project is to understand the processes controlling the concentration, distribution, and cycling of plutonium (Pu) in coastal waters and sediments. One problem being addressed is how, why, and where dissolved plutonium is being removed from the water column to sediments and/or suspended particles. The coastal zone is complex and many dynamic processes operate simultaneously; for example, in estuaries and on the continental shelves there are large temporal and spatial variations in river discharge, tidal exchange, salinity, pH, suspended matter concentrations, biological productivity, and circulation patterns.

Our studies combine both field work (i.e., collecting, filtering, and analyzing samples) and laboratory experiments which simulate the estuarine mixing of river water with seawater. Figure 3 illustrates our field results by showing the distribution of dissolved ^{239,240}Pu vs. salinity for samples collected in the Delaware River Estuary. The main feature is a pronounced minimum in the ^{239,240}Pu concentration at the low salinity end (0.5-7 parts per thousand). This minimum coincides with a maximum in the concentration of suspended particles (Figure 3). One interpretation of these data is that dissolved plutonium (^{239}Pu and ^{240}Pu) is being removed from freshwater and seawater by the scavenging or stripping action of particles which are continuously being resuspended by the estuarine water circulation.

The plutonium concentrations in Figure 3 are extremely low (10^{-16}g/1) and require special analytical procedures to be properly measured. This plutonium was introduced from global fallout, primarily in the mid-1960s. We are using this 20-year-old input of plutonium as a tool (or tracer) for understanding present-day chemical reactions in the coastal ocean. This information is important when trying to predict or determine the fate of plutonium (or similarly behaving radionuclides) introduced to estuarine and coastal waters.

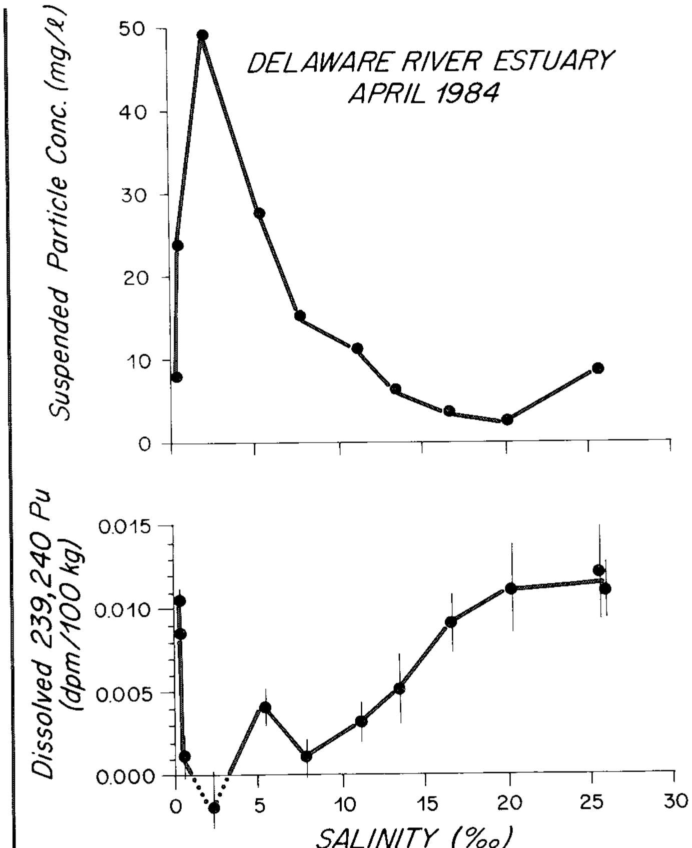


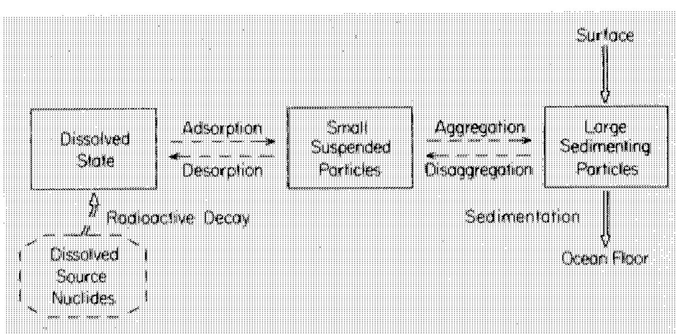
Figure 3
Concentration of dissolved plutonium (^{239,240} Pu) and suspended particles versus salinity in the Delaware River Estuary. Note that the maximum in particle concentration coincides with the minimum in plutonium concentration.

Natural Radionuclides

Michael P. Bacon

Shelley Lauzon

Mike Bacon



Schematic diagram illustrating the production, cycling and removal of reactive radionuclides that undergo chemical scavenging in the ocean.

An important property of the ocean as a chemical system is its ability to process the inputs of natural and artificial chemical substances and transport them to the sediments for burial. Certain heavy metals, radionuclides and organic compounds are removed from the oceanic water column (at least partly) by adsorptive uptake on particles followed by sedimentation. This process is often referred to as "chemical scavenging." An understanding of the uptake rates that govern this process is necessary to assess the ocean's capacity to assimilate waste materials.

For the past several years my co-workers and I have been engaged in studies of the natural radioactive elements in the ocean. Several of the daughter radionuclides that are formed within the natural radioactive decay series – isotopes of lead, polonium, thorium and protactinium – are strongly controlled in their oceanic concentrations and distributions by chemical scavenging. These daughter radionuclides are generated within the ocean by the radioactive decay of their parent radionuclides, which are dissolved in seawater. By appropriate sampling we can often follow the transport of the daughter radionuclides, resulting in large-scale natural tracer experiments in which elements of interest are continually introduced to the system under study at exactly known rates.

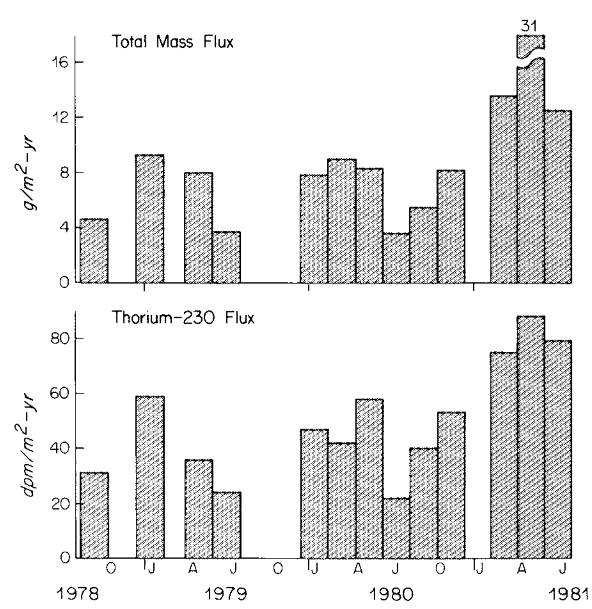
One of the key aspects of our research strategy is to examine how the radionuclides are partitioned between the dissolved state and the particulate state. Because of radioactive decay we are often able to deduce, from measurements of this partitioning, the rate at which the radionuclides are adsorbed from solution by the particle surfaces or desorbed back into solution. It is also possible to estimate the sinking rate of the particulate matter. In a recent study of thorium isotope distributuons, we were able to conclude that a thorium atom in the deep ocean generally remains in solution for approximately two years before it is taken up on the surface of one of the suspended particles, where it resides for approximately six months before it is released back into solution. During its residence on the particle, the Th atom is carried downward a hundred meters or so. This cycle is repeated many times until the Th atom finally reaches the sediment and is buried there. We now have a conception of chemical scavenging as a dynamic exchange process, in sharp contrast to our earlier view of scavenging as an irreversible binding of the radionuclides by the particles.

Much of our work depends on our ability to sample large quantities of particulate matter at all depths in the ocean. In this respect we have benefitted from a number of recent technological developments in sampling instrumentation at WHOI. We use two sampling techniques: (1) in situ filtration of large volumes of seawater (a few thousand cubic meters) with submersible pumps, which gives a measure of particle concentration; and (2) collection of the sinking particles (a few hundred milligrams required) with sediment traps, which gives a measure of particle flux. The two techniques are complementary. Filtration collects mainly the fine suspended matter, which constitutes most of the standing crop of particles in the water column but contributes little to the downward flux because of the very low sinking velocities (less than 1 meter per day). Trapping, on the other hand, collects mainly larger aggregates that sink rapidly (more than 100 meters per day) and are responsible for most of the flux but little of the sanding crop. Our submersible filtration systems also collect radionuclides present in the dissolved form by passing the filtered seawater stream through adsorbers containing manganese dioxide to scavenge the radionuclides from solution.

Our present view of the scavenging process in the deep ocean is that of a dynamic exchange equilibrium between seawater and the fine suspended particles, which have an average residence in the water column of 5-10 years. It is the fine particles, we believe, that control the adsorption/desorption reactions because of their large specific surface area. For significant removal from the water column, however, an aggregation process to increase the sinking speed in required.

New information has underscored the need for more research. Colleagues Werner Deuser and Susumu Honjo at WHOI have observed that the flux of particulate material reaching the deep ocean, measured with sediment traps, undergoes large seasonal fluctuations related to the seasonally varying productivity of the overlying surface waters. Our measurements of the fluxes of thorium-230 and other radionuclides in the trapped material show corresponding fluctuations in the rate of chemical scavenging in the deep ocean. This opens up the exciting possibility of using the seasonally-pulsed rain of particles as a probe for examining the dynamics of chemical and biological processes in the deep ocean. In parallel with their colleagues in other oceanographic disciplines, chemical oceanographers are discovering more and more variability on different spatial and temporal scales. One of the challenges of future work is the development of sampling strategies, instrumentation and analytical methodology for coping with this variability.

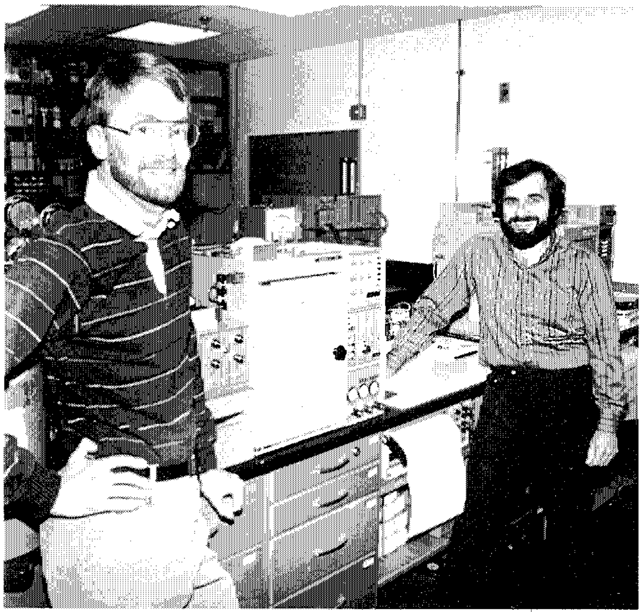
Rebecca Belastock



Top: Submersible pumping system built at WHOI and used to process large volumes of seawater in situ for determination of radionuclides in dissolved and particulate forms.
Bottom: Flux of thorium-230 at a depth of 3200 meters (approximately 10,500 feet) in the Sargasso Sea near Bermuda compared with total particle flux measured by Werner Deuser. The annual cycle observed in both records appears to be closely related to the annual cycle of productivity in the overlying surface waters. Thorium-230 radioactivity is given in disintegrations per minute.

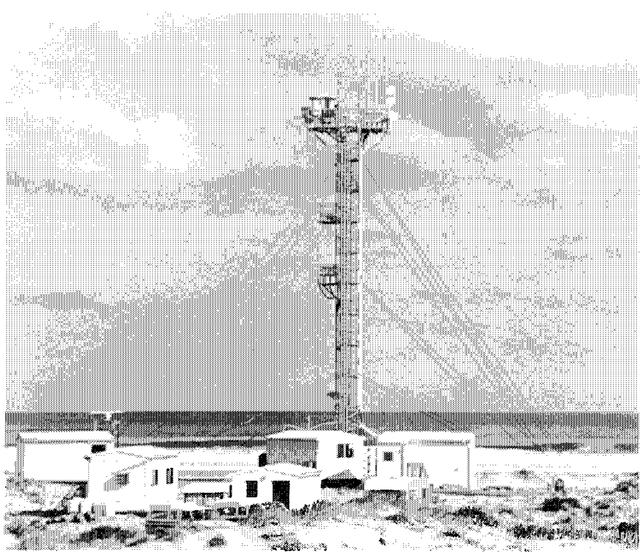
Atmospheric Transport of Material from the Continents to the Ocean

Robert B. Gagosian and Edward T. Peltzer



Shelley Lauzon

Ed Peltzer and Bob Gagosian



SEAREX Air Sampling Tower at the Ninety-Mile Beach experiment site on the west coast of North Island, New Zealand.

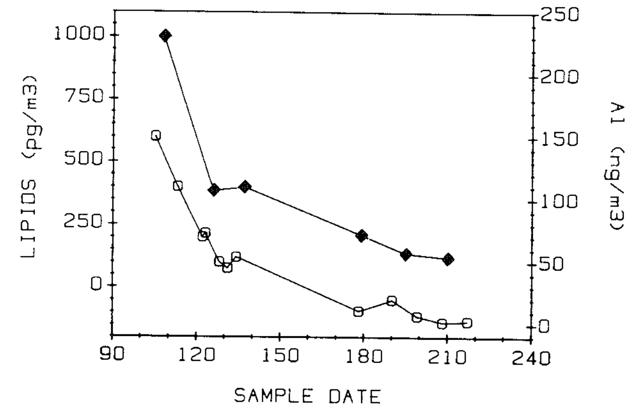
In recent years, there has been a growing interest in the role the atmosphere plays in transporting natural and anthropogenic (man-made) substances from the continents to the open ocean. Marine geochemists have been searching for a better understanding of the processes involved in this long range transport on a global scale. For the past seven years, we have been involved in the Sea-Air Exchange Program (SEAREX), a multi-institutional, multidisciplinary program funded by the National Science Foundation to investigate these transport processes. The program is a closely coordinated field and laboratory effort involving researchers from eight American, one British and one French institution.

SEAREX was designed to increase our understanding of atmospheric transport and transformation processes and their involvement as sources and sinks for materials found at the ocean surface. The primary objectives of the program are: 1) to measure the atmospheric concentrations and the sources of selected heavy metals, radioisotopes and organic compounds found in the marine atmosphers; 2) to investigate the meteorological processes that control the transport of materials from continental sources to the ocean and to model these processes; and 3) to conduct controlled laboratory and field experiments to investigate the mechanisms of exchange of these substances across the air/sea interface, to measure the net deposition of these substances to the ocean, and to assess the impact of atmospheric fluxes on chemical cycles in the ocean.

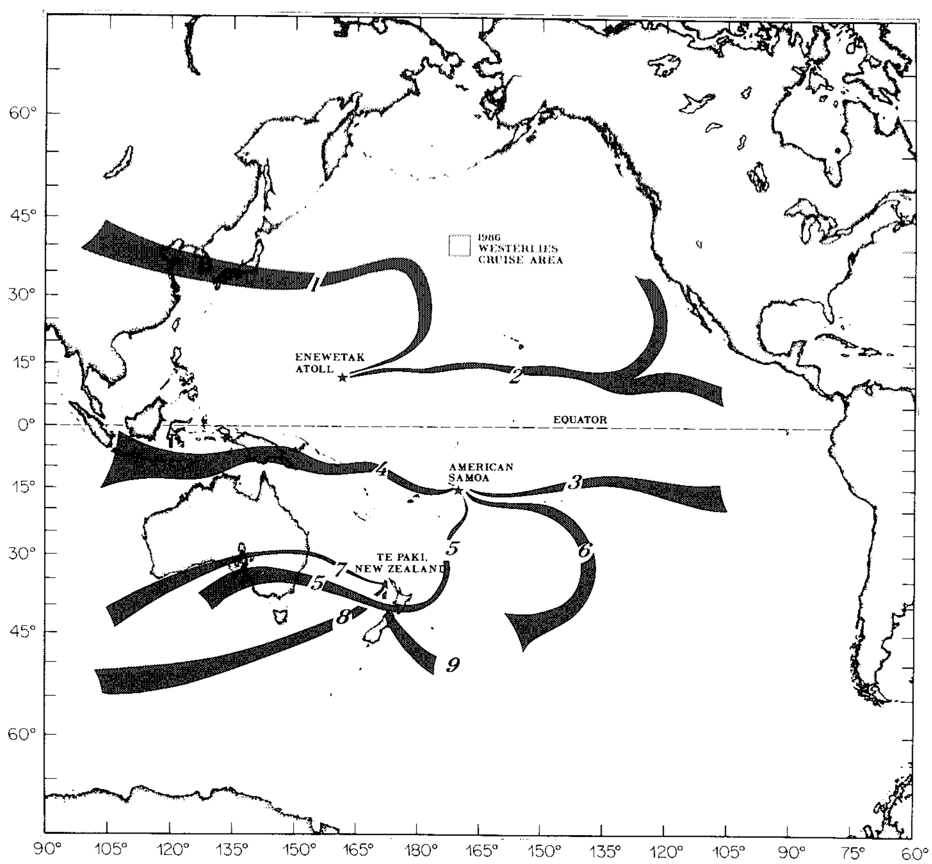
Our role in SEAREX has concentrated on the natural and anthropogenic organic compounds. Six compound classes were selected as indicators of these sources to atmospheric materials: n-alkanes, polycyclic aromatic hydrocarbons, fatty alcohols, fatty acids, sterols and wax esters. These "source marker" compounds have been used to differentiate atmospheric samples as primarily marine, terrestrial or anthropogenic in origin. In addition, within the various terrestrial and marine sources of these compound classes, there is a sufficient diversity of composition, allowing us to use the relative abundance patterns of the individual components as "chemical fingerprints" to assign a more specific source (such as soils, plant waxes, phytoplankton debris, etc.) or to assign a more definite source region.

The major focus in the SEAREX program has been to use an air sampling tower (photo left) to investigate material found in the atmosphere. This tower, used to collect both gaseous and particulate samples for a wide variety of chemical analyses, is situated at sampling sites far removed from the major land masses and sources of anthropogenic activity. The air sampling devices are mounted inside protective shelters along the windward railing at the top level of the tower (see photo). Four sites (see map) in each of the major wind systems of the Pacific Ocean were originally planned: Enewetak Atoll and American Samoa in the Northern/Southern Hemisphere tradewind systems, and New Zealand and a cruise north of Hawaii in the Southern/Northern Hemisphere westerlies. To date, three of these sites have been successfully occupied and samples have been collected; the fourth, the cruise north of Hawaii, will take place in the summer of 1986.

