Woods Hole Oceanographic Institution

Annual Report 1977

Cover Photo: The Research Vessel Atlantis II *returned 21 May 1977 from a 19-month cruise to the Indian Ocean. Her foremast flew the flags (top to bottom) of Brazil, South Africa, Mauritius, Kenya, Australia, and Indonesia. The flags of the other eight ports she visited on the cruise — Malta, Egypt, Israel, Djibouti (French flag), Iran, Pakistan, India, and Singapore — flew from the main mast. (Actually, they were originally strung mast to mast, but the line parted just before the ship reached Woods Hole harbor.) Flags for the ship's radio call letters — KADC — are also flying from the stack. The yellow quarantine flag at the yardarm flies until the ship is cleared by the Department of Agriculture when she comes from a foreign port.*

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Director's Comments

of how energy is transmitted to the sea from the winds requires knowledge of air-sea interactions at the scales of surface waves. At present our investigations into the exchange of energy between the largest and smallest scales are concentrated at the intermediate level of ocean eddies a few hundred kilometers in diameter. Once these are understood, we can move to experiments on the larger scale of Stommel's theory.

Similarly, in ecology we have not merely the geographic scales but the interactions between the components of the food web, and, as with fisheries, we are discovering how alterations at one point in the web may have effects on some quite different and apparently separate part of the ecosystem.

It is these interrelations that make oceanography such a fascinating — but difficult — study. Today, advances in this field are still usually made by developing continually broader and more general hypotheses rather than by isolating areas of the subject within which well-established rules of operation are developed. The essential core of the scientific process is continuing basic research by individual investigators.

Certainly, there are important areas where adequately reliable information is available. It is apparent that geological theory and techniques are highly applicable in relation to offshore oil exploration. Coastal engineering is a well accepted applied discipline and its extension to offshore structures is being established. Yet many of the questions presently being asked go beyond these aspects. The problems of multi-species management of fish stocks involve basic marine ecology. The large scale and longer term *effects* of pollution are still speculative. Questions of deep-sea waste disposal demand a degree of certainty that is not available from our present knowledge of physical, chemical, and biological processes taking place near the seabed.

The role of the oceans in climatic change is a fascinating but relatively new topic with major implications for our release of such substances as carbon dioxide and nitrous oxide. For such larger questions the public and the authorities look directly to the active scientist and especially to independent, established institutions like this one.

There are several possible responses. One, which has come from certain European universities, is to set up departments such as "Environmental Engineering." This, to me, suggests a semantic rather than a technological solution to the problem. A second response is to restrict answers to limited questions such as coastal engineering, thereby refusing to become involved in major problems at the practical level. In many cases this is justified not only in terms of the psychology of the individual investigator but also as a response to the nature of environmental problems.

Yet within institutions whose field of study is the world oceans, the unique combination of knowledge and ideas requires that we play a role in finding answers to questions of major concern. Although significant parts of our knowledge may have this "hypothetical" quality, it would be wrong to exclude them from the processes of decision making. This institution and others *have* responded. There is increasing consideration of multidisciplinary projects; a recognition that programs may need to be modified to meet certain applied ends; a general willingness to ensure that the results of research in the sea are made available as rapidly as possible.

There is, however, as I have suggested, a further consequence. If the results of research are to be used straight from the research ship, then not only must oceanographers change their attitudes but so must the recipients. We are becoming familiar with occasional failures of advanced technology that are often an indication of the difficulties in defining the boundary between scientific research and technological development. This applies even more within science itself. The hypothesis-test-hypothesis process could be defined more simply as learning from our mistakes. It requires great flexibility and a capacity to adapt ideas and techniques to changing and developing knowledge. I believe a similar attitude is needed in those who require scientific advice and then make decisions on this basis. There is a need for a process of adaptive management.