Although sea salt (derived from sea spray) is the major form of particulate material in the atmosphere, samples collected at Enewetak Atoll revealed an extremely high concentration of unequivocably terrestrially-derived material. Not only did the atmospheric aerosol samples contain very high levels of soil dust and terrestrial plant wax material given this site's extreme remote location, but the concentration levels of this material were found to vary dramatically with the season. In April, atmospheric dust levels were at a maximum; then they slowly declined throughout the spring and summer months. This can



Total land plant lipid compounds (◆) and particulate aluminum (0) concentrations of aerosol samples as a function of time during the Enewetak field experiment. Sample dates are Julian days, 1979.



Locations of the major SEAREX sampling sites and some of the typical air mass trajectories for each site. (1) Enewetak dry season, April - May, 1979; (2) Enewetak wet season, July - August, 1979; (3 - 6) Samoa, January - February and July - August, 1981; (7 - 9) New Zealand, June - August, 1983.

clearly be seen in the figure at left where plots for total particulate land plant lipid concentrations (indicators of a continental source) and particulate aluminum concentrations (indicators of crustal material) show a decreasing trend with time. An investigation of meteorological records revealed the presence of extensive dust storms in northern China in the late winter and early spring and a high altitude wind system which can transport this material from central Asia to the tropical central Pacific ocean (map trajectory 1). Subsequent studies of this phenomenon have shown that it is an annual event and that the dust from China can be seen throughout the North Pacific at locations other than Enewetak Atoll, including Hawaii and the Aleutian islands. During the summer months when the source of Asian dust is quite weak, meteorological and chemical evidence suggests that the source for particulate material in the atmosphere at Enewetak comes from the western United States and possibly northern Central America (map trajectory 2).

The sampling expedition to American Samoa resulted in very different results. Because of the El Nino/Southern Oscillation, the trade winds at Samoa in 1981 were much weaker than we had experienced at Enewetak, and the southern edge of the Inter-Tropical Convergence Zone (ITCZ) was very close to American Samoa. The ITCZ is a zone separating the Northern and Southern Hemispiere atmospheric circulation systems. Thus we found that the trade wind conditions which had made the weather ideal for sampling at Enewetak were frequently interspersed with periods of stagnant air or even reverse-flow conditions at Samoa. Meteorological calculations have revealed that instead of collecting a suite of samples from a single major source region whose source strength varied with time (as occurred in Enewetak), the samples from Samoa represent air masses from a variety of sources (map trajectories 3-6). In effect, we were sitting at the meteorological crossroads of the Southern and Northern Hemispheres. Air mass trajectories include sources from a diverse suite of locations: South America, Australia, New Zealand, New Guinea-Solomon Islands, and some transport from the Northern Hemisphere, probably from the Panama-Central American region.

These Samoan air mass trajectories calculated from meteorological data are strongly supported by the results of chemical analyses of the atmospheric particulate matter. The long transport trajectories (map trajectories 3-6) proposed by the program meteorologist (J. T. Merrill, URI) suggest that we should find very low concentrations of terrestrial material; and indeed, the Samoan samples have the lowest concentrations measured to date. Furthermore, the Samoan samples exhibited a wide range of organic compound compositions. While each sample would be classified as having a terrestrial plant wax source, only rarely was the chemical fingerprint of one sample identical to another. Like forensic scientists, we seek to match the chemical fingerprints of the samples with the chemical fingerprints of the sources. Some samples are dominated by relatively high molecular weight compounds which are an indicator of the plant waxes of tropical plants. Other samples contain lower molecular weight compound distributions which suggest that the source is a mixture of temperate land plant waxes. We are currently correlating the chemical compositions of the samples with the various air mass trajectories to further pin-point the source regions.

At our third air sampling site at the northern tip of North Island, New Zealand, air was sampled from the Southern Hemisphere westerlies. Unlike the trade wind systems which are known for their consistency, the westerlies are known for their variability in both velocity and direction. Due to this variability, we were able to collect an excellent suite of air samples representing a variety of sources (based on the air mass trajectories). The expedition was completed in late 1983, and the initial results of the analysis of these samples are quite exciting. Concentrations of terrestrially derived materials at New Zealand range from some of the lowest levels measured in Samoa to levels in excess of those measured in Enewetak at the height of the dust season. Air mass trajectories indicate that samples of air were collected that had recently passed over Australia (map trajectory 7) and the Southern Ocean (map trajectory 8). In addition, samples were collected from air masses that passed over New Zealand, went out to sea, then passed over our tower site (map trajectory 9). The chemical composition of the samples from the various sources are quite distinct, with some bearing a strong resemblence to the air samples collected in Samoa which were thought to have an Australian or New Zealand origin (map trajectory 5).

As these examples indicate, we are just beginning to understand the interplay between atmospheric chemistry and meteorology in transporting material from the land to the sea. Models are being developed which will allow us to determine quantitatively the source strengths of the organic substances. With this additional information and the long-range meteorological trajectory analyses, we will be in a position to better understand the global distribution of organic material in the marine atmosphere.

Upper Ocean Gas Exchange

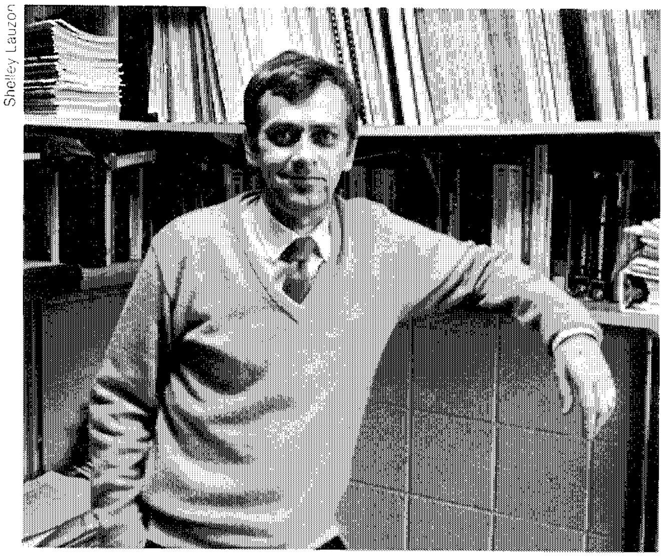
Peter G. Brewer

The carbon dioxide issue, by which we mean an understanding of the causes and consequences of the fluctuating concentrations of this trace gas in the atmosphere, is of fundamental concern to a wide range of ocean scientists. The broad picture is reasonably well known: atmospheric CO_2 levels late in the last century appear to have been in the 270-290 parts per million (ppm) range. The level today is about 345 ppm. The rising level is attributed to the burning of fossil fuels and to changing storage of vegetative carbon in the earths' terrestrial biosphere. The Ocean is the principal buffer against change, taking up annually some 40% of the CO_2 produced. The CO_2 capacity of the ocean is so vast that over geologic time scales it is the cycling of carbon within the ocean that determines the atmospheric CO_2 level. The rising CO_2 levels will eventually cause a climatic warming and a rise in sea level.

A major effort to understand these processes was made with the Transient Tracers in the Ocean (TTO) program in 1981. This multi-institutional effort involving scientists from the Scripps Institution of Oceanography, the Lamont-Doherty Geological Observatory, the University of Miami, Princeton University, and Woods Hole occupied the R/V *Knorr* for a nine-month field effort covering 23,000 miles of cruise track and 250 hydrographic stations. In participating in this venture, we had as our goal the accurate measurement of fundamental ocean CO_2 properties: the alkalinity and total carbon dioxide concentration of sea water. Moreover, the North Atlantic is the site of formation of much of the deep water of the world ocean, and thus our studies could ascertain the "labelling" of the deep water source areas by man's industrial contaminants.

Some of the results of our measurements are displayed in the figure on the opposite page. The presentation is a three-dimensional perspective view of the partial pressure of CO_2 gas (pCO_2) in the North Atlantic ocean in 1981. The figure was prepared by D. K. Shafer with the WHOI computer system. The ocean is seen from height above mid-continent with respect to a "floor" of atmospheric equilibrium at about 340 ppm. There has been one correction applied, that for the small amount of excess oxygen in surface waters. Data are contoured between widely spaced stations, and the map cannot be synoptic but reflects the spring-summer-fall tour of the *Knorr* around the ocean basin. In spite of these problems, important features emerge, and questions wait to be answered. What causes this particular pattern of highs, representing evasion of CO_2 to the atmosphere, and lows, representing invasion of CO_2 to the ocean, to be established? What are

Shelley Lauzon

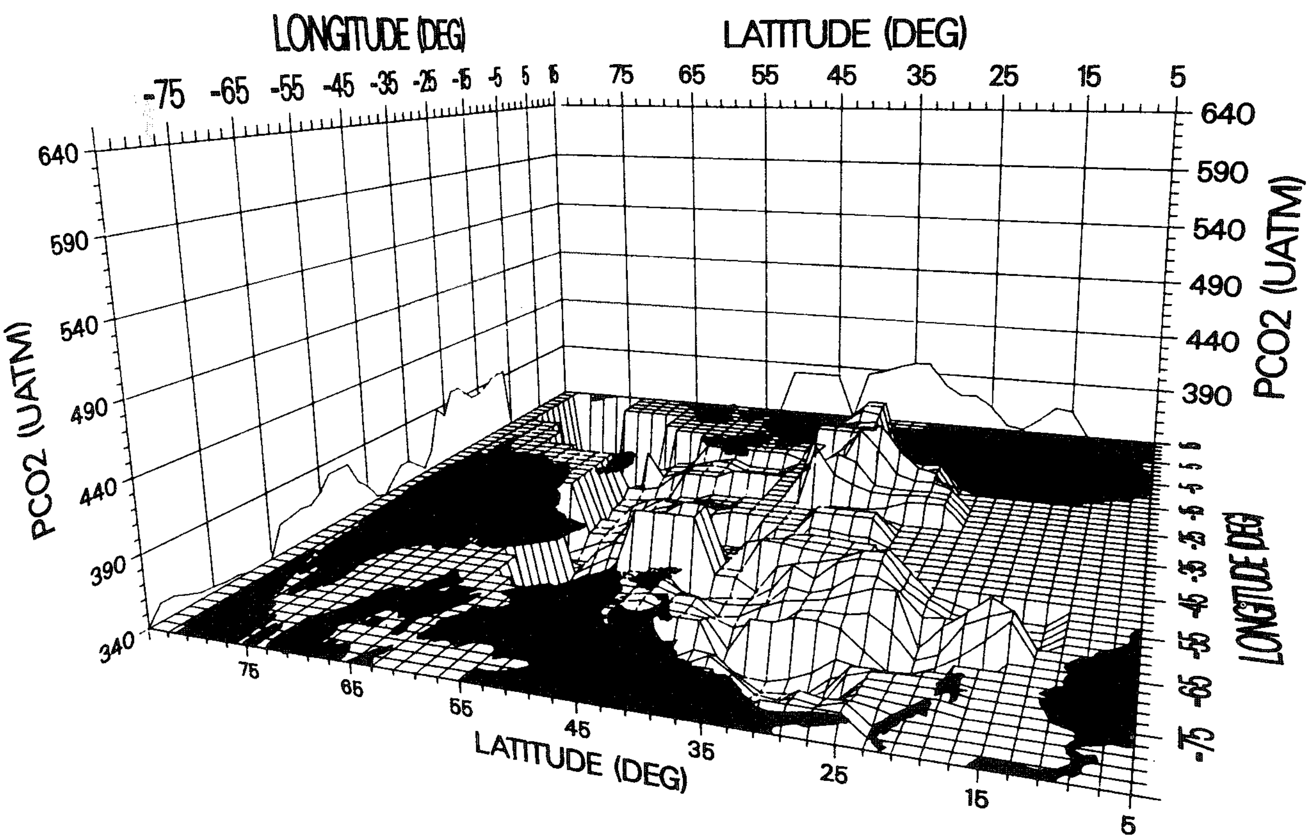


Peter Brewer

the seasonal fluctuations? How sensitive is such a pattern to change? In searching for answers, we found that the arguments presented by our colleagues fell into two distinct and opposing groups. There are those who see in this picture an expression of the photosynthetic activity of the upper ocean. The low values north of 55° are then drawn down by primary productivity fixing CO_2. High values off Africa represent upwelling of CO_2 rich deep water, followed by intense lowering of the CO_2 levels in this biologically rich area. Other investigators see the predominant signal here as the physical heating and cooling of the water. Indeed, models connecting CO_2 fluxes between sea and atmosphere appear to rely entirely upon simulation of purely physical variables. In the last year, we have constructed instruments and carried out cruises designed to resolve these issues.

Our results show a strong correlation with the ocean heat flux. For instance, the high values off Newfoundland are caused by the advection southwards of bitterly cold water in the Labrador Current. on reaching the Grand Banks, the water receives heat from condensation of water vapor and the absorption of radiant energy. The warming elevates the pCO_2 levels more rapidly than gaseous exchange with the atmosphere can restore equilibrium, and from the interplay of these two rate processes, the observed signal is created.

TTO SURFACE (1-15M)



Three-dimensional view of the partial pressure of CO_2 gas (pCO_2) in surface waters of the North Atlantic Ocean, viewed from high over the United States and looking east toward Europe and Africa. Cape Cod is shown at approximately 41° latitude. The ocean "floor" or flat surface area is at atmospheric equilibrium. High values represent evasion of gas from sea to air; lows represent invasion of gas from the air into the ocean.

In the Gulf Stream recirculation region, the opposing effect occurs. There, warm water at equilibrium with the atmosphere is rapidly advected northwards to colder climes. Swept by cold dry continental air over much of the year, strong evaporation and cooling occurs. Again, the balance of heat and gas exchange rates results in a net residual signal, here a lowering of the pCO_2. North of 55°N, biological processes appear to dominate, the low values found there resulting from summertime primary productivity.

By combining our insights into numerical models, we are attempting to reconstruct the seasonal cycles of CO_2 in the surface ocean, to construct synoptic maps, and to devise experiments to verify our hypotheses. Hidden within these data lie important information on the climatic, biological and chemical processes of the upper ocean. Sea water contains approximately 2,000 micromoles of dissolved CO_2 per kilogram of sea water. Our calculations and analyses show that at latitudes of about 15°N the seasonal amplitude of the surface signal is about 10 micromoles/kg; at 30°N about 30 micromoles/kg; and at 65°N about 100 micromoles/kg. Clearly, demanding experimental work will be required to make these accurate measurements and to document in the face of such natural complexity the changing nature of ocean CO_2 chemistry.

Marine Organic Chemistry: The Influence of Living Organisms

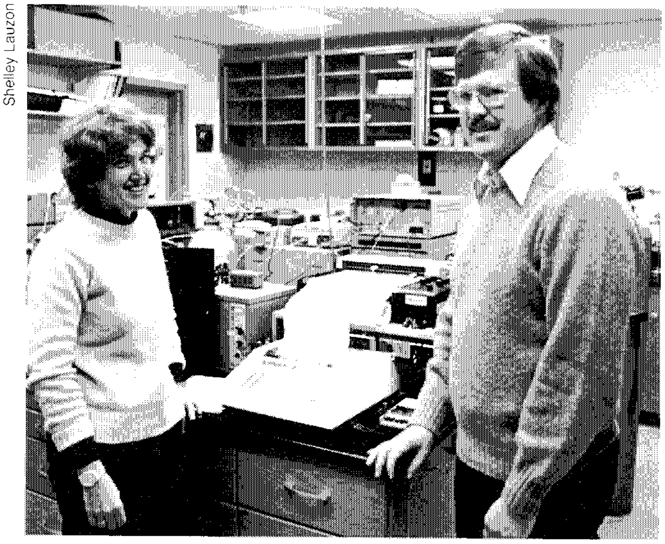
Cindy Lee and Stuart G. Wakeham

Many of the organic chemicals found in the ocean are produced by living organisms. This process begins when carbon dioxide (CO_2) enters the ocean from the atmosphere and is taken up by phytoplankton. Phytoplankton use the CO_2 during photosynthesis to produce the biochemicals necessary for metabolism and growth. Other marine organisms live by consuming the organic chemicals produced by phytoplankton. For example, zooplankton eat phytoplankton directly while bacteria consume the metabolic products of both phytoplankton and zooplankton. Bacteria are particularly important organisms in seawater because they consume dissolved compounds. The composition of dissolved organic carbon in seawater largely reflects a balance between compounds produced by plankton and those consumed by bacteria as sources of nutrition.

Marine organic chemists are interested in the processes which control the distribution of organic compounds in the ocean. Photosynthesis converts inorganic carbon dioxide to organic carbon, but there are elements other than carbon which are also important in organic compounds. Two of these elements are nitrogen and sulfur, found most notably in proteins, which play a part in almost every structural, regulatory, and metabolic process in living organisms. Protein and its component amino acids are commonly found in the marine environment in living organisms, in detrital particulate matter, and dissolved in seawater. One of the projects under investigation in our marine organic chemistry laboratories at WHOI is the production and decomposition of organic nitrogen and sulfur compounds derived from the degradation of protein.

Our studies of organic chemical reactions are usually broken into two parts. First, we determine the mechanism of a reaction, that is, the starting materials and end products and how the reaction occurs. Then we measure the rate of the reaction in different places and try to determine the environmental conditions which influence that rate. In order to look at reaction mechanisms, it is useful to work in an area which is easily sampled at any time of the year. A local coastal pond, Salt Pond in Falmouth, was selected as a site for our work. Salt Pond is a shallow, semi-enclosed glacial pond surrounded by a bird sanctuary and relatively undisturbed by man. Since Salt Pond has also been studied by other WHOI scientists, we know much about its geology, biology, and inorganic chemistry.

Shelley Lauzon



Cindy Lee and Stu Wakeham

$$H_2N\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}NH_2$$

Putrescine

$$H_2N\text{-}CH_2\text{-}CH_2\text{-}CH_2\text{-}\overset{NH_2}{\underset{H}{C}}\text{-}COOH$$

Ornithine

$$CH_3SCH_3$$

Dimethylsulfide (DMS)

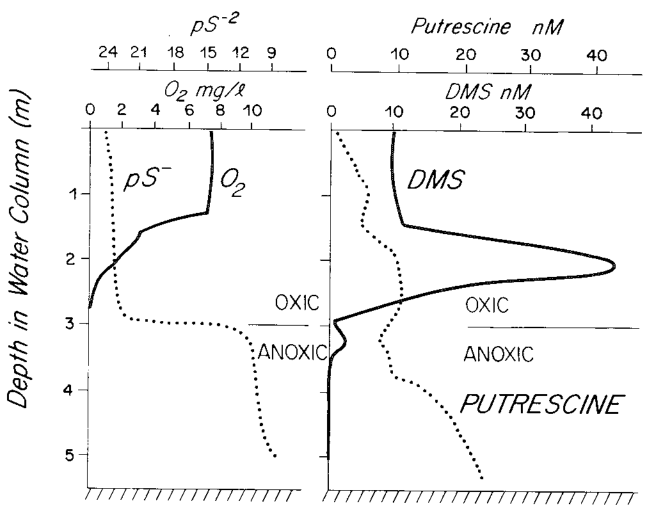
$$(CH_3)_2S^{+}\text{-}CH_2\text{-}CH_2COO^{-}$$

Dimethylpropiothetin

In our Salt Pond studies, we are investigating the role of phytoplankton in producing, and bacteria in consuming, certain dissolved nitrogen and sulfur compounds. To do this, we use radiolabelled tracers to follow the fate of these compounds. By taking a water sample from the pond and incubating it in the laboratory with small amounts of a ^{14}C-labelled compound, we can trace the pathway of the carbon through bacterial incorporation and respiration processes.

Results show the influence of several environmental factors in controlling the concentration of dissolved organic compounds in seawater. These include seasonal changes in the organisms present, the amount of oxygen in the water, the presence of light, and depth of the mixed layer. For example, we have studied the organic nitrogen compound putrescine.

Putrescine and DMS Concentrations in Salt Pond



Putrescine and DMS concentrations in Salt Pond are related to the character of the water column. Putrescine concentrations build up in the anoxic waters where oxygen (O^2) is absent and hydrogen sulfide (as shown by pS^{-2}) is present. The maximum concentrations of DMS are found in the suboxic zone where oxygen concentrations are decreasing but above the depth at which sulfide can be detected (3 meters, or 10 feet, depth).

Putrescine is formed during putrefaction, or the decomposition of protein and free amino acids, notably arginine and ornithine. The concentration of putrescine usually increases with depth in Salt Pond and is highest in the deeper anoxic waters (see figure). Uptake and respiration by bacteria are highest there. Putrescine in the deep waters is, most likely, coming from two sources, decomposition of protein in sinking particles, and production from ornithine diffusing out of the sediments.

At certain times of the year when conditions in the pond cause a phytoplankton bloom to occur in the surface waters, there is a large increase in the consumption of putrescine. Using radio labelled putrescine in incubation experiments, we can follow the path that natural putrescine takes through the food chain. By measuring the amount of putrescine which is lost from the system to the bacteria, we can estimate how much must have entered from the phytoplankton. Radiotracers are a particularly important tool in estimating production because the concentration of putrescine does not change during these production and consumption processes. They remain in balance since bacteria are taking up putrescine as fast as it is being produced. Thus, if we measured only the concentration, we would not know how dynamic the system really is.

Another compound we have studied in Salt Pond is dimethyl sulfide, or DMS. This organic sulfur compound has its highest concentration at a depth just above the oxic/anoxic interface (see figure). The vertical distribution of DMS in the pond parallels the seasonal changes in the oxic/anoxic boundary. During winter, wind-driven mixing of the water column drives this interface to greater depths (or eliminates it completely if the pond overturns). In summer, the pond becomes thermally stratified and the oxic/anoxic interface is more shallow. Throughout the year, the DMS peak "rides" just above the interface. We believe that the peak in concentration is due to production of DMS under low oxygen conditions, either by decomposition of dead algal matter or by physiological stress on live cells at low oxygen tensions. The most likely source of production of DMS is dimethylpropiothetin, an osmoregulator related to the amino acid methionine whch is abundant in some species of phytoplankton. Concentrations of DMS are always very low in the anoxic waters of the pond, suggesting active consumption by anaerobic microorganisms. We plan to conduct radiotracer experiments in the summer of 1985 which will verify DMS production and consumption mechanisms.

Falmouth's Salt Pond has been successfully used to develop methods to measure organic compounds and reaction rates and to determine reaction mechanisms. We are ready to apply this knowledge more efficiently to processes affecting organic compounds in the open ocean.

Oxygen Isotopes Record the Annual Sedimentation Cycle

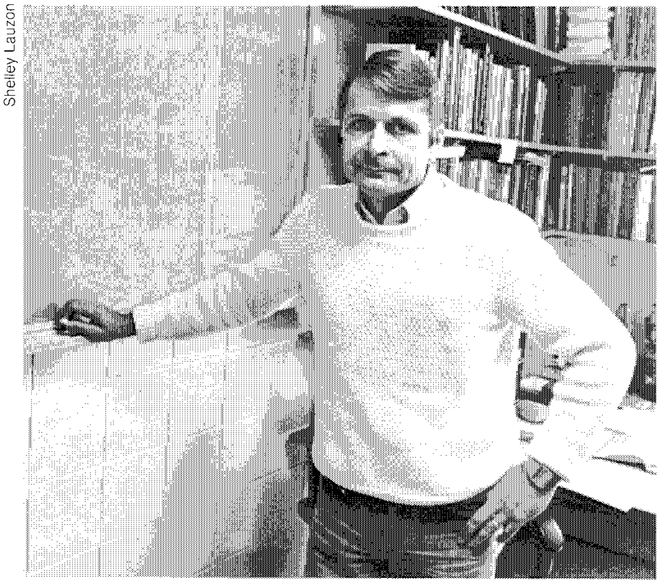
Werner G. Deuser

Until a few years ago oceanographers generally assumed the deep ocean to be invariable over long periods of time. Snapshot measurements of any property in a given place were thought to give values representative of that property for centuries or more. Differences occasionally found between repeated snapshots were attributed to differences between methods or investigators rather than to changes in the properties. After all, the deep sea was known to be permanently cold and dark, and vertical transport processes of any consequence were thought to be so slow as to shield the deep sea completely from the variability to which the surface ocean is exposed, except on the long time scale of climatic change, such as the coming and going of ice ages.

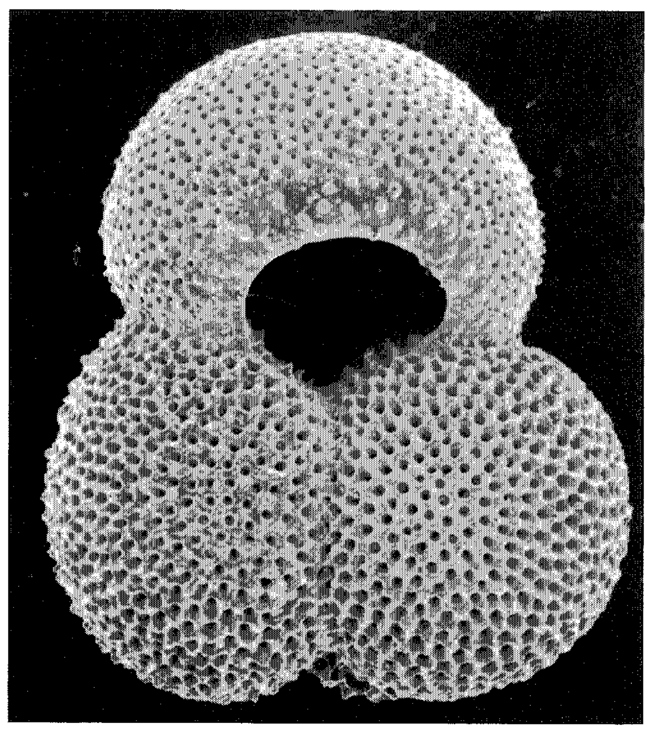
A number of independent lines of evidence emerged within just a few years which drastically altered this traditional view of the deep sea. Annual layers (varves) were identified in sediments of the deepest part of the Black Sea which underlie more than 2000 meters (approximately 6,500 feet) of water and are devoid of life forms other than bacteria. Radioisotope dating of deep-sea clams suggested that their shells' growth bands might be annual; some deep-sea animals were found to have annual reproduction cycles. These diverse types of evidence found a simple explanation a few years ago when we discovered pronounced seasonality in the flux of particles sinking into the deep Sargasso Sea. Similar variations have since been measured in other parts of the ocean. These findings indicate how rapidly particles descend to the deepest parts of the ocean and how they provide a conveyor by which chemical and biological signals of seasonal change at the surface are transmitted to the deep sea.

We have extended our studies of seasonal and year-to-year variations in the quantity and composition of particles approaching the sea floor. In May 1984 we completed a six-year series of measurements off Bermuda in which we used a sediment trap moored at a depth of 3200 meters (approximately 10,500 feet) and suspended 1000 meters (approximately 3,300 feet) above the sea floor. We recovered the mooring and collected the material accumulated in the trap every other month. The location we chose for the experiment was close to Station S, the site of the longest series of open ocean hydrographic measurements (begun in 1954 and carried out in close cooperation between the Woods Hole Oceanographic

Shelley Lauzon



Werner Deuser



Globigerinoides ruber × 190
This species spends its short life of days to weeks in the surface water and is abundant in the subtropics throughout the year.

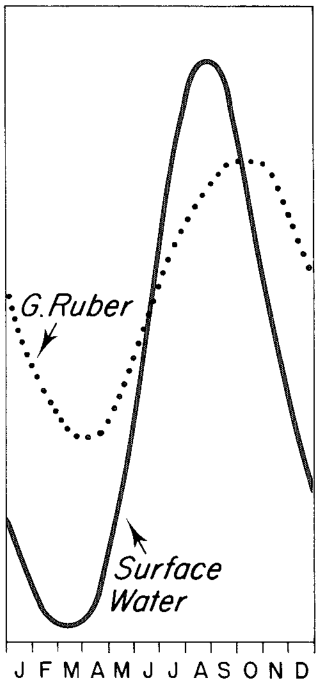


Figure 1
Temperature variation at the surface and the delayed arrival of its record in *G. ruber* skeletons at a depth of 3200 meters (approximately 10,500 feet).

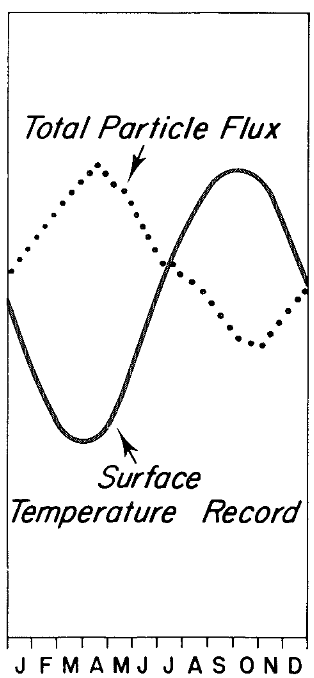


Figure 2
Inverse relationship between surface temperature and deep particle flux in the Sargasso Sea.

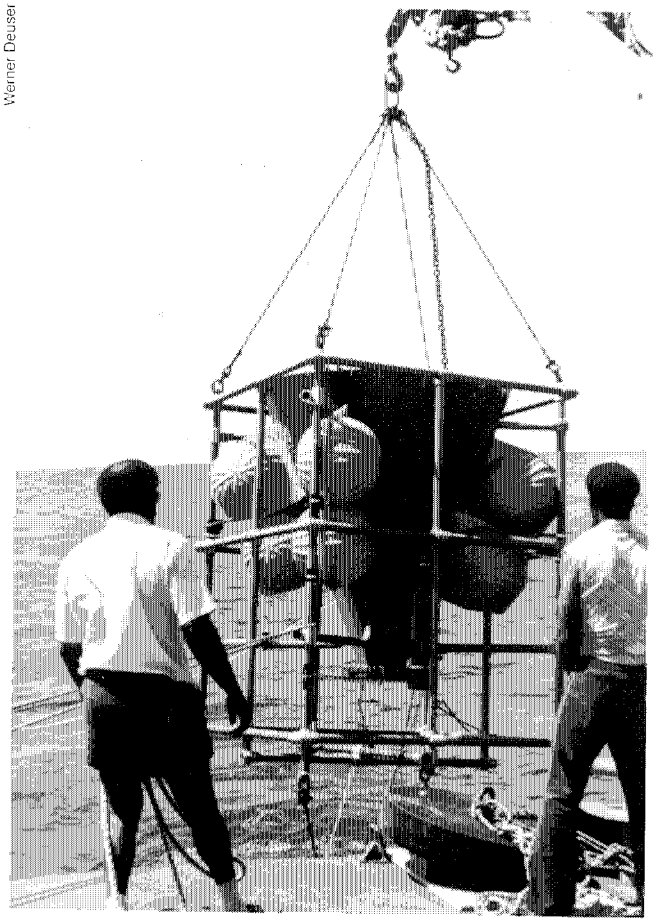
Institution and the Bermuda Biological Station). The Station S measurements have produced an excellent record of the seasonal and year-to-year temperature and salinity variations in the waters around Bermuda.

Planktonic foraminifera, a group of single-celled organisms inhabiting the surface ocean, build a temperature record of their environment into their skeletons: the ratio of the isotopes of oxygen depends on the temperature at which the skeletons are built. One species, *Globigerinoides ruber*, spends its short life of days to weeks in the surface water and is quite abundant in the subtropics throughout the year. Its skeletons constantly "rain down" to the sea floor (at an average rate of 100 per square meter per day) and carry with them a record of their life-time ambient temperature which may then be preserved in the sediment for millions of years. With our sediment trap we have intercepted many *G. ruber* skeletons along with all the other debris which settles through the water column. By measuring their oxygen-isotope ratios we can use these tiny particles as recorders in our samples of the temperature prevailing at the time the collected material left the sea surface. Moreover, by comparing the variations in their isotopic temperature record with the variations of surface water temperatures as given by the Station S measurements, we detect a delay of about one month between the temperature extremes at the surface and the arrival of their records in the sediment trap. This delay is a good measure of the time spent by the particles in sinking from the surface to 3200 meters (figure 1).

Our isotopic recorder of sea surface temperature in the sediment trap samples revealed a close dependence of particle flux to the deep sea on surface temperature (figure 2). Annual averages derived from our six-year experiment show a clear inverse relationship between the mean variations of sea surface temperature and particle flux. At the time of the late winter temperature minimum in the Sargasso Sea, the quantity of particles sinking out of the euphotic zone (the sunlit upper layer of the ocean in which organisms produce the great majority of particles) is at its maximum. Conversely, the late summer temperature maximum is associated with minimal particle flux. Although we do not yet have quantitative data on the relationship between primary production at the surface and deep water particle flux, we can now infer such a relationship. We know that the wintertime cooling provides the mechanism for fertilizing the surface ocean with nutrients convected upward from the deeper water. We also know that this fertilization stimulates primary production into what is often called the "spring bloom". It follows from our data that a signature of this spring bloom is carried to the deep ocean within one month, and that throughout the year the permanently dark and cold deep sea and its creatures are closely coupled to the seasonal temperature cycle at the earth's surface by means of a similar cycle in the supply of food and sediment.

The information on temperature dependence of particle fluxes and on sinking rates revealed by the "isotopic recorder" are examples of the insights gained by repeated measurements at one site. Modern instruments make it possible to measure variabilities of more and more properties in the deep ocean on time scales from hours to decades. Assessing variability is the key to understanding the nature and rates of processes which govern the ocean and life within it.

Werner Deuser



Deployment of a sediment trap off Bermuda. Material accumulates in the jar at the bottom of the cone.

Petroleum Geochemistry

Jean K. Whelan, John W. Farrington and John M. Hunt

Shelley Lauzon

John Farrington and Jean Whelan, above. John Hunt, left.

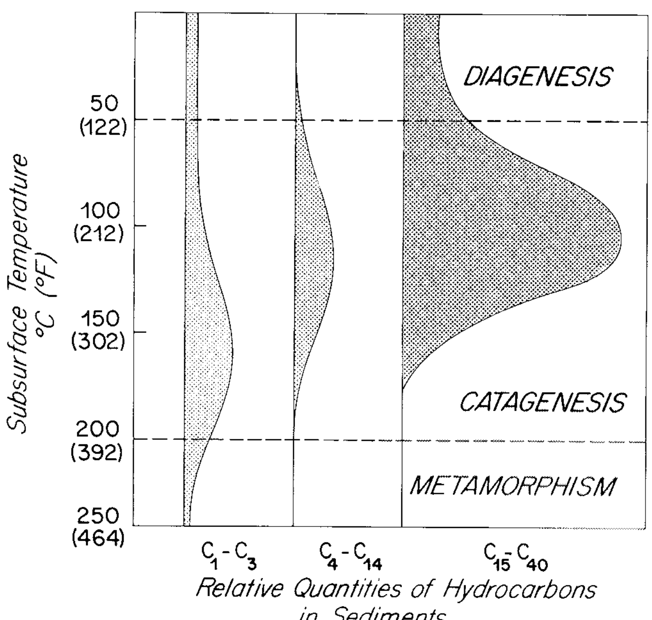


Figure 1
Distribution of hydrocarbons generated in sedimentary rocks at various subsurface temperatures. Temperatures start at 0°C (32°F) at the sediment-water interface (top of figure) and then increase with sediment depth.

Oil and gas, which form from the remains of organisms in deeply buried aquatic sediments, are the major focuses of research in our laboratory. Petroleum companies, of economic necessity, usually confine their research to questions related directly to exploration – finding new sources of oil and gas. It is left to academic and government laboratories (such as our own and the U.S. Geological Survey) to answer more fundamental questions which have long range importance in successful exploration as well as in using the sediment organic matter record to understand geological processes in the ocean. The importance of viewing oil formation/migration as a continuum that begins at the sediment/water interface can be seen by taking a brief look at current thinking about how petroleum generation occurs.

Oil and gas originate from the organic matter (kerogen) that is deposited in the sedimentary basins on the continents and continental margins of the world. These basins are shallow depressions hundreds of square miles in area that intermittently have been covered with water and now are filled or are filling with sediments. These sediments include 1) sands and clay muds containing organic matter formed on continents that were eroded from hills and mountains and carried to the basins by rivers and streams, 2) lime (carbonate) muds like those on the east coast of Florida that form from the shell material of millions of organisms, 3) chemical precipitates such as salt, anhydrite, and chert, and 4) organic matter formed in the water column over the basins.

Petroleum is made up of a complex mixture of hydrocarbons – only a small amount of which is produced by living organisms. The rest of petroleum comes from the thermal alteration of sediment organic material (polymeric), called kerogen. Heat flows outward from the center of the earth causing the temperature of sedimentary basins to increase with depth. The temperature increase is variable, but averages about 3°C (approximately 37°F) per 100 meters of increasing sediment depth. This heat cooks organic matter and produces oil in the same way that an oven cooks a roast, except that the rate of heating is slower and the times required longer. The temperatures at which oil and gas form have been well defined. During the first stages of burial, diagenesis (less that 50°C, or 120°F), methanogenic bacteria form methane from substrates in the sediments. Traces of C^2 to C^{14} and some C^{15} to C^{40} hydrocarbons in crude oil also are formed from the organic matter as a result of low-temperature biological and chemical reactions. During catagenesis (50 to 200°C, 120° to 400°F), most oil and gas are formed from the cracking (thermal break down) of organic matter in the sediment (figure 1). In the last stage, metagenesis or metamorphism (greater than 200°C, 400°F), only gas (methane) is formed in appreciable quantities. The maximum sediment depth below which no oil accumulation of economic value forms varies between about 3 and 7km (2 to 4 miles) depending on the geothermal gradient (although there is still some controversy on this point, as discussed further below). With the thermal regime of petroleum generation now being relatively well defined, petroleum geochemists are turning their attention to the more difficult problem of unraveling the processes by which oil and gas migrate out of fine-grained source beds into porous formations (eg. sand, porous carbonate rocks, etc.) where it is concentrated in reservoirs.