In Europe and possibly in North America there is often a desire on the part of managers concerned with environmental protection to have a set of predetermined standards or rules for general application. Obviously, this is legally and administratively convenient. Yet this implies a generality in our scientific knowledge which I am sure does not exist and precludes the gradual development and adaptation of regulations appropriate to a given problem. I believe that such processes of adaptive management would be in the best interests of both developers and conservationists because it would usually correspond most closely to the nature of the associated scientific investigations.

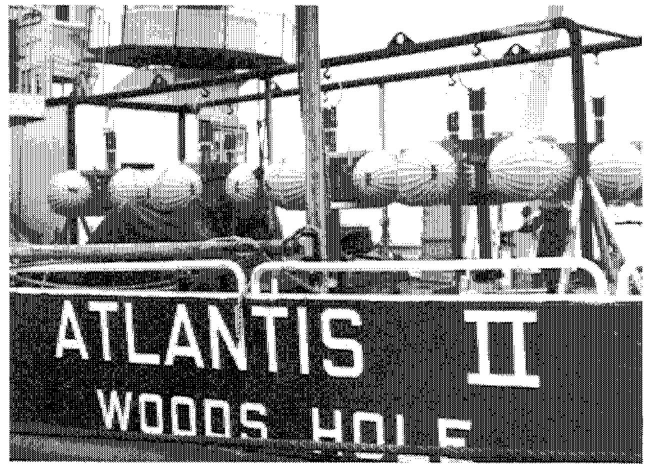
In the recent Godkin Lectures at Harvard, Dr. Charles L. Schultze, formerly of the Brookings Institution and now Chairman of the Council of Economic Advisors, pointed out that "social intervention can be *process oriented* seeking to correct the faulty process, or *output oriented* seeking to bypass the process and determine outputs directly by regulation. In fact, social intervention has almost always been output oriented, and this has been a costly bias. It has taxed well beyond its limit the ability of government to make complex output decisions." Charles Schultze was referring to social and economic problems, but I believe his remarks apply equally to the use of environmental science.

In the last year, I have come to appreciate the existence of this longer-term commitment to the science of oceanography by the Trustees of this Institution. They are interested not only in the fascinating results emerging from our work but also in the processes by which our understanding is developed. This knowledge and concern provides an essential link in the relations between the work of marine science and the urgent questions of what my distinguished predecessor Paul Fye, now President of the Corporation, has often referred to as the wise use of the oceans.