Recent work in our laboratory has dealt with several important aspects of the processes outlined above. For example, in terms of the generation process, the correct type of organic material (i.e. the amount of hydrogen rich organic matter) must be present in a sediment. Our work has concentrated on thermal techniques, including development of new instrumentation, which is now widely used in the petroleum industry (figure 2). A few milligrams of sample are gradually heated – first to low temperatures in the range of 150 to 250°C in order to drive off petroleum which has already been formed naturally in the sediment – and then to high enough temperatures (450 to 550°C) to crack (or break off) hydrocarbons from the kerogen. The total amount and composition of the products produced indicates the total amount and type (i.e. gas vs. kerosene vs. oil, etc.) of petroleum which already has been generated and which would be generated if the sediment were buried more deeply. Thus, the explorationist is in a position not only to know whether the proper formations to trap oil are present underground via the traditional seismic profiling, but also, once a test site is drilled, to determine if the sediments feeding the potential petroleum trap or reservoir are of the proper type to have ever generated oil.

Another important way in which pyrolysis techniques are being used in our laboratory is in determination of how deep oil and gas generation might occur. As mentioned above, as sediment organic matter is exposed to high temperatures in very deep hot formations, all the oil and gas winds up being cooked out of the sediment. Our approach to determination of the maximum depth of oil and gas formation (a topic which has generated considerable controversy) has been to subject very old and deeply buried sediments to pyrolysis to see if any hydrocarbons can be generated even with extreme heating conditions. A successful resolution of this question has obvious economic implications when it is considered that the cost of drilling increases exponentially with increasing depth in deep wells. It is very difficult to obtain suitable samples for this type of work. We are fortunate in being involved in two collaborative research projects – one with a government laboratory and one with industry – which have provided suitable samples as well as shared data directed toward a resolution of the deep oil and gas question. One suite of samples, provided by the U.S. Geological Survey and by Chevron, comes from a series of wells drilled on the Alaskan North Slope (figure 3). These wells, which include a complex intermixing of marine and continental sediments, are ideal for examining the "deep gas" question, because they were once buried more deeply than at present and were subsequently uplifted and eroded. Therefore, deep drilling was not required to recover these overmature sediments. A second set of more carbonaceous marine sediments from Texas (provided by Chevron) are also being examined.

We have also conducted research to unravel processes of generation and migration of the lightest petroleum components, those with less than 9 carbon atoms in the molecule (the C^1 to C^8 hydrocarbons). These compounds are important in understanding the basic processes of petroleum migration because they are among the first components of petroleum to migrate. We found the light hydrocarbons to be present throughout the sedimentary column at the parts-per-billion level in shallow sediments and at the parts-per-million level in deeper sediments. These low levels of light hydrocarbons near the surface have caused and are still causing problems in exploration studies because it was initially thought that they represented compounds migrating up from deeply buried reservoirs. However, our research has shown that small amounts of many of these compounds can form by a combination of low temperature chemical and biological processes in recent sediments. In a number of cases, we have determined the specific types of compounds expected from various types of depositional environments and have found the levels of these compounds to depths of about 500 meters (approximately 1500 feet) are low enough to have been generated by natural processes operating near the sediment-water interface at the time of deposition. Furthermore, our research as well as that of others indicates that even these light compounds (with the exception of methane) do not migrate easily through consolidated fine-grained sediments. In fact, current thinking in our laboratory is that migration does not generally occur at all until the petroleum generation process is well underway. However, it is well known that oil does migrate by some process into reservoirs and that thermally generated hydrocarbons can sometimes be detected in surface sediments above or near a petro-

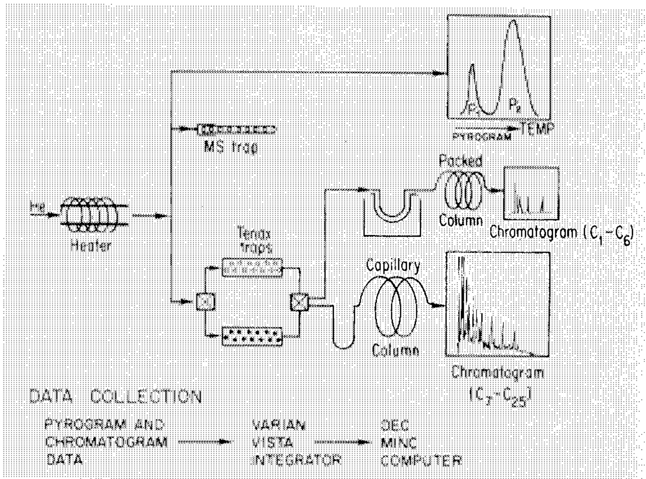


Figure 2
Diagram of thermal distillation — pyrolysis-gas chromatography apparatus. Wet sample in quartz tube is treated by a platinum coil heater. Compounds evolved during heating are swept from sample in a gas (helium) stream and analyzed further either by gas chromatography (GC) or GC Mass Spectrometry (GCMS). Data collection has been automated as shown.

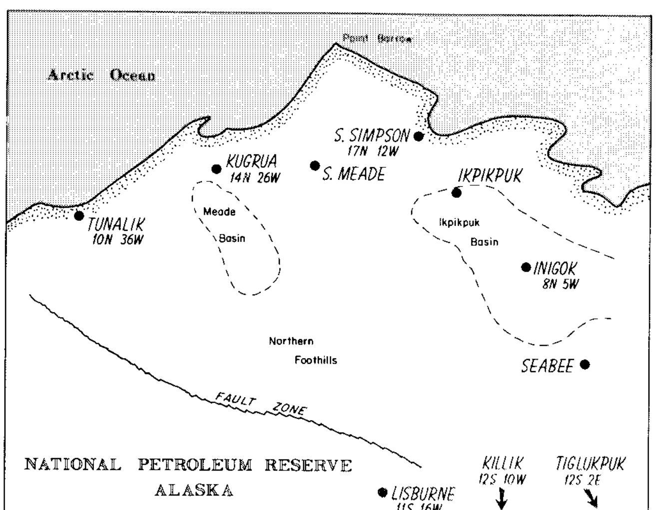


Figure 3
Location of Alaskan North Slope petroleum wells from which samples have been analyzed.

leum reservoir. Based on our own and other research, we believe that these hydrocarbons are migrating to the surface along vertical permeability channels. We are currently attempting to get detailed concentration profiles of hydrocarbons near such features in order to better distinguish between various possible migration mechanisms.

Hydrogen rich organic material can be biodegraded by microorganisms at the time sediments are deposited on the sea floor, so that the resulting sediment organic matter will never be able to generate oil. We believe some of the Alaskan North Slope sediments we have examined fall in this category. However, these sediments have been so altered through deep burial and subsequent uplifting that it is difficult to distinguish the influence of depositional from later thermal alteration in these ancient sediments. Thus, the influence of depositional conditions on the petroleum generation process is not well understood and, therefore, has not generally been considered in exploration studies. This is an area where an oceanographic institution, with recent organic rich sediments from well defined depositional environments, can make a unique contribution. Work in our laboratory has been carried out on shallow sediments from many areas including the Persian Gulf, the Arabian Sea, the Gulf of Maine and Southwest Africa. Recent work has concentrated on two types of settings thought to be particularly important in formation of good petroleum source rocks: 1) sediments from the upwelling area off the coast of Peru and 2) sediments from the Mississippi River delta in the Gulf of Mexico. By characterizing organic matter in these recent sediments by a variety of techniques and then extending our results to deeper horizons, we hope to be able to recognize better oceanographic processes which operated in the past and left their imprint on ancient sediment.

Marine Photochemistry

Oliver C. Zafiriou

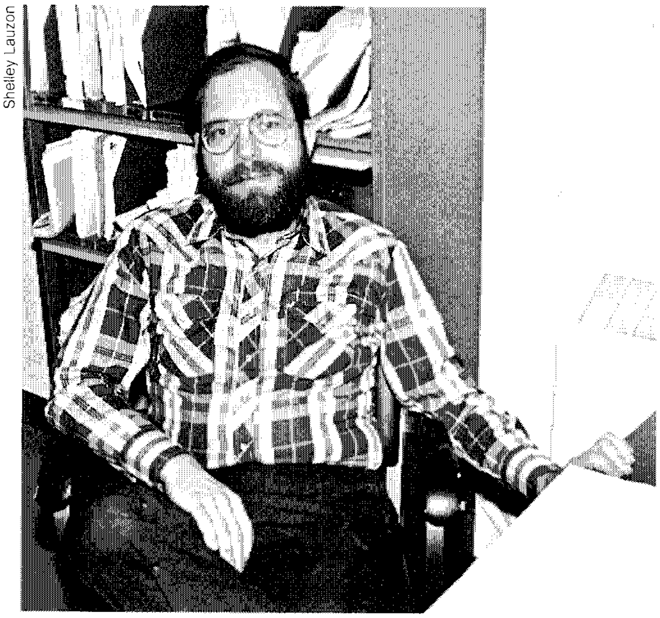
Sunlight warms surface waters and promotes the growth of photosynthetic organisms, thereby influencing the properties of the surface ocean. In the past decade, an extensive suite of more subtle chemical effects traceable to sunlight-induced reactions – photochemistry – has also been discovered. My colleagues and I initiated the first systematic studies of such processes in marine systems in the early 1970s at WHOI. A summary of our progress in the field and some current areas of research are described in this report.

In September 1983, we organized the first international scientific conference on "Natural Water Photochemistry," which took place at WHOI under the sponsorship of the NATO Scientific Affairs Programme. Some of the most important questions and points that have emerged from our studies and this conference concern the processes that are initiated by the absorption of light by molecules in the system. What are the light absorbing molecules in a given water mass? Where do they come from? What are the products of their photolysis; how do these interact further with the natural system? What is the efficiency of a given process? How is the balance maintained between production of light-sensitive compounds and their photochemical destruction?

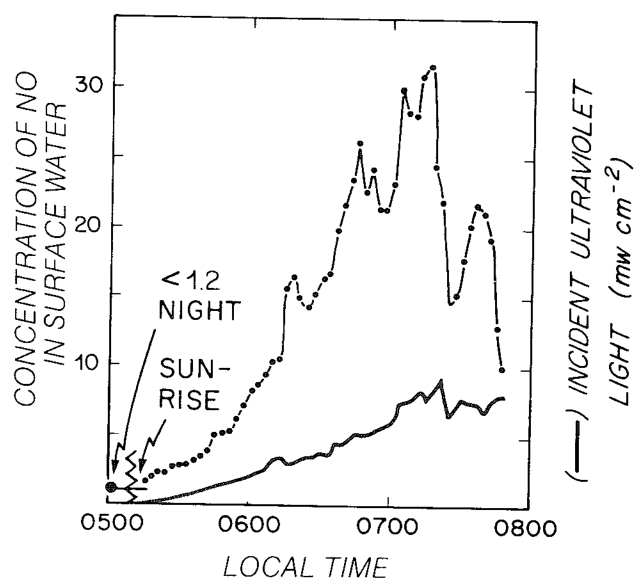
The earlier work in marine systems at Woods Hole focused on inorganic photochemistry in marine systems, particularly of nitrite and nitrate, two photochemically reactive species that are important as biologically available forms of fixed nitrogen – often a growth-limiting element in surface waters. Contrary to earlier work, it was found that nitrate is extremely stable to sunlight in seawater, while nitrite is lost at surface-light intensities at rates varying from about 2 to 25 percent per day. This wide variation is probably due to ill-understood effects of other trace components in the water, such as transition metals and unknown organic compounds. More recent work aims to break completely new ground in this area. It is known that many photochemical reactions produce free radicals – highly reactive molecules with an odd number of electrons – that go on to react further. For example, the photolysis of nitrite produces hydroxyl radical, famous as the "key" specxies in tropospheric chemistry. In many cases, formation of free radicals might be far more significant than the disappearance of the molecules that formed them.

In 1979, we detected for the first time a free radical (nitric oxide, NO) directly in surface seawater being exposed to sunlight. This technically-difficult observation is direct evidence of the presence of a radical in a natural water system under natural conditions, and

Shelley Lauzon



Ollie Zafiriou



Mantle Geochemistry

Mark D. Kurz

confirms the hypothesis that such species are formed by sunlight. Figure 1 shows how the detected radical concentration in surface waters of the equatorial Pacific, containing nitrite, rises after sunrise as the light intensity increases. Even though the radical is being formed rapidly, its concentration is low because it also reacts rapidly – in this case half of it is gone within about 100 seconds after formation. Other, more reactive radicals disappear much faster. For example, the OH radical mentioned above, which lasts about 1 second in the atmosphere, reacts in seawater in much less than a microsecond.

Encouraged by this success, we are now attempting to devise methods to detect the superoxide radical in natural water systems. It is probably formed photochemically, but could also have biological sources or come from dark chemical reactions. We are trying to measure superoxide, because it is a "key" species from both the chemical and biological points of view. Chemically, it forms in the first step in the reaction of dissolved oxygen, the major oxidizing agent in surface waters. Biologically, superoxide is thought to be ubiquitous in aerobic organisms, and to be responsible for cell damage leading to such diverse effects as ageing, death, and in people, arthritis. We hypothesize that formation of superoxide radical is ubiquitous in marine systems, and that most of it comes from photolysis of dissolved organic compounds. The new methods will hopefully have the extreme sensitivity necessary to test this hypothesis and enable us to investigate the concentrations, sources, and reactions of superoxide in surface waters.

Another area of interest has been the photochemical reactions that take place at the air-sea interface, where the average light intensitity is highest and surface films enriched in reactive components are often present. Although it is virtually impossible to make relevant measurements in this film, model calculations suggest that both photochemistry in the film and diffusion of highly reactive species from the atmosphere to the ocean surface may cause some unusual effects there. An heuristic model of these effects as they may influence the geochemical cycling of the element iodine in the ocean and atmosphere is shown in Figure 3.

Much of our understanding of the chemistry of the earth's mantle comes from studies of oceanic volcanic rocks. Despite the fact that the mantle, the region between the lower crust and the core of the earth, constitutes most of the mass of our planet, it is very difficult to sample. The basalts erupting in the ocean basins are of interest because the crust through which they pass is relatively thin, and they are essentially uncontaminated by it. To some extent, therefore, the products of melting in the mantle can be used as a "window" into the mantle. Isotope geochemistry is one of the most powerful means of studying these samples because, in many cases, shallow contamination processes are negligible.

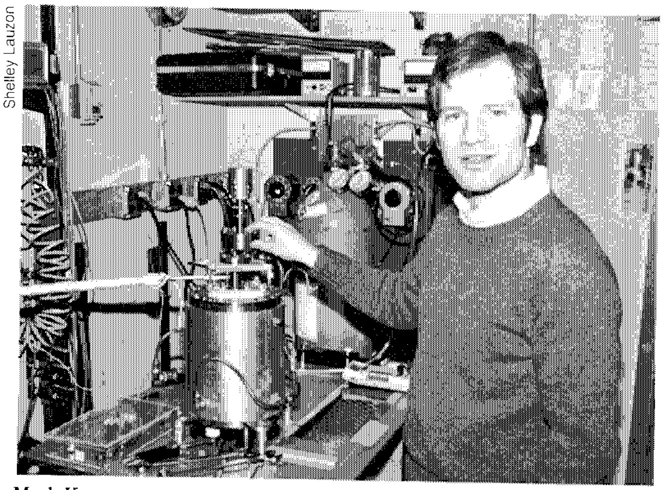
At WHOI, we have focused on the gases, particularly helium (He), in these basalts. The magmas erupted on the sea floor offer a great advantage to this type of research. They are erupted at great depth (mid-ocean ridges are an average 3 kilometers, 1.8 miles, deep) and at low temperature, so the molten rock is rapidly chilled to form glass. The glass traps some of the mantle-derived magmatic gases, uncontaminated by seawater or atmosphere. By analyzing the helium in the glasses, we can learn about their mantle source. There are two isotopes of helium: helium-4, which is produced by natural radioactive decay of thorium and uranium; and helium-3, whose major source is the gas trapped during earth formation 4.6 billion years ago. By measuring the ratio between these isotopes, we can search for "primitive" samples, i.e., those that come from segments of the mantle that have remained relatively undegassed for eons. For example, the basalts erupted at the islands of Hawaii and Iceland are enriched in the rare isotope helium-3 to a greater extent than mid-ocean ridge basalts. We infer that the island basalts are derived from a more undegassed "primitive" mantle source. In contrast, islands such as Tristan da Cunha and Gough consist of basalts with relatively less helium-3 when compared to mid-ocean ridge basalts, and are therefore derived from a less primitive source.

These variations within oceanic rocks have helped constrain structural models for the earth's interior. We now know that a minimum of three distinct mantle sources must exist. Although the real nature and origin of these mantle "types" is currently a matter of vigorous debate, one simple model to explain the observations would involve a layered mantle. In such a model, the lower mantle layer would be most primitive, having been isolated for a long period of time (perhaps as long as 4.5 billion years), and the less primitive upper mantle would be the source for mid-ocean ridge basalts. The third mantle source could be explained by a small amount of "recycled" oceanic crust and sediments that is reinjected back into the mantle at subduction zones and mixed with the ambient mantle. Developing this type of model requires information not only from the field of geochemistry but also from geophysics and fluid dynamics, which makes isotope geochemistry even more exciting to investigators.

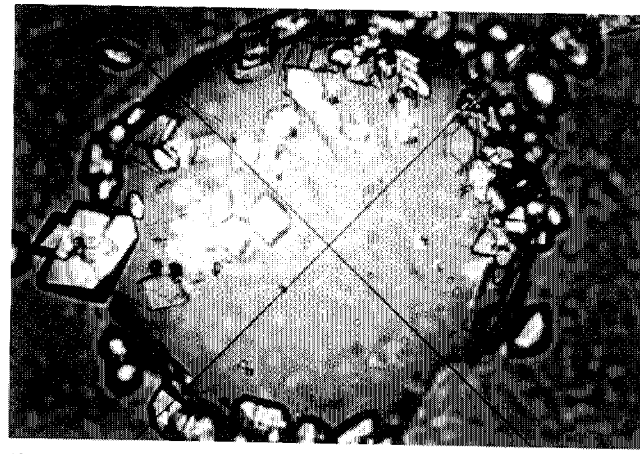
Basalts are not the only available material that can be used to study the mantle. Ultramafic zenoliths are fragments of the mantle that are brought directly to the surface by the violent action of a volcanic eruption. An interesting subset of this sample type now under study at WHOI are diamonds. Aside from their economic importance, diamond is unique as a mantle sample because it is formed at depths greater than 100 kilometers (62 miles). This alone makes it important since no other material can unequivocally be attributed to such great depths. The diamonds often contain microscopic mineral inclusions that are fragments of the mantle from which the diamonds formed. They offer clues to the formation conditions and hence to the origin of diamond. These inclusions drastically decrease the market value of any diamond because they are imperfections in the crystal structure, but increase the diamond's scientific value. We are studying the gases associated with the inclusions by breaking them in vacuum and measuring the gases that are released. Because diamond is the hardest substance known, it is difficult to break, and a sample must be heated to over 2000 °C in order to thermally release its gases. However, the microscopic features of these diamonds contain information that is well worth deciphering.

Another advantage of isotope techniques is their use for time evolution studies of the mantle using different parent-daughter pairs. For example, just as helium-4 is the stable daughter of thorium and uranium decay, xenon-129 is the stable daughter of short-lived iodine-129. Iodine-129 has a very short half-life (15 million years) and although it was present when the earth formed, there is no longer any naturally occurring iodine-129. Therefore, the variations in abundance of its stable daughter xenon-129 can be used to study the very early history of the earth. We are now expanding our gas measurement capabilities to include argon and xenon. The new solid source mass spectrometer, which will arrive in summer 1985, will allow us to measure the isotopes of strontium, neodymium and lead. Each isotope system has a unique story to tell, and when applied to the right samples can yield information about global processes.

Shelley Lauzon



Mark Kurz



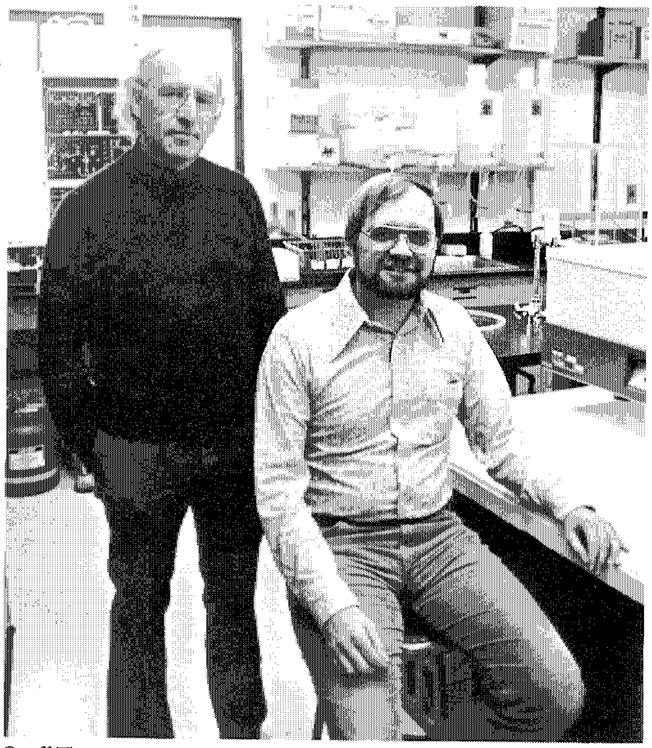
Above: Photomicrograph of a gas-containing bubble in a matrix of basaltic glass. The small crystals around the bubble are olivines that grew from the melt at the melt-bubble interface. The width of the field is 0.5 millimeters.

Right: Photograph of a one carat diamond, showing the original octahedral growth form of diamond. Two inclusions are visible near the center, one black chromite and the second a paler, colored garnet.

Interaction of Seawater with the Rocks of the Sea Floor

Geoffrey Thompson and Michael J. Mottl

Shelley Lauzon



Geoff Thompson and Mike Mottl

Artist's rendering of the hot spring on the axis of the East Pacific Rise at 10° 56′ north visited by *Alvin* in May 1984. The view is to the south. The dark area in the upper right represents the main axial rift valley. A mound comprised of spires of massive sulfides and active "black smoker" vents is shown in the center, perched on a three-meter high fault scarp. A collapsed lava lake with basalt pillars can be seen to the right. Drawn by S. McConnville from data collected by T. McConachy, M. Mottl and R. Von Herzen.

Reaction of seawater with igneous rocks on and in the sea floor is now recognized to have a major effect on the nature of the oceanic crust and on the composition of seawater itself. Appreciation of this effect has grown mainly over the past decade, during which seawater-fed hot springs were first discovered and sampled on the seafloor. These springs have been found mainly along the axis of the mid-ocean ridge system, where molten rock rises from the Earth's mantle to form new oceanic crust as the great tectonic plates of the earth's outer shell spread apart. We now know that seawater percolates downward through cracks in the newly formed crust, becomes heated by contact with the hot rock, and reacts with it, replacing the original minerals with a different assemblage and exchanging chemically with the rock in the process. The hot water which exits from the springs thus has a different composition from seawater, having gained some chemical species from the rock and lost others to it. The whole process thereby represents a net transfer of various chemicals from the oceans to the crust and vice versa.

It has been recognized since the 1950's that the rate of input of chemicals to the oceans via rivers, derived from the weathering of continental rocks, is very high compared to the amount of those same chemicals dissolved in the oceans. Thus the chemicals dissolved in the oceans could be supplied on a time scale that is very short compared to the age of the oceans. This implies that the ocean's dissolved salts are present in a nearly steady state condition, and that output processes and their rates relative to the input rates are the major mechanism controlling the composition of seawater. A major task in geochemistry has been to identify the important input and output processes and to determine their rates. Much of our research at WHOI on basalt-seawater interaction has focussed on this task.

The upper part of the igneous oceanic basement consists of basaltic lava. This basalt undergoes reaction with seawater over a range of temperatures, time and locale. The nature of the chemical reaction and the fluxes of ions exchanged between the oceans and the igneous basement are mostly dependent on the temperature of reaction and the relative proportion of the reactants. These vary in respect to the location of the water circulation and distance from the heat source. Four examples of seawater-basalt interactions are considered and the net exchange fluxes are calculated; these examples cover the range of temperature and water:rock ratios typically found in the ocean floor.

Estimates of Hydrothermal Fluxes between Oceanic Basement and Seawater

	x 10^{14} g/yr				x 10^{10} g/yr			
	Si	Ca	Mg	K	B	Li	Rb	Ba
Case A								
Surface	–0.006	–0.045	–0.03	+0.013	+0.45	+0.44	+0.14	+0.43
Basin	–0.52	–0.082	–0.26	+0.09	+2.69	+2.42	+1.37	+2.73
Flanks	–0.2	–0.47	–0.11	+0.22	+5.12	+3.7	+4.23	+1.1
Axis	–0.87	–1.3	+1.87	0.49	(–)*0	–111	–20.5	–46
Total	–1.60	–1.90	+	1.47	–0.17	+8.26	–104.54	–14.76
River	–1.99	–4.88	–1.33	–0.74	–47.0	–9.4	–3.2	–137.3
Basement Flux as % of River Flux	80.4	38.9	110.5	23.0	17.6	1112	461	30.4
Case B								
Surface	–0.006	–0.045	–0.03	+0.013	+0.45	+0.44	+0.14	+0.43
Basin	–0.52	–0.082	–0.25	+0.09	+2.69	+2.42	+1.37	+2.73
Flanks	–0.2	–0.47	–0.11	+0.22	+5.12	+3.7	+4.23	+1.1
Axis	–0.087	–0.13	+1.0	–0.049 (–)*0	–11.1	–2.05	–4.6	
Total	–0.82	–0.73	+0.6	+0.27	+8.26	–4.54	+3.69	–0.34
River	–1.99	–4.88	–1.33	–0.74	–47.0	–9.4	–3.2	–137.3
Basement Flux as % of River Flux	41.2	14.9	45.1	36.5	17.6	48.3	115.3	0.2

\+ = Gained by rock, lost from seawater
– = Lost from rock gained by seawater

Si (silicon), Ca (calcium), Mg (magnesium), K (potassium), B (boron), Li (lithium), Rb (rubidium), Ba (barium)

*Boron is not seen in the Galapagos vents but is at 21°N on the East Pacific Rise. Edmond (personal communication) believes the low temperature subsurface mixing at Galapagos results in B uptake from the hydrothermal solution. Calculation of the B flux for high temperature reaction will have to await the completion of analytical data for the 21°N vents.

Low temperature, high water:rock ratio is typical of the exchange in the upper few meters of the oceanic basement. only about 0.1% of new oceanic crust undergoes this reaction which extends over a time period of tens of millions of years. The annual fluxes produced are not very large. Low temperature, low water:rock ratio is typical of the reaction in the deeper parts of the oceanic basement. About 8% of newly formed oceanic crust can be expected to undergo this reaction over a period of a few million years. Reactions and fluxes on the flanks of mid-ocean ridge spreading centers are at moderate temperatures and water:rock ratios. These reactions are relatively short lived, but the fluxes produced are quite high. High temperature reaction of seawater and basalt (in excess of 100°C, 212°F) takes place at spreading center axes. These reactions are fast but result in very high fluxes and formation of polymetallic sulfides or iron and manganese oxides. The products of this reaction and the direction of exchange for some ionic species are quite different compared to the lower temperature reactions.

The net effect of the basalt-seawater exchange is the sum of all the reaction fluxes over the full temperature range. This calculated net flux indicates that the basalt is a source for ions such as Si, Ca, Ba, Li, Fe, Mn, Cu, Zn and hydrogen ions. It also is the sink for ions such as Mg, K, B, Rb, H_2O, Cs and U. The annual fluxes calculated for some of these species is of the same order of magnitude as the annual river influxes into the ocean.

1984 Degree Recipients

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

Doctor of Philosophy

ELLEN D. BROWN
B.A. Princeton University
Special Field: Physical Oceanography
Dissertation: *Eddy Forcing of the Mean Circulation in the Western North Atlantic*

DAVID A. CARON
B.S., M.S. University of Rhode Island
Special Field: Biological Oceanography
Dissertation: *The Role of Heterotrophic Microflagellates in Plankton Communities*

KA HOU CHU
A.B. University of California, Berkeley
Special Field: Oceanographic Engineering
Dissertation: *Sodium and Glucose Transport across the* in vitro *Perfused Midgut of the Blue Crab,* Calinectes sapidus *Rathbun*

HEIN J. W. DE BAAR
B.S., M.S. Delft University of Technology, Netherlands
Special Field: Chemical Oceanography
Dissertation: *The Marine Geochemistry of the Rare Earth Elements*

CHERYL ANN HANNAN
B.A., M.A. San Jose State University
Special Field: Biological Oceanography
Dissertation: *Initial Settlement of Marine Invertebrate Larvae: The Role of Passive Sinking in a Near-Bottom Turbulent Flow Environment*

RUI XIN HUANG
University of Science and Technology of China; Graduate College, University of Science and Technology of China
Special Field: Physical Oceanography
Dissertation: *The Thermocline and Current Structure in Subtropical/Subpolar Basins*

STEPHEN P. MEACHAM
B.A. Queen's College, Cambridge University
Special Field: Physical Oceanography
Dissertation: *Baroclinic Instability of a Meridionally Varying Basic State*

LAWRENCE P. SANFORD
Sc.B. Brown University
Special Field: Oceanographic Engineering
Dissertation: *Interaction of Internal Waves and the Bottom Boundary Layer on the Continental Shelf*

GLENN C. SASAKI
B.A. University of California, Berkeley
Special Field: Biological Oceanography
Dissertation: *Biochemical Changes Associated with Embryonic and Larval Development in the American Lobster* Homarus americanus *Milne Edwards*

PAUL E. SPEER
B.A. Williams College
Special Field: Marine Geology
Dissertation: *Tidal Distortion in Shallow Estuaries*

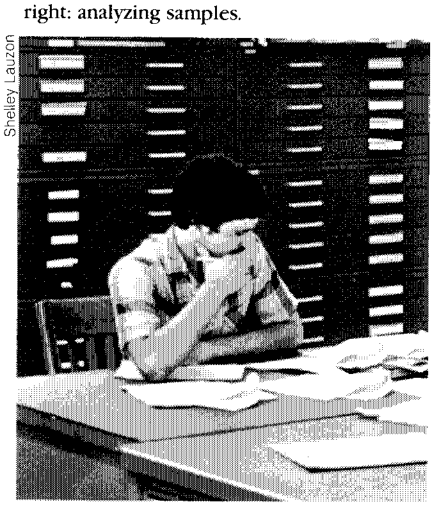
KAREN L. VON DAMM
B.S. Yale University
Special Field: Chemical Oceanography
Dissertation: *Chemistry of Submarine Hydrothermal Solutions at 21° North, East Pacific Rise and Guaymas Basin, Gulf of California*

Doctor of Science

HIROSHI KAWAHARA
B.S. Humboldt State University
Special Field: Oceanographic Engineering
Dissertation: *Asymptotic Analysis of Ocean Bottom Reflected Acoustic Fields*

Below: hard at work; center: box coring; right: analyzing samples.

Shelley Lauzon



Shelley Lauzon

Dean's Comments

Charles D. Hollister
Dean of Graduate Studies

The need has never been greater for more marine scientists, and yet graduate schools of oceanography are receiving fewer and fewer applications. We are struggling now with relatively small numbers to fulfill the increasingly complex and tantalizing agenda before us. During the past five years we have seen a steady decline in the number of applicants to graduate schools of oceanography, and among that pool, we have seen increasingly fewer applicants from the undergraduate fields of physics, mathematics and chemistry.

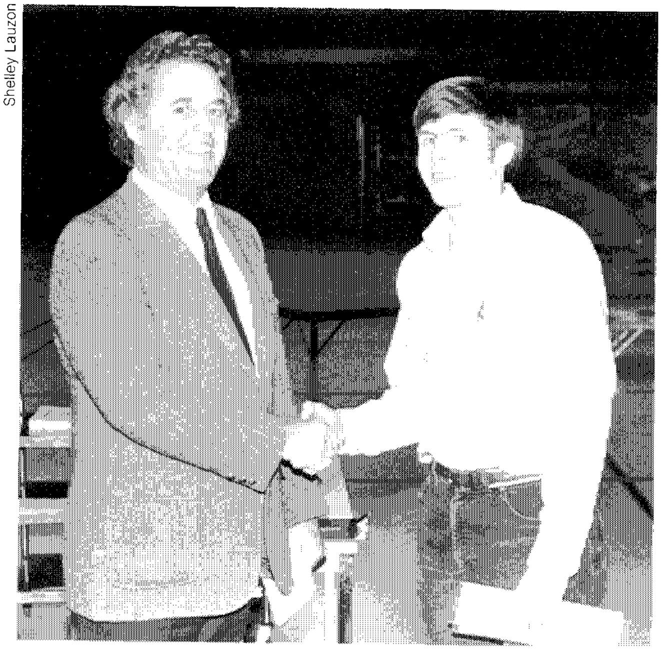
The steady decline in applicants, coupled with the spiralling growth of applied technology, such as the planned oceanographic satellites and their related marine science opportunities, may present us with a serious dilemma in five to ten years. Will there be enough well-trained oceanographers on hand to take full advantage of these new opportunites?

For the first time in more than a decade, we saw this year a decrease in the number of applicants to biological oceanography, the field that has always had the greatest number of applicants. These findings are based on information from the ten largest schools and institutions offering doctoral degree programs in all subfields of oceanography. At our annual Deans' "Retreat" at Scripps Institution of Oceanography in December, we agreed to begin as soon as possible a program at each of our schools to attract more physics graduates. We plan to invite physics teachers from nearby four-year colleges to summer "informational" seminars on physical oceanography, geophysics and oceanographic engineering. We hope to reach the undergraduate students and majors of physics through their teachers. There is no federal funding yet for such a program, and it addresses only part of the problem. But it is a start.

We also agreed to explore the feasibility of establishing a traineeship program at major national laboratories in an effort to give undergraduate students as much hands-on experience as possible with supercomputers and other systems still generally inaccessible to them.

Another conclusion from the Deans' meetings: We are just beginning to understand the importance of viewing the ocean through the eyes of more than one scientific discipline. We need to encourage our graduate students to follow their curiousity across the traditional barriers between highly-specialized fields so that they may understand, as we are only beginning to, the interaction between physics, biology, chemistry and geology in the ocean. Knowledge of these interactions lead us to fundamental insights into how the oceans work.

Shelley Lauzon



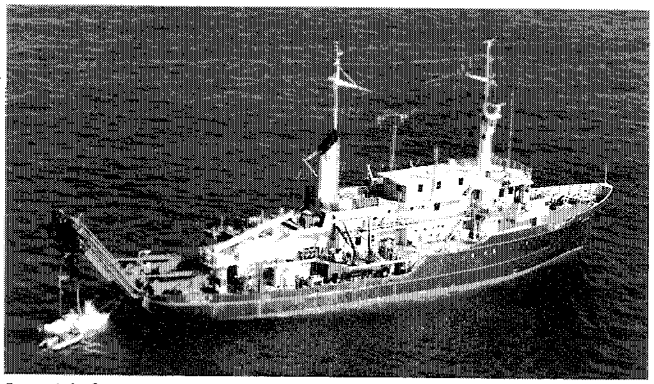
Dean Charles Hollister congratulates 1984 Falmouth Science Fair overall winner Roger Hayward. Roger received the Institution's $1,000 college scholarship.

Anne Rabushka

Jim Broda of the Geology and Geophysics Department explains core samples to visiting students.

Ashore & Afloat

Larry Workman



Sea trials for *Atlantis II/Alvin* operations off Charleston, South Carolina, in February.

Shelley Lauzon

Corporation Member Halsey Herreshoff spoke on the 1983 America's Cup defense at the spring Associates Dinners.

Dr. Edward Goldberg speaks with Mrs. Bostwick Ketchum and Director John Steele following the first Ketchum Lecture 30 April.

Shelley Lauzon

A new era of ocean exploration began 24 January when *Atlantis II*, with *Alvin* aboard, departed Woods Hole on Leg I of extended Voyage #112 to the Pacific. The departure ended a two-year mid-life refit and overhaul for the ship, during which time it was also converted to handle submersible operations. A 41-foot hydraulic A-frame designed and built by Caley Hydraulics Ltd. in Glasgow, Scotland, was installed on the fantail in 1983 for submersible launch and recovery; a new stern deck hangar enables the sub's crew to work under cover for the first time. Sea trials and inspections were held in late January-early February off Charleston, South Carolina, where the weather was considerably milder than in wintery Woods Hole. The first scientific dives using the new hoist system followed on the Blake Plateau in the western North Atlantic. After smoothing out a few bugs, the *Alvin* group was enthusiastic about the A-frame system, which allows quick deployment and recovery in sea conditions too rough for previous support vessel *Lulu*'s lift system.

Congressman Mervin M. Dymally of California spoke on "Science and Politics: Implications for Blacks in the 1980s" 3 February in Redfield Auditorium as part of a series of events in celebration of Black History Month. The February lectures were jointly sponsored by the Institution, National Marine Fisheries Service, Marine Biological Laboratory, and the U.S. Geological Survey.

In February, the Institution received a $650,000 four-year grant from The Andrew W. Mellon Foundation to support ongoing research and new initiatives at the Coastal Research Center. The Foundation provided $750,000 in 1980 to support professional staff at the Center for five years and established a flexible fund for response to emerging research opportunities in coastal studies.