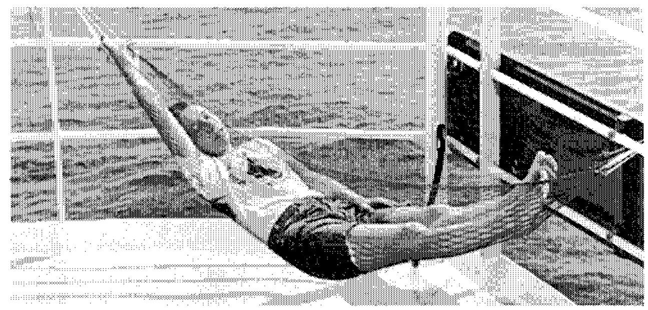
JOHN H. STEELE

PHOTOS BY VICKY CULLEN

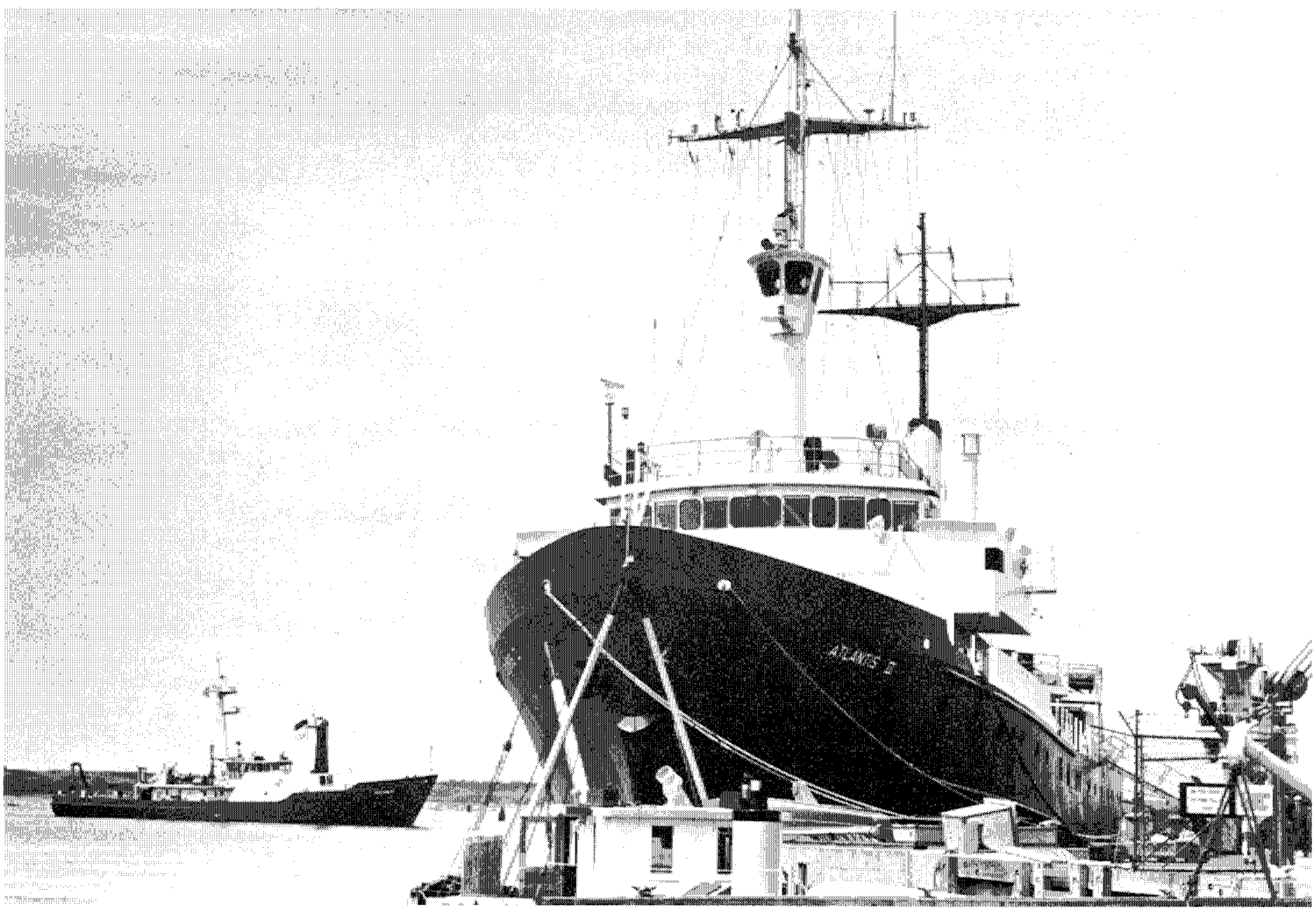
Asterias heads through the drawbridge towards Eel Pond berth.



Ocean bottom hydrophones line fantail as *Atlantis II* loads for cruise.



Exhausted student, Mary Jo Richardson, grabs a few rays on *A-II* "beach."



Oceanus comes home from June voyage as *Atlantis II* prepares to depart.

Research

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. Among the research interests of Institution biologists are microbiology, planktonology, benthic biology, physiology, aquaculture, and pollution. 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, and high pressures. 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 upwelling areas where deep nutrient-rich waters replace surface waters that are driven offshore by prevailing winds, and in laboratory experiments that complement field investigations. The use of sound by marine animals and their sensitivity to electrical fields are being studied. Other work concentrates on a salt marsh ecosystem, and there are research projects on aquaculture and waste water recycling and on the productivity of a salmon river in Canada.

Biology

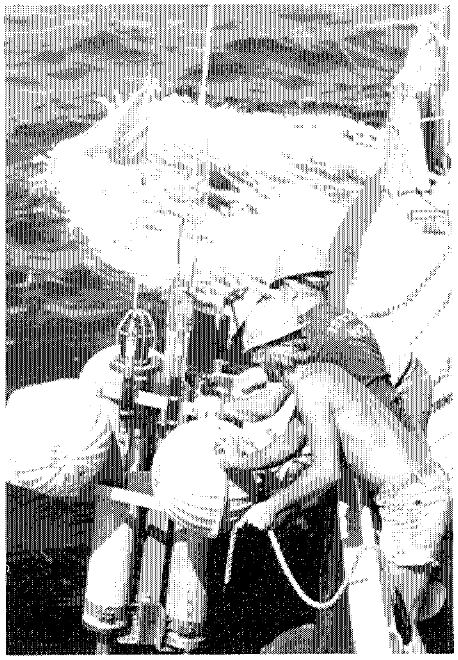
CHEMICAL oceanographers are concerned with the composition of the ocean environment. They seek to understand the processes that have brought seawater and sediments to their present composition and that contribute to the observed variability. They also seek understanding of the extent to which the environment may be changed by both natural and manmade phenomena operating on a variety of time scales. Input from rivers and reactions at the air-sea and seawater-sediment boundaries are under investigation as chemists consider the processes taking place at major ocean boundaries. Some critical questions in chemical oceanography revolve around transformations in particles as they fall from the surface waters to the bottom of the water column. The genesis and composition of the oceanic crust and its interaction with seawater is important to a general understanding of the oceanic system. Work on the fluxes of organic carbon includes determination of the amount of organic carbon produced by photosynthesis in surface waters and studies of processes responsible for formation of organic matter in sediments. While studying radioactive isotopes in the oceans 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 and of biological and chemical processes that change the composition of seawater.

Chemistry

THE shape of the sea floor and its underlying structures as well as the physical properties of sediment and sea floor are studied by marine geologists and geophysicists. The structure, evolution, and dynamics of the oceanic crust and lithosphere are investigated through studies of variations, often minute, in gravity, magnetism, and temperature along with seismic studies of crustal components and layering of overlying sediment. Detailed studies are being made of continental margins and marginal basins as well as the margins of the huge crustal plates on which the continents ride. Measurements of particulate flux and the dissolution of carbonates and silicates and determination of sediment dynamics contribute to an understanding of deposition on the sea floor. Analysis of the fossil record in rocks and sediment reveals historical changes in climate and oceanic circulation patterns, volcanic activity, and other geologic events.

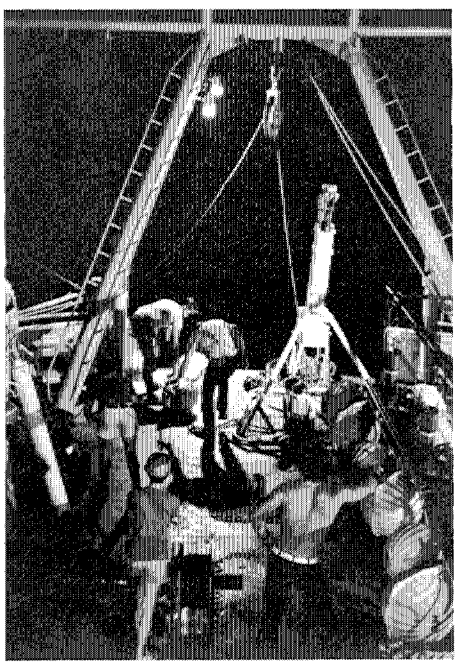
Geology & Geophysics

CAROLYN DEAN



Ocean bottom hydrophone goes over the side during *Atlantis II* survey of Kane Fracture Zone.

VICKY CULLEN



Sediment trap mooring is set at night from *Atlantis II* on Sohm Abyssal Plain.