Director John H. Steele met with local media representatives, the Falmouth Board of Selectmen, and community groups in February and March to discuss the Institution's opposition to a proposed bylaw to make Falmouth a nuclear-free zone. A letter from the Director explaining the management decision to oppose the proposed bylaw appeared in the employee *Newsletter*. The Director stressed that the Institution "is involved predominantly with basic research in the ocean. This is our mission in which we take great pride, but which carries concomitant duties. My concern is with the ability of our scientists to carry out their research freely and with the responsibility of the Woods Hole Oceanographic Institution not only to our community but to the national interest." Considerable discussion of the issue took place throughout the Institution and in the press. The proposed bylaw was indefinitely postponed at Town Meeting in April.

Once again *Alvin* dives in support to geological studies revealed an unexpected and unusual animal community, this time in the Gulf of Mexico. An oasis of exotic marine life, similar to that found at hydrothermal vents in the eastern Pacific, was discovered 9 March during dives on the West Florida Escarpment off Tampa, Florida. The community, the first found outside the eastern Pacific, was discovered at a depth of approximately 10,000 feet during erosion studies on the Escarpment, a steep slope leading to the floor of the Gulf of Mexico. Unlike the Pacific communities, this oasis does not occur at a spreading center or plate boundary and is not associated with high temperatures. Florida's aquifers are thought to supply the sulfur that supports the food-producing processes of the chemosynthetic bacteria.

Director John Steele, Associate Director of Research Derek Spencer, and Ocean Engineering Department Chairman Robert Spindel visited Southeastern Massachusetts University (SMU) in North Dartmouth 13 March to discuss possible research collaboration with SMU Dean of Faculty and Graduate Studies Donald Douglas and others. In 1983 Governor Michael S. Dukakis proposed Centers of Excellence throughout Massachusetts and indicated WHOI as a major factor in designating southeasten Massachusetts the Center of Excellence in Marine Science.

Falmouth High School Senior Roger Hayward was the 1984 recipient of the Institution's $1,000 college scholarship as the overall winner of the sixth annual Falmouth Science Fair 17 March at Falmouth High School. Roger's project on computer-aided analyses in aerodynamics also won a third place award in the prestigious Westinghouse Science Talent Search. He is the son of Research Assistant Nancy Hayward of the Chemistry Department.

A $133,000 grant from The Tinker Foundation was received in March to support a three-year project on the development of a marine management plan for Ecuador's Galapagos Islands. A four-member team from the Marine Policy and Ocean Management Center visited the Islands in the summer of 1983 to gather data for the Presidential High-Level Commission, which is developing a Master Plan for the Galapagos Islands to cover coastal and marine resource management.

The Coastal Research Center's Rapid Response Funds allowed Institution scientists to coordinate initial contacts and monitor the grounded freighter *Eldia* on Nauset Beach. The vessel ran aground during a 29 March storm and was refloated with considerable effort six weeks later. Geologist David Aubrey, a member of the Rapid Response Team, has conducted extensive studies on sediment transport and erosion in the area of the grounding and was able to provide important information to the salvage effort.

Two hundred twenty-five Associates and guests attended the annual spring dinner 18 April at the Boston Museum of Science and 90 attended the New York dinner a week later at the Lotos Club. Corporation Member Halsey Herreshoff, navigator on the 1983 American defender *Liberty*, spoke about "The America's Cup 1983 Defense and the Future" in an illustrated lecture. Poster displays on oceanographic instrumentation and careers in oceanography provided background during the cocktail hours.

The first Bostwick H. Ketchum Award was presented 30 April to Dr. Edward D. Goldberg, Professor of Chemistry at the Scripps Institution of Oceanography, for his "pioneering efforts and continuing leadership in environmental quality research in coastal and open ocean areas of the world." More than 150 employees and guests of the Institution attended the award presentation in Redfield Auditorium and reception at Endeavour House. Dr. Goldberg, an internationally-known marine geochemist, spoke on "Informational Needs for Ocean Waste Disposal." His lecture focused on who makes the decision as to how much information is needed in order to pursue a course of action.

Knorr returned to Woods Hole 11 May after a 10-month voyage to the South Atlantic. Scientific activities during the cruise involved primarily geological, geochemical, and physical oceanographic studies. The ship spent nearly two months of the voyage in the Antarctic.

Thirty-five new Associates and their guests had an opportunity to learn more about Institution activities during their visit 25 May. The group heard several presentations and toured the Environmental Systems Laboratory, Coastal Research Laboratory, and McLean Laboratory.

Institution Biologists J. Frederick Grassle, Holger Jannasch, and Peter Wiebe were among the 269 Fellows of the American Association for the Advancement of Science (AAAS) elected during the group's annual meeting 24-29 May in New York City.

Physical Oceanographer Henry Stommel was elected a Foreign Associate of the Academie des Sciences of France. The Academie was founded in 1666 by Louis XIV and is equivalent to the U.S. National Academy of Sciences.

A new methane-producing bacterium which thrives in hot deep sea hydrothermal vents has been named for Institution Microbiologist Holger Jannasch. *Methanococcus jannaschii* is significant because it is the first methane-producing bacterium to grow at extremely high temperatures and at a very fast rate. The senior scientist was also honored with election as a Corresponding Member of the Gottingen Academy of Sciences in West Germany. The Academy was founded in 1751 and is limited to 120 regular and corresponding members.

David Ross, Director of the Marine Policy and Ocean Management Center, and George Grice, Associate Director for Scientific Operations, spent a week in Jordan during May meeting with representatives of various marine science facilities to develop and define priorities for a potential U.S.-Jordanian cooperative program.

Shelley Lauzon

Roger Goldsmith explains computer graphics equipment during the June Associates Dinner Open House at IPC.

Anne Rabushka

Shelley Lauzon

Above: Senator Edward Kennedy visited WHOI in November and discussed ocean research funding with staff members in the *Oceanus* galley.

Left: Director John Steele presents an aerial view of Woods Hole and a 30-year pin to R. Lorraine Barbour in ceremonies 14 December.

Twenty-four Trustees, Honorary Trustees, and Trustees-elect assembled 21 June prior to the Annual Meetings for a meeting and dinner. The following day, fifty-six Corporation Members and Trustees attended the Annual Meetings. Associate Scientist G. Michael Purdy presented the science report on "The Seismic Structure of Oceanic Lithosphere." A highlight of the day's activities was the presentation of the ninth Henry Bryant Bigelow Medal to Physical Oceanographer Arnold L. Gordon of Lamont-Doherty Geological Observatory for his work in the Antarctic. The medal, established by the Trustees in honor of WHOI's first Director, is awarded to those who make significant inquiries into the phenomena of the sea. Dr. Gordon was recognized for his "dedication in completing the Antarctic Circumpolar Survey" and for his "continuing scientific leadership in Antarctic oceanography." Later that evening, after Open Houses at the Information Processing Center, radiocarbon laboratory in McLean Laboratory, and the Coastal Research Laboratory, three-hundred forty Trustees, Corporation Members and Associates attended the annual Woods Hole dinner under a tent on the Fenno House grounds.

Alvin celebrated its 20th birthday in June hard at work in the eastern Pacific engaged in its first dives on the Gorda and Juan de Fuca Ridges off the Oregon and Washington coasts. *Alvin* was commissioned 5 June 1964; through the end of 1984 the sub had made 1,502 dives. During the Juan de Fuca Ridge dives scientists discovered exotic marine life and black smokers like those found further south along the East Pacific Rise.

The Penzance Foundation made a $100,000 award to the Institution, to be used at the discretion of Director John Steele. In accepting the award, Dr. Steele noted the "immense value" of unrestricted grants in allowing the Institution to take initiatives that would not otherwise be possible. The Penzance Foundation was established through the estate of the late Edna McConnell Clark and W. Van Alan Clark.

Twelve doctorates were awarded in the MIT/WHOI Joint Program in 1984, bringing the total number of degrees awarded since the program was founded in 1968 to 144 doctorates and 21 engineers degrees. Three WHOI degrees have also been awarded, for a total of 156 degrees. The 1984 entering class consisted of twenty-one students, including eight women and four foreign students. Susan Allen, a physics major from Queens University in Canada, received the Paul M. Fye Fellowship as the outstanding applicant.

Associate Scientist Frank Carey of the Biology Department got a rare chance to study a great white shark when a 654-pound specimen was brought to the Institution 23 July for dissection. The 11-foot juvenile shark was donated to the National Marine Fisheries Service and Dr. Carey by fishermen who captured it in Cape Cod Bay.

The Board of Ocean Science and Policy (BOSP), organized by the National Research Council of the National Academy of Sciences and the National Academy of Engineering, met 27-31 August at the Carriage House on the Quissett Campus to discuss "Oceans 2000," a major study of future trends and new opportunities in ocean science and policy to the year 2000. Director John Steele and President Paul Fye are members of the Board.

Ninety Associates and guests were treated to the antics of a score of humpback whales during the annual whale watch expedition 7 September off Provincetown aboard the charter vessel *Dolphin IV.*

After nearly twenty years of service as *Alvin*'s support vessel, *R/V Lulu* departed Woods Hole 18 September on her last voyage, a transit cruise to San Diego to begin a new career as support vessel for the Navy submersibles *Sea Cliff* and *Turtle.* A bit of a scare occurred shortly after the 44-day transit began when radio contact with *Lulu* was lost for several days; the culprit turned out to be a tempermental radio. *Lulu* arrived safely in San Diego on 31 October and was officially transferred to the Navy on 14 December.

The tenth annual meeting of the International Association of Marine Science Libraries and Information Centers was held in Woods Hole 2-5 October. More than 100 from 21 states and seven foreign nations attended the conference, the third in Woods Hole. Research Librarian Carolyn Winn is Past President and founding organizer of the group.

Coastweek 84 was celebrated 6-14 October, during which time more than 500 visitors toured the Exhibit Center at Endeavour House. As part of the week's activities, fifty local officials directly involved in environmental management decisions attended a 13 October workshop in Redfield Auditorium to discuss issues affecting Cape Cod and the Islands. Topics were shellfish and public health, chemical use for pest control, coastal pond pollution, protection of coastal banks and beaches, and interaction between conservation commissions and the state Department of Environmental Quality Engineering. The workshop was jointly sponsored by the Institution's Coastal Research Center and Sea Grant Program and the Cape Cod Coalition of Conservation Commissions.

The Coastal Research Center received a three-year $250,000 grant from the Richard King Mellon Foundation to support ongoing research and new initiatives.

Thirty-year service awards were presented 14 December to employees R. Lorraine Barbour, Richard S. Edwards and Michael Palmieri, Jr., in ceremonies in Clark 507 as friends, family members, and colleagues stood by. Eleven individuals who retired in 1984, representing 265 years of service, were also honored.

More than 170 employees and guests attended the annual Institution Christmas Party 15 December at the New Seabury Inn and Country Club.

Among the many visitors to the Institution during the year were Secretary of the Navy John F. Lehman, Jr., who visited in July, Oceanographer of the Navy Captain John R. Seesholtz, who visited in August, and deans from the service academies who spoke with WHOI Dean Charles Hollister about possible educational collaboration. Thirty-four nations were represented in the Naval Command College class of senior officers which visited the Institution 1 June. The International Commission for the Conservation of Antarctic Living Marine Resources held a workshop 11-15 June at Carriage House on data collection and handling; Director John Steele, a member of the Commission, was one of 30 attending the meeting. "Forensic Oceanography – Tides and Currents" was the topic of Associate Scientist Kenneth Brink's lecture to 100 Harvard Associates in Police Science during the group's visit 27 June. Representatives of *Planet Earth,* a new public television series and university telecourse produced by WQED/Pittsburgh in association with the National Academy of Sciences, conducted a series of preliminary interviews with Institution scientists in August. The series, scheduled to air in the fall of 1985, is being funded by the Annenburg/CPB project and IBM. The Ocean Industry Program sponsored two September meetings: "Slope Oceanography" was attended by fifteen and "Geochemistry of Sealevel Changes" attracted seventeen participants. Dr. George Cahill, Director of Research at the Howard Hughes Medical Institute, discussed possible research collaboration during a September visit. More than one hundred twenty-five members of the Association of Engineering Geologists participated in a Columbus Day field trip to Woods Hole. The 12 October meeting on "Deep Seismic Reflectors on Continental Shelves" sponsored by Senior Scientist James Heirtzler of the Geology and Geophysics Department attracted fifty-five participants. Ten Vannevar Bush Fellows spent 18 October talking with staff scientists and visiting research laboratories; the Fellowship Program at MIT allows journalists to take courses and visit research centers in New England in an attempt to make them better prepared to report on science and technology.

Publications

1984 Publications of record as of 1 March 1985. Institution contribution number appears at end of each entry. 1982 and 1983 publications not listed in 1983 Annual Report are included here; the date appears in parenthesis preceding the contribution number.

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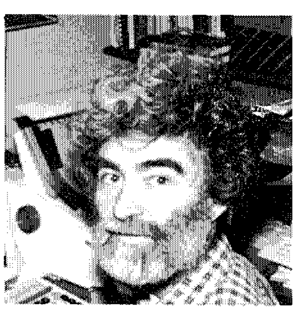

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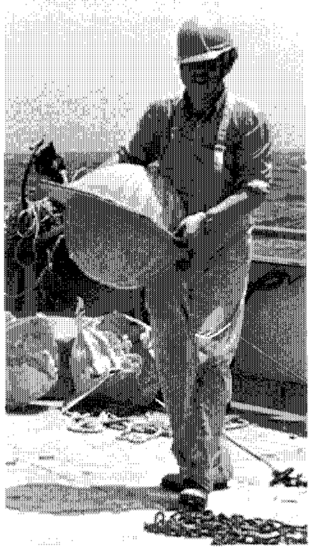

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Bob Ballard

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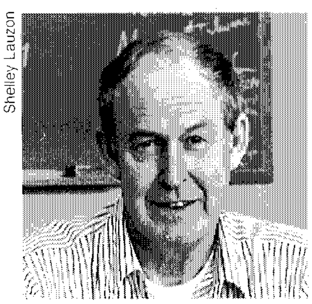

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Eric H. Frank, Jr. . . . . . Systems & Procedures Manager
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Ellen M. Gately . . . . . Sea Grant Administrator
Gordon K. Glass . . . . . Executive Assistant/Ocean Engineering
Arthur T. Henderson . . . . . Purchasing Manager
Hartley Hoskins . . . . . Coordinator, Ocean Industries Program
Charles S. Innis, Jr. . . . . . Executive Assistant to Director/Security Officer
Philomena S. Jenney . . . . . Development Administrator
Susan Kadar . . . . . Executive Assistant/Chemistry
Victoria A. Kaharl . . . . . Science Writer/Assistant to the Dean
Judith L. Kleindinst . . . . . Executive Assistant/Biology
Shelley M. Lauzon . . . . . Publications & Information Manager
Virginia A. LeFavor . . . . . Accounting Operations Administrator
Charlene R. Lewis . . . . . Marine Policy Administrator
Jack N. Lindon . . . . . Assistant Personnel Manager (Benefits/Marine Employment)
Frank L. Lowenstein . . . . . Assistant Editor, *Oceanus*
Shirley-Anne Long . . . . . Personnel Administrator
#Carolyn B. Miller . . . . . Affirmative Action Administrator
David J. Miller . . . . . Assistant Sponsored Programs Administrator
Elizabeth A. Miller . . . . . Assistant Editor, *Oceanus*
Mozart P. Moniz . . . . . Assistant Purchasing Manager
Theresa G. Monroe . . . . . Benefits Administrator
Laura A. Murphy . . . . . Payroll Administrator
A. Lawrence Peirson III . . . . . Assistant Dean & Registrar
Anne I. Rabushka . . . . . Public Information Officer
Christine M. Rinaldi . . . . . Executive Assistant/Development
R. David Rudden, Jr. . . . . . Assistant Controller
Paul R. Ryan . . . . . Editor, *Oceanus*
C. L. Roy Smith . . . . . Executive Assistant/Geology & Geophysics
Maurice J. Tavares . . . . . Sponsored Programs Administrator
#Harold R. VanSiclen, Jr . . . . . Assistant Controller for Accounting Operations
Gary B. Walker . . . . . Controller
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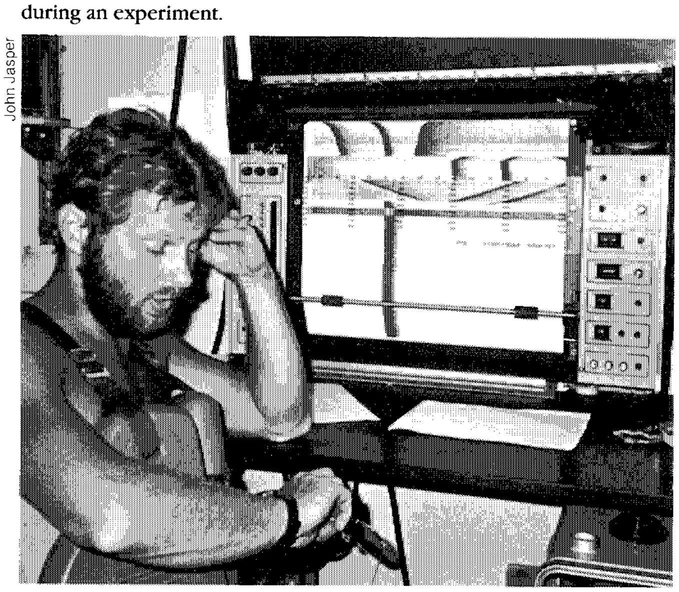
Mary Nan Weiss . . . . . Executive Assistant/Associates Program
Barbara Wickenden . . . . . Personnel Manager
Claire R. Xander . . . . . Executive Assistant/Physical Oceanography
Bernard L. Zentz . . . . . Personnel Manager

Steve Manganini checks the time during an experiment.



John Jasper

Diana Franks prepares microbiological samples.

Shelley Lauzon

Facilities, Services and Marine Operations Staff

Reuben R. Baker, Jr.	Master, R/V *Atlantis II*
John P. Bizzozero	Chief Engineer, R/V *Atlantis II*
Edward L. Bland, Jr.	Research Associate, *Alvin* Operations
Richard J. Bowen	Master, R/V *Knorr*
Richard S. Chandler	Manager, Shipboard Scientific Support Group
Ernest G. Charette	Assistant Facilities Manager
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Dudley B. Foster	Pilot, DSV *Alvin*
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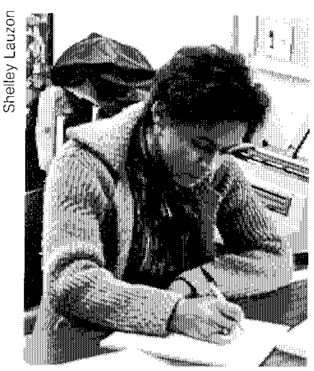

Beth Andrews

Kittie Elliott

Anne Rabushka

Kevin Kay

Mel Briscoe

Shelley Lauzon

Anne Rabushka

Shelley Lauzon

Top: Tom Kleindinst; left: Laurel Swain; right: Pat Garcia

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Albert Santiago, Sr.
Roland R. Simmons
Robert Wichterman

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Patricia E. Thompson

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Kittie E. Elliott
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+Henry P. Hirschel
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Albert C. Jefferson
John P. Kamataris
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Stephen D. Murphy
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Michael Palmieri, Jr.
Randall B. Perry
#Samuel F. Pierce
Joseph Ribeiro
#Harry Rougas
+Douglas L. Shores
Richard F. Simpkin
Ernest G. Smith, Jr.
+Harry H. Stanton
John K. Sweet, Jr.
Herman Wagner
Stephen T. Wessling
Linda G. Wilson
Jonathan M. Wood

\+ Leave of Absence
\# Disability Leave of Absence

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University of Hawaii

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Colorado State University

Gaboury Benoit
Yale University

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Bowling Green State University

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Janice I. Campbell
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+ Paola Cessi
University of Bologna, Italy

+ Emily H. Childs
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Northeastern University

Joon Won Choi
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+ Not registered

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Ellyn Montgomery launches an XBT from *Oceanus.*

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Sophie Wacongne
University of Pierre and Marie Curie, France
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Michael S. Wengrovitz
Southern Methodist University
University of Virginia
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Tamara M. Wood
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Kurt Fristrup
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Ann McNichol prepares samples in a nitrogen atmosphere for studies of anoxic sediments.