SCIENTISTS in the Ocean Engineering Department study sound propagation in seawater and how it is affected by temporal and spatial variations in temperature, density, and other factors. Sound waves are employed to detect and measure organisms, physical properties, and pollutants. Development of instruments for use in the hostile marine environment and their refinement for reliability, accuracy, and endurance are among the important tasks of the Ocean Engineering Department. Computers are vital to modern oceanography both at sea and in land-based analysis of data, and much of this development is the responsibility of computer groups within the Ocean Engineering Department. The Alvin group, responsible for development of the submersible as a unique scientific window on the depths of the ocean, is also based here.

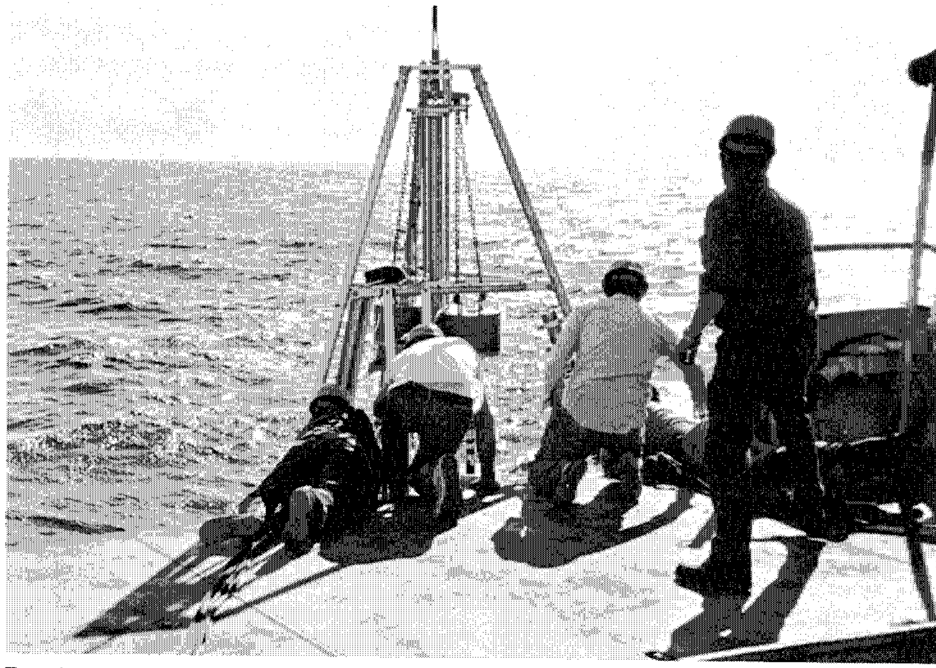
Ocean Engineering

OCEAN currents, their driving forces, and their interactions are the major interest of physical oceanographers. Such properties as variations in temperature, salinity, pressure, and large and small scale motions of the waters are measured and plotted on long cruise tracks and with moored and drifting instruments. Exchanges of energy between air and sea present important questions as one affects the other and their interaction becomes part of the world climate. Effects of bottom and coastal topography on ocean circulation systems are under investigation. Advancement of technology for extended-period measurements is mandatory so that trends can be recognized. Large and small current systems are modelled toward the ultimate goal of understanding the structure and movement of the world's oceans and the interaction of the sea with its boundaries.

Physical Oceanography

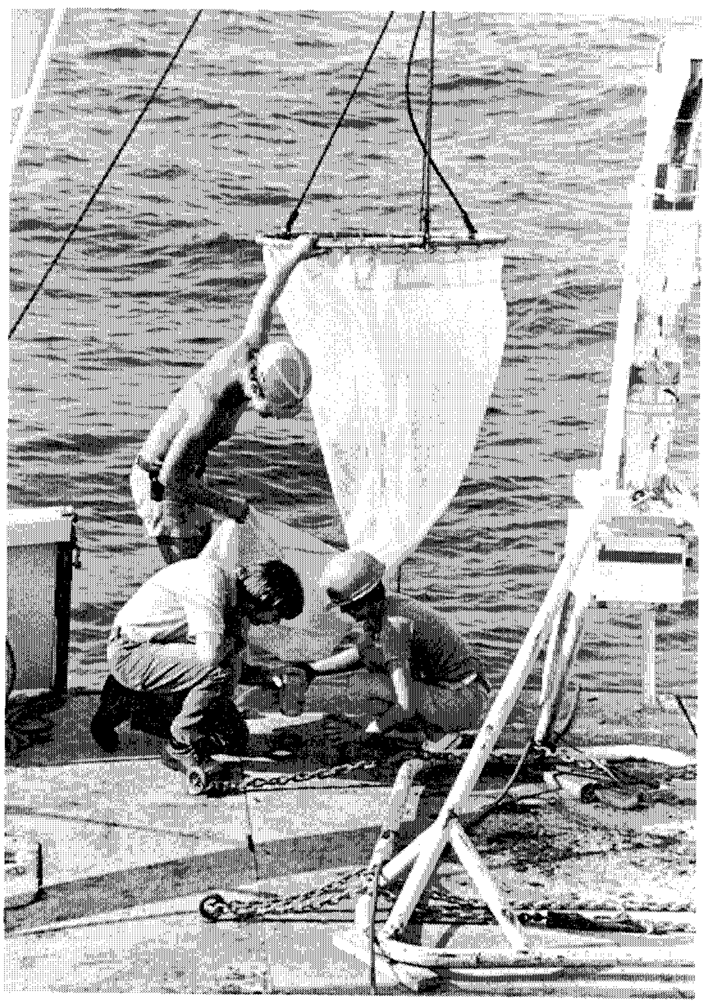
THE Marine Policy and Ocean Management program supports interdisciplinary research by marine and social scientists on problems generated by man's increasing use of the sea. The program offers fellowships and research opportunities to individuals from such fields as anthropology, economics, international affairs, law, management, and political science. Program participants work with scientists while investigating marine-related problems in their own disciplines.

Marine Policy & Ocean Management

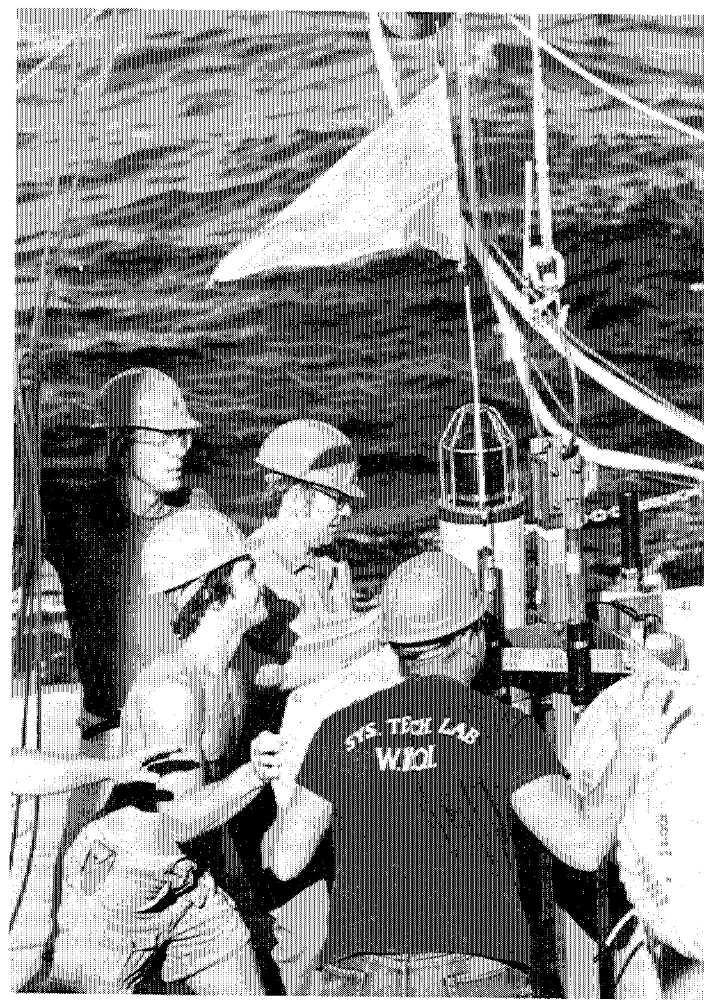


SUSAN KADAR

Tripod rigged for studies of water contained in sediments is launched from fantail of *Knorr.*