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Brookhaven National Laboratories

Shelley Lauzon

E. Paul Oberlander and John Cook at work in Graphic Services.

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National University of Engineering, Peru

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Yale University

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Carleton College

Theodore G. Shepherd
Massachusetts Institute of Technology

Samuel M. Welch
University of New Hampshire

Nicole L. Wolf
Kalamazoo College

Voyage Statistics

R/V *Lulu*

Total Nautical Miles for 1984 – 5,143 miles
Total Days at Sea – 35 days

Voyage	*Cruise Period*	*Principal Objectives, Area of Operations*	*Ports of Call (Destination)*
	7 Jun-7 Jun 25 Aug-26 Aug	To shipyard From shipyard	Boston Woods Hole
121	18 Sep-29 Oct	Transit to San Diego for transfer to Navy, COMSUBDEVGRU ONE for use with Navy submersible SEA CLIFF	Rodman Naval Base Balboa Acapulco, Mexico San Diego, California

R/V *Lulu* spent the first five months of the year at the Woods Hole pier awaiting word on Navy plans for the vessel. Commencing 1 June 1984 WHOI personnel began preparation to deliver *Lulu* to the Boston Shipyard Corporation for certain repairs and overhaul as required in order to bring the ship to readiness condition for delivery to Submarine Development Group ONE in San Diego, CA. On 14 December, after repairs and transit had been completed, responsibility for *Lulu* was passed to Tracor Marine in San Diego.

R/V *Knorr*

Total Nautical Miles for 1984 – 26,500 miles
Total Days at Sea – 186 days

Voyage	*Cruise Period*	*Principal Objective, Area of Operations*	*Ports of Call (Destination)*	*Chief Scientist*
104-VI	11 Jan-19 Feb	Hydrographic stations and data collection on the general circulation of the South Atlantic and southern oceans	Punta Arenas, Chile	Nowlin (TAMU)
104-VII	28 Feb-13 Mar	Hydrographic and XBT stations in the Falkland and Brazil Currents for biological studies of the western South Atlantic	Recife, Brazil	Hart Watson
104-VIII	17 Mar-7 Apr	Studies of the dynamic response of the upper equatorial Atlantic Ocean to seasonally varying surface winds for the SEQUAL program	Dakar, Senegal	Weisberg (NCS)
104-IX	14 Apr-21 Apr	Hydrographic station in the eastern North Atlantic for chemical studies	Ponta Delgada, Azores	Ferek (FSU)
104-X	24 Apr-11 May	Deployment of a sediment trap mooring, box coring, and hydrographic stations for studies of marine phytoplankton, foraminifera and pore water chemistry	Woods Hole	Corliss Andreae (FSU)
105	15 May-16 May 12 Aug-13 Aug	To shipyard From shipyard	East Boston Woods Hole	
106	18 Aug-28 Aug	Geological and ocean engineering studies at the High Energy Benthic Boundary Layer Experiment (HEBBLE) site to characterize the effects of the Western Boundary Undercurrent on the Nova Scotian continental rise	Woods Hole	Hollister
107	5 Sep-9 Sep	Engineering tests of newly developed deep ocean vehicles	Woods Hole	Marquet
108	14 Sep-24 Sep	Performance evaluations of the ARGO testbeds and other deep sea floor exploration tethered vehicle systems	Woods Hole	Ballard
109	2 Oct-2 Oct	Navy inspection	Woods Hole	
110-I	12 Oct-22 Oct	Deployment of three free-drifting buoy systems for the Real-Time Link and Aquisition Yare System (RELAYS) program	Bridgetown, Barbados	Walden
110-II	25 Oct-15 Nov	Collection of sediment core samples from the Ceara Rise in the equatorial Atlantic	Bridgetown, Barbados	Curry Lohmann
110-III	18 Nov-28 Nov	Recovery of three RELAYS buoy systems deployed on Leg I	Woods Hole	O'Malley
111	9 Dec-18 Dec	Continuation of geological and ocean engineering studies at the HEBBLE site	Woods Hole	Hollister

Anne Rabushka

Larry Workman

Rod Catanach

Top: *Knorr* returns home in May after a 10-month South Atlantic cruise. Left: Testing the new *Alvin* lift system aboard *Atlantis II* during sea trials in February. Above: *Lulu* departs Woods Hole for San Diego and a new career in September.

R/V Oceanus

Total Nautical Miles for 1984 – 22,581 miles
Total Days at Sea – 250 days

Voyage	Cruise Period	Principal Objectives, Area of Operations	Ports of Call (Destination)	Chief Scientist
144	9 Jan-19 Jan	Deployment of five subsurface current meter moorings in the core of the Gulf Stream east of Cape Hatteras	Woods Hole	Watts (URI)
145	22 Jan-29 Jan	Deployment of a surface current meter mooring, CTD and XBT stations at the Long Term Upper Ocean Study (LOTUS) site at 34°N, 70°W	Woods Hole	Briscoe
146	1 Feb-7 Feb	Collection of samples for the continuing Georges Bank Sediment and Organism Monitoring Program	Woods Hole	Petrecca Hampson
147	13 Feb-18 Feb	Deployment of moored instrumentation for the Shelf Edge Exchange Processes (SEEP) program	Woods Hole	Hopkins (BNL)
148	23 Feb-8 Mar	Continuation of studies for the SEEP program and a hydrographic survey on the continental shelf and slope south of Long Island	Woods Hole	Smith (BNL)
149	12 Mar-19 Mar	Recovery and deployment of subsurface moorings and tripods, hydrographic survey across the outer shelf and slope from 68°W to 71°W	Woods Hole	Butman (USGS)
150	22 Mar-28 Mar	Retrieval of seven subsurface moorings for the SEEP program, CTD and XBT stations	Woods Hole	Biscaye (LDGO)
151	1 Apr-12 Apr	Continuation of studies for the SEEP program, recovery of eight moorings, deployment/recovery of sediment traps, CTD and box core stations	Woods Hole	Whitledge (BNL)
152	17 Apr-1 May	Continuation of studies for the SEEP program, deployment of seven subsurface moorings, CTD and XBT stations	Woods Hole	Biscaye (LDGO)
153	2 May-10 May	Biological studies to assess the impact of exploratory drilling on benthic communities in Lease Block #372 off Cape May, New Jersey, at 38°36'N,72°55'W	Woods Hole	Petrecca Grassle
154	16 May-23 May	Recovery of five current meter moorings from the LOTUS site, CTD and XBT stations	Woods Hole	Briscoe
155	13 Jun-1 Jul	Water column measurements of the carbon dioxide content of seawater related to meteorological and biological observations	Woods Hole	Brewer
156	5 Jul-5 Jul 22 Jul-22 Jul	To shipyard From shipyard	Newport, Rhode Island Woods Hole	
157	29 Jul-31 Jul	Studies of internal gravity waves in Massachusetts Bay generated by the interaction of the semi-diurnal tide with Stellwagen Bank	Woods Hole	Joyce
158-I	8 Aug-3 Sep	Diving, mid-water trawling, and plankton net tows to assess feeding behavior and energetics of gelatinous zooplankton	Ponta Delgada, Azores	Madin
158-II	9 Sep-6 Oct	Studies of Mediterranean salt lenses in the Canary Basin, CTD and XBT stations, deployment of SOFAR (Sound Fixing and Ranging) floats	Funchal, Madeira	Armi (SIO)
158-III	8 Oct-23 Oct	Deployment of a net of Autonomous Listening Stations (ALS) and a cluster of SOFAR floats in the Canary Basin centered at 31°N, 23°W	Ponta Delgada, Azores	Valdes
158-IV	26 Oct-5 Nov	Deployment of 15 SOFAR floats southwest of the Azores near 33°N, 33°W, three transponding beacons at 38°N, 59°W, and one SOFAR float at 40.5°N, 63°W	Woods Hole	Owens
159	13 Nov-20 Nov	Recovery of six subsurface current moorings, three surface buoys, one bottom tripod, and a hydrographic survey as part of the USGS Slope Experiment	Woods Hole	Butman (USGS)
160	27 Nov-10 Dec	Box cores and hydrographic casts to investigate the impact of exploratory drilling activities on benthic communities on the Mid-Atlantic Continental Slope off the New Jersey/Delaware coast	Woods Hole	Petrecca Grassle
161	14 Dec-17 Dec	Recovery of four subsurface moorings at 36°14'N, 73°30'W	Woods Hole	Spiesberger

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

Total Nautical Miles for 1984 – 15,900
Total Days at Sea – 274
Total Dives – 174

Voyage	*Cruise Period*	*Principal Objectives, Area of Operations*	*Ports of Call (Destination)*	*Chief Scientist*
Trial	12 Jan-12 Jan	Test of DSV *Alvin* handling system	Woods Hole	
112-I	24 Jan-27 Jan	Transit to warmer climate for testing and certification of DSV *Alvin* handling system	Charleston, South Carolina	Grice
Trial	31 Jan-31 Jan	Test of DSV *Alvin* handling system	Charleston, South Carolina	
112-II	3 Feb-15 Feb	Studies of abyssal bedforms created by deep-sea currents on the Blake Plateau; four *Alvin* dives	West Palm Beach, Florida	Flood (LDGO)
112-III	18 Feb-2 Mar	Four dives off the northern Bahamas to study carbonate deposition, five dives at the AUTEC Range in the Tongue of the Ocean for inspection and servicing of various arrays	Andros Island Tampa, Florida	Neumann (UNC) Ricci (NUSC)
112-IV	6 Mar-19 Mar	Studies of slope evolution and biological communities on the West Florida Escarpment; seven *Alvin* dives	Cristobal, Panama	Paull (SIO)
112-V	26 Mar-18 Apr	Chemical and biological studies of the sediment-water interface in the Pacific Guatemala Basin; fifteen *Alvin* dives	Acapulco, Mexico	Grassle
112-VI	24 Apr-14 May	Exploration and sampling of hydrothermal vents on the East Pacific Rise; seventeen *Alvin* dives	Acapulco, Mexico	Craig (SIO) Edmond (MIT)
112-VII	17 May-26 May	Continuation of studies of East Pacific Rise hydrothermal vents; six *Alvin* dives	Manzanillo, Mexico	Mottl Von Herzen
112-VIII	29 May-23 Jun	Geological studies of two volcanoes on the East Pacific Rise; seventeen *Alvin* dives	San Diego, California	Batiza (WU)
112-IX	5 Jul-26 Jul	Studies of rift morphology and vent deposits on the Gorda and Juan de Fuca Ridges; sixteen *Alvin* dives	Newport, Oregon	Malahoff (NOAA)
112-X	30 Jul-16 Aug	Sixteen dives off the central Oregon and southern Washington coasts for geological studies	Astoria, Oregon	Kulm (OSU)
112-XI	20 Aug-10 Sep	Studies of crustal accretion processes on the Juan de Fuca Ridge; nineteen *Alvin* dives	Astoria, Oregon	Delaney (UW) Johnson (UW)
112-XII	14 Sep-5 Oct	Continuation of studies of the structural and metallogenic processes on the Juan de Fuca Ridge; nine *Alvin* dives	San Diego, California	Normark (USGS)
112-XIII	12 Oct-29 Oct	Observation and sampling of young cratered volcanic seamounts off the California coast for geological and biological studies; twelve *Alvin* dives	San Diego, California	Lonsdale (SIO) Levin (UNC)
112-XIV	2 Nov-3 Nov	Orientation of Navy personnel and one dive to test and evaluate *Alvin* navigation systems	San Diego, California	Walden
112-XV	7 Nov-11 Nov	Five dives for engineering tests of ALVIN sampling equipment	San Diego, California	Childress (UCSD)
112-XVI	17 Nov-30 Nov	Ecological energy transfer studies of the benthic boundary layer in the Santa Catalina Basin; twelve *Alvin* dives	San Diego, California	Smith (SIO)
112-XVII	4 Dec-10 Dec	Studies of feeding activities of zooplankton at the benthic boundary layer off the California coast; five *Alvin* dives	San Diego, California	Wishner (URI)
112-XVIII	13 Dec-18 Dec	Investigations of fauna and dynamics of sediment mounds on the floor of the Santa Catalina Basin; four *Alvin* dives	San Diego, California	Jumars (UW) Smith (SIO)

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In Memoriam

Noel B. McLean

Former Chairman of the Board of Trustees Noel B. McLean died 17 September 1984 at age 77. Mr. McLean's formal association with the Institution began in 1953 when he became one of the founding members of the Associates, which he served as President from 1955 to 1961. He was elected a Member of the Corporation in 1954 and a Trustee in 1956. In 1961 he was elected Chairman of the Board of Trustees, serving in that capacity until 1973. During his tenure as Chairman of the Board, the Institution experienced significant growth in many areas: the number of personnel doubled, operating funds nearly tripled, the market value of Institution endowment fund assets increased sixfold, and real property holdings increased tenfold.

Following his term as Chairman Mr. McLean served on several Trustee committees including the Development Committee from 1966 to 1982 and as Chairman of the Campaign for the 1980s and Beyond. In June 1980 during the Institution's 50th anniversary celebration the newly constructed Geosciences Laboratory on the Quissett Campus was dedicated and named for Noel McLean, "distinguished industrialist to whom all of marine science is deeply indebted for his unusual interest and leadership in expanding man's knowledge of the ocean in all its facets."

Mr. McLean's industrial career began in 1927 at Bendix Corporation. He was named Executive Vice President and Director of the EDO Corporation, manufacturer of airborne and underwater electronics systems, in 1946; in 1950 he was named President and in 1962 Chairman of the Board, retiring in 1972. Noel McLean spent his life assisting the technical and scientific communities, energetically and enthusiastically pursuing various means of coordinating modern technology with the useful exploitation of the sea.

Daniel Merriman

Long-time Corporation Member and Trustee Daniel Merriman died 6 August 1984 at his home in Bethany, Connecticut, at age 76. His association with the Institution began in 1931 when, as a student at Harvard University, he was invited by the Institution's first Director, Dr. Henry B. Bigelow, to sail as a member of the *Atlantis* crew on her maiden voyage from Copenhagen to Boston to Woods Hole. A biologist who served on the faculty of Yale University for many years, Dr. Merriman was elected a Member of the Corporation in 1944 and served as a Trustee from 1944 to 1964. Through the years he served on numerous committees and was named an Honorary Trustee and Honorary Member in 1979. In 1980 on the occasion of the Institution's 50th anniversary he chaired the Third International Congress on the History of Oceanography in Woods Hole and co-edited an 812-page volume of proceedings with Dr. Mary Sears.

Philip S. Weld

Well-known sailor and newspaperman Philip S. Weld died 6 November 1984 in Boston at age 70. Mr. Weld was the first American winner of the Observor Single-Handed Transatlantic Race (OSTAR) in 1980, sailing *Moxie* 2,810 miles from Plymouth, England, to Newport, Rhode Island, in just under 18 days. His long career in journalism began as a reporter in Chicago and later Boston. He served as President and Publisher of the *Gloucester Daily Times* and associated newspapers on the North Shore of Massachusetts and as President, Publisher and Editor of the European edition of the *New York Herald Tribune*. He also served on the Board of Directors of Affiliated Publications which publishes *The Boston Globe*. In 1982 Mr. Weld endowed his alma mater, Harvard University, with $1 million to finance a professorship in atmospheric chemistry. He was elected a Member of the Corporation of the Institution in 1982.

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Watching for a sediment trap to surface in the Panama Basin.

Sus Honjo

Financial Statements

Highlights:

The institution's total operating revenue increased 6% in 1984 to $48,997,255 compared with a 21% increase and total revenues of $46,351,069 in 1983. Current unrestricted funds of $2,000,000 were transferred to Unexpended Plant Funds.

Funding for Sponsored Programs increased 4% in 1984 as compared to 1983. The increase results partly from continued strong funding from the United States Navy which increased from $11,511,000 in 1983 to $13,058,000 in 1984, an increase of 13%. Included in the increase was $589,000 awarded as part of the Department of Defense Instrumentation Enhancement Program, as well as additional funds for the Deep Submergence Laboratory and acoustics research. The increase in funding from the National Science Foundation and the Office of Naval Research with general decreases in funding from other agencies reflect the reprioritization that has been occurring in the federal research effort over the last several years.

	1984	*1983*	*Increase (Decrease)*
National Science Foundation	$20,936,000	$19,978,000	4.8%
Office of Naval Research	13,058,000	11,511,000	13.4%
Department of Energy	533,000	812,000	(34.4%)
National Oceanic & Atmospheric Administration	1,389,000	1,869,000	(25.7%)
Other Government	1,775,000	1,819,000	(2.4%)
Restricted Endowment Income	723,000	685,000	5.5%
Other Restricted Gifts, Grants, and Contracts	4,180,000	4,262,000	(1.9%)
	$42,594,000	$40,936,000	4.0%

Capital expenditures including year-end work in progress were $1,306,000, a decrease of 42% over 1983 expenditures of $2,265,000. Included in the total for 1983 was $1,250,000 applied toward completion of the Paul M. Fye Laboratory. Funds expended in 1984 were used for continuing renovations to our older facilities, additional warehouse space and the upgrading and replacement of our computer resources. Funds for capital improvements were derived from gifts, depreciation recovery, and use of other Institution unrestricted income.