Plankton net haul gets rapt attention aboard *Atlantis II.*



CAROLYN DEAN

Handling ocean bottom hydrophone takes many hands.

Research: Ocean Bottom Processes

This section is not an attempt to give an overall view of the research underway at the Woods Hole Oceanographic Institution. It is rather a discussion of some of our scientists' investigations into the processes taking place at the bottom of the ocean. Derek Spencer, Chairman of the Department of Chemistry, has served as scientific editor for this report, and his introduction follows.

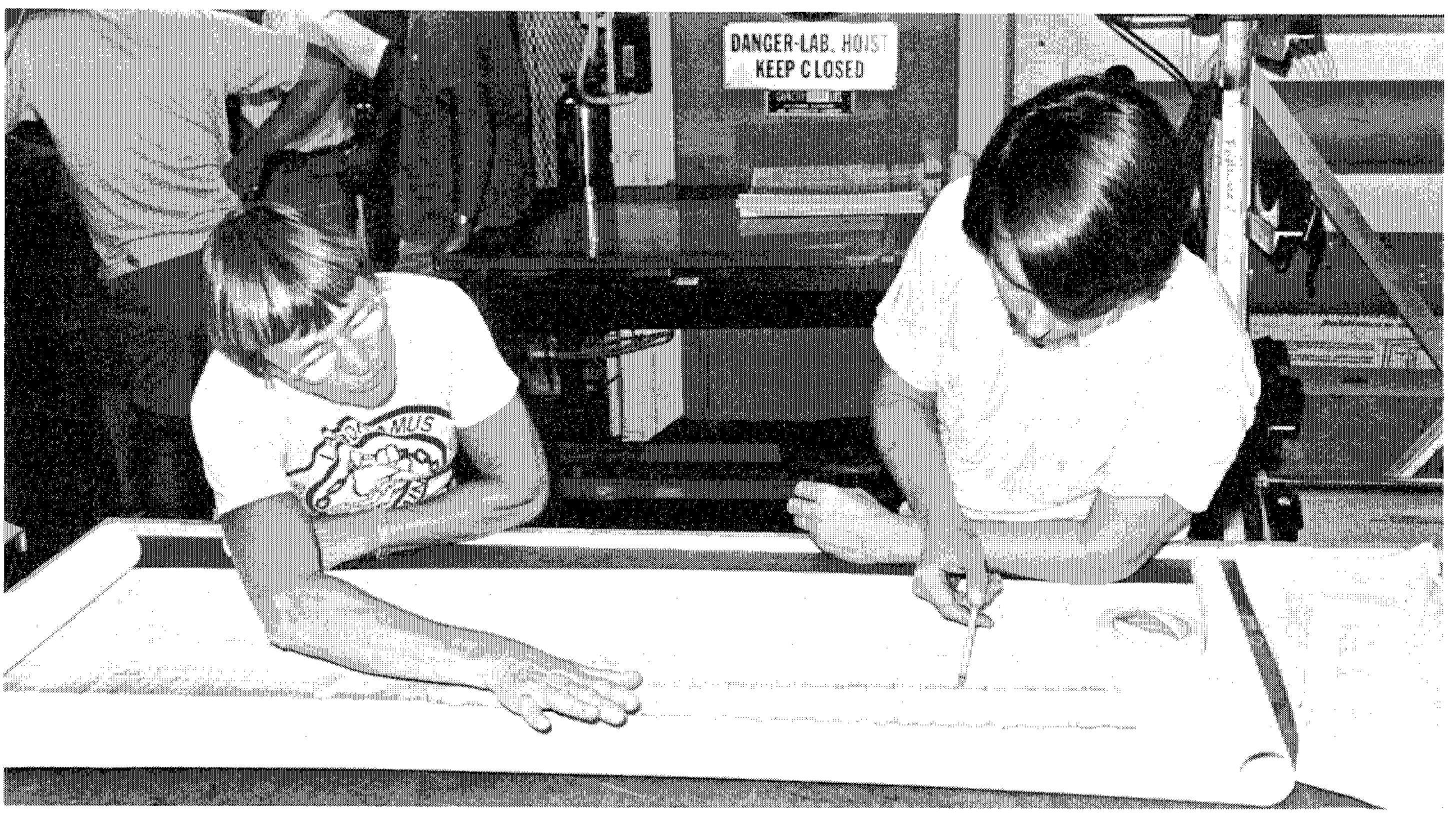
THE sediment-water interface in the world's oceans, particularly in the abyssal regions, is one of the least explored areas of the earth. For many years, it was believed that the deep ocean was a calm, quiet place. The sediments of the deep-sea floor were assumed to be accumulating slowly and regularly by a rain of fine detritus introduced from various regions of the continental shelves and from biological growth in the surface layer. Biological activity and chemical reactions in the sediments were thought to be minimal and certainly of little consequence to the ocean itself. In the last several years, evidence has accumulated to indicate that these early conceptions are quite wrong. There are many places where the deep-sea floor is being eroded by strong bottom-current activity, and resuspended sediment may be transported over great distances. Biological activity is much greater than was believed, and many chemical reactions that may have major effects on the composition of the ocean are taking place at the boundary.