Other selected statistics are:	*1984*	*1983*	*Increase (Decrease)*
Full time Equivalent Employees	771	772	(0.1%)
Total Compensation (including Overtime and Benefits)	$25,780,000	$23,550,000	9.5%
Retirement Trust Contribution	2,119,000	2,184,000	(3.0%)
Endowment Income (net)	3,221,000	2,634,000	22.2%
Additions to Endowment Principal	57,000	791,000	(92.8%)
Endowment Principal (year-end at market value)	56,441,000	57,473,000	(1.8%)

Gifts and grants from private sources including the 1,455 WHOI Associates totaled $1,813,000 in 1984 of which $985,000 was restricted and $828,000 was unrestricted as follows:

Addition to Endowment Principal	$ 56,000
Laboratory Construction	35,000
Marine Policy & Ocean Management	116,000
Benthonic Foraminifera Studies	62,000
Education Program	69,000
Coastal Research Programs	514,000
Other Research Programs	21,000
OCEANUS Magazine	20,000
Whale Bioacoustics	92,000
Unrestricted	828,000
	$1,813,000

Funds availed of in support of the Education Program were derived principally from endowment income received in 1984 totaling $1,617,000. In addition to other funds restricted for education, unrestricted funds of $451,000 were availed of for the Education Program. Funds of $838,000 for student tuition and stipend support were provided either directly by charges to Research Grants and Contracts or indirectly through the General and Administrative overhead rate.

Your attention is invited to the Financial Statements and the notes accompanying them, audited by Coopers & Lybrand.

Joseph Kiebala, Jr.
Assistant Director for Finance and Administration
Kenneth S. Safe, Jr.
Treasurer
Gary B. Walker
Controller

Balance Sheets, December 31, 1984 and 1983

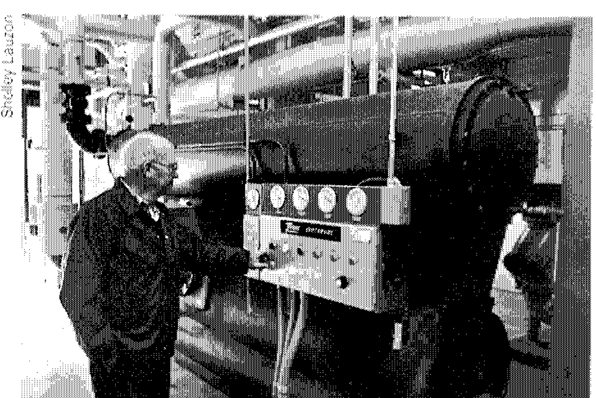
ASSETS	1984	1983
Current Fund Assets (Note A):		
Cash	$ (297,484)	$ (136,327)
Short-term investments, at cost which approximates market	13,479,552	11,837,079
Accrued interest	199,040	106,587
Reimbursable costs and fees:		
Billed	949,552	423,347
Unbilled	227,153	631,902
Other receivables	333,558	380,888
Inventories	442,522	449,106
Deferred charges and prepaid expenses	210,272	91,468
Deferred fixed rate variances	(565,568)	164,431
Due to other funds	(5,974,165)	(4,247,263)
	9,004,432	**9,701,218**
Endowment and Similar Fund Assets (Notes A and B):		
Investments, at market:		
Bonds	18,417,993	18,072,639
Stocks	32,461,532	35,743,528
Other	595,013	113,720
Total investments (cost $43,796,201 in 1984 and $45,463,470 in 1983)	51,474,538	53,929,887
Cash and cash equivalents	4,956,614	3,543,605
Due from current fund	10,200	—
	56,441,352	**57,473,492**
Annuity Fund Assets (Note A):		
Investments, at market (cost $69,614 in 1984 and $67,951 in 1983)	100,580	102,700
Cash	1,727	1,928
	102,307	**104,628**
Plant Fund Assets:		
Land, buildings, and improvements	22,502,765	21,840,140
Vessels and dock facilities	7,430,092	7,420,676
Laboratory and other equipment	2,984,951	3,703,389
Construction in progress	151,560	23,665
	33,069,368	32,987,870
Less accumulated depreciation	11,749,854	11,724,960
	21,319,514	21,262,910
Due from current fund	5,963,965	4,247,263
	27,283,479	**25,510,173**
	$92,831,570	**$92,789,511**

LIABILITIES AND FUND BALANCES	1984	1983
Current Fund Liabilities and Balances:		
Accounts payable, other accrued expenses and deferred revenues	$ 1,866,436	$ 1,936,298
Accrued payroll related liabilities	1,846,677	1,923,641
Unexpended balances restricted for:		
Sponsored research	807,021	1,713,233
Education program	425,409	384,316
Total restricted balances	1,232,430	2,097,549
Unrestricted balances designated for:		
Income and salary stabilization	3,213,784	2,949,998
Ocean Industry Program	298,543	273,177
Unrestricted current fund	546,562	520,555
Total unrestricted balances	4,058,889	3,743,730
	9,004,432	**9,701,218**
Endowment and Similar Fund Liabilities and Balances:		
Endowment:		
Income restricted	34,375,632	35,003,586
Income unrestricted	660,710	651,782
Term endowment	3,630,173	3,700,359
Quasi-endowment:		
Income restricted	8,195,972	8,353,700
Income unrestricted	9,578,865	9,764,065
	56,441,352	**57,473,492**
Annuity Fund Liabilities and Balance:		
Annuities payable	22,351	23,381
Fund balance	79,956	81,247
	102,307	**104,628**
Plant Fund Balances:		
Invested in plant	21,319,514	21,262,910
Unexpended, unrestricted	5,963,965	4,247,263
	27,283,479	**25,510,173**
	$92,831,570	**$92,789,511**

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

Anne Rabushka

Shelley Lauzon



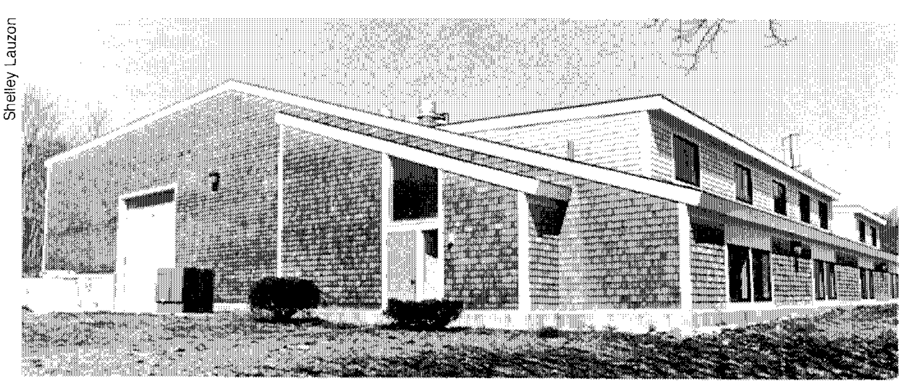
Left: Director John Steele greets *Knorr* upon the ship's arrival in Woods Hole in May following a 10-month South Atlantic voyage. Right: Tom Rennie checks controls in the Clark power plant.

Statement of Current Fund Revenues and Expenses for the years ended December 31, 1984 and 1983

Revenues	**1984**	**1983**
Sponsored Research:		
Government	$ 37,690,433	$ 35,988,942
Nongovernment	4,904,224	4,946,970
	42,594,657	40,935,912
Education funds availed of	1,868,849	1,720,821
Total restricted	44,463,506	42,656,733
Unrestricted:		
Fees	486,229	484,334
Endowment and similar fund income	791,357	648,833
Gifts	827,868	659,089
Tuition	788,101	645,523
Investment income	1,141,562	764,853
Oceanus subscriptions	246,871	244,157
Other	251,761	247,547
Total unrestricted	4,533,749	3,694,336
Total revenues	**48,997,255**	**46,351,069**
Expenses		
Sponsored research:		
Salaries and fringe benefits	12,822,261	11,913,384
Ships and submersibles	7,923,030	7,370,509
Materials and equipment	6,265,839	5,581,783
Subcontracts	1,016,392	854,341
Laboratory Overhead	3,460,402	3,463,170
Other	6,612,020	7,589,201
General and administrative	4,494,713	4,163,524
	42,594,657	40,935,912
Education:		
Faculty expense	522,052	421,188
Student expense	1,000,533	861,555
Postdoctoral programs	338,302	319,618
Other	227,270	214,022
General and administrative	231,340	285,417
	2,319,497	2,101,800
Unsponsored research	632,486	918,858
Oceanus magazine	303,102	292,507
Other activities	588,210	544,595
General and administrative	184,144	231,522
	1,707,942	1,987,482
Total expenses	**46,622,096**	**45,025,194**
Net increase – unrestricted current fund	**$ 2,375,159**	**$ 1,325,875**
Designated for:		
Income and salary stabilization	$ 263,786	$ 216,278
Ocean Industry Program	25,366	(15,887)
Unrestricted current fund	26,007	66,490
Innovative research fund	60,000	–
Endowment fund	–	58,994
Plant fund, unexpended	2,000,000	1,000,000
Total	**$ 2,375,159**	**$ 1,325,875**

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

Shelley Lauzon



Coastal Research Laboratory, Quissett Campus.

Report of the Certified Public Accountants

To the Board of Trustees of Woods Hole Oceanographic Institution:

We have examined the balance sheets of Woods Hole Oceanographic Institution as of December 31, 1984, and 1983, and the related statements of changes in fund balances, and of current fund revenues, expenses and transfers for the years then ended. Our examinations were made in accordance with generally accepted auditing standards and, accordingly, included such tests of the accounting records and such other auditing procedures as we considered necessary in the circumstances.

In our opinion, the financial statements referred to above present fairly the financial position of Woods Hole Oceanographic Institution as of December 31, 1984, and 1983, the changes in its fund balances, and its current fund revenues, expenses and transfers for the years then ended, in conformity with generally accepted accounting principles applied on a consistent basis.

Coopers & Lybrand

Boston, Massachusetts
March 27, 1985

WOODS HOLE OCEANOGRAPHIC INSTITUTION 1930

Statement of Changes in Fund Balances for the years ended December 31, 1984 and 1983

	Current Fund					Plant Fund		
1984	**Restricted**	**Unrestricted**	**Total**	**Endowment and Similar Funds**	**Annuity Fund**	**Invested In Plant**	**Unexpended**	**Total Funds**
Increases:								
Gifts, grants and contracts:								
Government	$37,175,769		$37,175,769					$ 37,175,769
Nongovernment	3,841,643	$ 827,868	4,669,511	$ 56,200			$ 35,120	4,760,831
Endowment and similar funds investment income (Note D)	2,429,846	791,357	3,221,203					3,221,203
Net increase in realized and unrealized appreciation				(1,089,117)				(1,089,117)
Other	91,906	2,914,524	3,006,430		$ (1,291)			3,005,139
Total increases	43,539,164	4,533,749	48,072,913	(1,032,917)	(1,291)		35,120	47,073,825
Decreases:								
Expenditures	(44,463,506)	(2,158,590)	(46,622,096)					(46,622,096)
Depreciation (Note A)						$ (1,248,974)	987,160	(261,814)
Total decreases	(44,463,506)	(2,158,590)	(46,622,096)			(1,248,974)	987,160	(46,883,910)
Net change before transfers	(924,342)	2,375,159	1,450,817	(1,032,917)	(1,291)	(1,248,974)	1,022,280	189,915
Transfers – additions (deductions):								
Current revenues to plant fund		(2,000,000)	(2,000,000)				2,000,000	–
Current revenues to endowment	(777)		(777)	777				–
Current revenues to innovative research fund	60,000	(60,000)						–
Plant asset additions						1,305,578	(1,305,578)	–
Total transfers	59,223	(2,060,000)	(2,000,777)	777		1,305,578	694,422	–
Change in fund balance for the year	(865,119)	315,159	(549,960)	(1,032,140)	(1,291)	56,604	1,716,702	189,915
Fund balance, December 31, 1983	2,097,549	3,743,730	5,841,279	57,473,492	81,247	21,262,910	4,247,263	88,906,191
Fund balance, December 31, 1984	**$1,232,430**	**$4,058,889**	**$5,291,319**	**$56,441,352**	**$79,956**	**$21,319,514**	**$5,963,965**	**$89,096,106**
1983								
Increases:								
Gifts, grants and contracts:								
Government	$35,775,134		$35,775,134					$ 35,775,134
Nongovernment	4,362,960	$ 659,089	5,022,049	$ 326,496			$ 683,625	6,032,170
Endowment and similar funds investment income (Note D)	1,985,502	648,833	2,634,335					2,634,335
Net increase in realized and unrealized appreciation				3,889,689				3,889,689
Other	71,946	2,386,414	2,458,360		$ 5,655			2,464,015
Total increases	42,195,542	3,694,336	45,889,878	4,216,185	5,655		683,625	50,795,343
Decreases:								
Expenditures	(42,656,733)	(2,368,461)	(45,025,194)					(45,025,194)
Depreciation (Note A)						$ (1,099,057)	837,243	(261,814)
Other						197		197
Total decreases	(42,656,733)	(2,368,461)	(45,025,194)			(1,098,860)	837,243	(45,286,811)
Net change before transfers	(461,191)	1,325,875	864,684	4,216,185	5,655	(1,098,860)	1,520,868	5,508,532
Transfers – additions (deductions):								
Current revenues to plant fund		(1,000,000)	(1,000,000)				1,000,000	–
Current revenues to endowment	(597)	(148,548)	(149,145)	149,145				–
Fiftieth anniversary fund to endowment		(315,643)	(315,643)	315,643				–
Plant asset additions						2,264,874	(2,264,874)	–
Total transfers	(597)	(1,464,191)	(1,464,788)	464,788		2,264,874	(1,264,874)	–
Change in fund balance for the year	(461,788)	(138,316)	(600,104)	4,680,973	5,655	1,166,014	255,994	5,508,532
Fund balance, December 31, 1982	2,559,337	3,882,046	6,441,383	52,792,519	75,592	20,096,896	3,991,269	83,397,659
Fund balance, December 31, 1983	**$2,097,549**	**$3,743,730**	**$5,841,279**	**$57,473,492**	**$81,247**	**$21,262,910**	**$4,247,263**	**$88,906,191**

Notes to Financial Statements

A. Summary of Significant Accounting Policies:

Fund Accounting

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.

Investments

Investments in securities are stated 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. Investments for which a readily determinable market value cannot be established are stated at cost.

Income, net of investment expenses, is distributed on the unit method. Unrestricted investment income is recognized as revenue when received and restricted investment income is recognized as revenue when it is expended for its stated purpose. Realized and unrealized gains and losses are attributed to the principal balance of the funds involved.

The Institution follows the accrual basis of accounting except that endowment and similar fund investment income is recorded on a cash basis. The difference between such basis and the accrual basis does not have a material effect on the determination of investment income earned on a year-to-year basis.

Contracts and Grants

Revenues associated with contracts and grants are recognized as related costs are incurred. Beginning with fiscal 1978, the Institution has negotiated with the government fixed rates for the recovery of certain indirect costs. Such recoveries are subject to carryforward provisions that provide for an adjustment to be included in the negotiation of future fixed rates.

Gifts

Gifts are recorded in the applicable funds when received. 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 of $1 until such time as the value becomes known. Unrestricted gifts are recognized as revenue when received and restricted gifts are recognized as revenue as they are expended for their stated purposes.

Plant

Plant assets are stated at cost. Depreciation is provided at annual rates of 2% to 8½% on buildings, 3 1/4% on *Atlantis II* and 5% to 33 1/3% on equipment. Depreciation expense on Institution-purchased plant assets amounting to $987,160 in 1984 and $837,243 in 1983 has been charged to operating expenses. Depreciation on certain government funded facilities (*Atlantis II*, 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.

Plant assets were reduced $1,126,000 for fully depreciated assets no longer in service and those items which no longer meet the Institution's criteria for capitalization.

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

Annuity Funds

On the date of receipt of annuity fund gifts, the actuarially computed value of the future payments to annuitants is recorded as a liability and any excess amount of the gift is credited to the fund balance. The actuarial values of the liabilities are recomputed annually.

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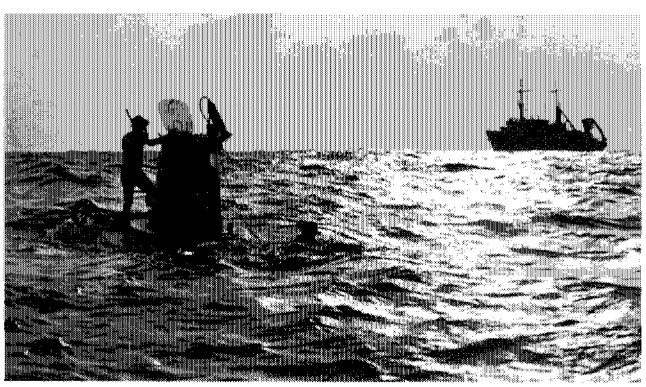

***Alvin* returns from a dive as *Atlantis II* approaches for recovery.**

B. Endowment and Similar Fund Investments:

The cost and market value of investments held at December 31, 1984, and 1983, are as follows:

	December 31, 1984		December 31, 1983	
	Cost	Market	Cost	Market
Government and government agencies	$ 15,191,373	$ 15,949,425	$ 14,405,246	$ 14,692,093
Convertible bonds	268,125	287,000	786,563	745,250
Corporate bonds	2,162,592	2,181,568	2,533,246	2,635,296
Convertible preferred stocks	295,715	222,000	596,790	496,000
Common stocks	25,297,331	32,239,532	27,041,625	35,247,528
Other..............	581,065	595,013	100,000	113,720
Total investments ...	**$43,796,201**	**$51,474,538**	**$45,463,470**	**$53,929,887**

C. Pooled Investment Units:

The value of an investment unit at December 31, 1984, and 1983, was $1.2652 and $1.2896, respectively. The investment income per unit for 1984 and 1983 was $.0723 and $.0594, respectively.

	1984	1983
Unit value beginning of year	$ 1.2896	$ 1.2011
Unit value end of year	1.2652	1.2896
Net change for the year	(.0244)	.0885
Investment income per unit for the year	.0723	.0594
Total return per unit	**$ .0479**	**$ .1479**

D. Endowment and Similar Fund Income:

Income of endowment and similar funds consisted of the following:

	1984	1983
Dividends	$ 995,476	$ 888,367
Interest	2,534,382	2,074,335
	3,529,858	2,962,702
Investment management costs	(308,655)	(328,367)
Net investment income	**$3,221,203**	**$2,634,335**

E. Retirement Plan:

The Institution has a noncontributory defined benefit trusteed retirement plan covering substantially all full-time employees. The Institution's policy is to fund pension cost accrued which includes amortization of prior service costs over a 30-year period. Retirement plan costs charged to operating expense amounted to $2,310,000 in 1984 and $2,352,000 in 1983, including $190,700 and $168,000, respectively, relating to expenses of the retirement trust. As of January 1, 1984 (the most recent valuation date) the comparison of accumulated plan benefits and plan net assets is as follows:

	January 1	
	1984	1983
Actuarial present value of accumulated plan benefits:		
Vested	$ 21,570,874	$ 19,282,937
Nonvested..................................	1,161,858	1,032,504
Total actuarial present value of accumulated plan benefits	$ 22,732,732	$ 20,315,441
Net assets available for plan benefits	**$31,286,294**	**$25,435,384**

The assumed rate of return used in determining the actuarial present value of accumulated plan benefits was six and one-half percent compounded annually.

F. Post-Retirement 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 or elect early retirement with certain time-in-service limitations. The cost of retiree health care is recognized as an expense when paid. For 1984, those costs totaled $103,779.