There is now strong evidence that the major flux of particles to the sea floor is not solely in fine detritus that settles slowly, taking many years to transit the water column. A major flux, in the form of large particles that are produced principally by the feeding and excretion of animals, is now known to couple the ocean surface and the bottom sediments. These particles, which may settle to the ocean bottom in periods of days to weeks, provide a mechanism for the deep ocean sediments to respond to surface changes on a very short time scale.

The series of articles that follow describes part of the research that is helping to document and provide an understanding of the mechanisms and rates of processes affecting the ocean floor. A complete understanding of the benthic boundary layer, which may be loosely defined as the zone from several hundreds of meters above to about a meter below the sea floor, requires investigations into the mechanisms by which energy, momentum, and materials are transported from the surface ocean, investigations of the dynamics of the boundary layer, and investigations of the biological activity and chemical reactions occurring above and within the bottom sediments. The joint experience and talents of physicists, chemists, biologists, geologists, and engineers are needed for such studies.

Our increasing use of the sea floor for mineral resources and waste disposal and our lack of knowledge about the interaction of the sea floor with the global ocean-atmosphere system provide strong sociological drives for this work, but it is intellectual curiosity that motivates most of the researchers to explore and try to understand this last remaining frontier of the earth's surface.

DEREK SPENCER



Betty Bunce and 1977 Joint Program Graduate Ed Laine look over seismic profiles of the Bermuda Rise on *Atlantis II* Voyage 96.

Ocean Bottom Processes

Deep Western Boundary Currents in the World Ocean

Bruce Warren

SINCE the middle of the eighteenth century it has been known that deep water in the tropics was cold, like surface water in high latitudes, and that it must therefore derive from polar regions by sinking at the sea surface. The specific source areas are now known to be the Norwegian Sea and a few locations around Antarctica, most notably the Weddell Sea. Until the middle of this century, oceanographers supposed that the deep water then moved away toward the equator as a broad, slow, ocean-wide drift (in the mean).

Henry Stommel, however, realized that such a flow scheme was physically inconsistent with two other simple and "reasonable" notions: namely, that (1) there is a general, slow, upward movement of cold water at mid-depths to balance the downward diffusive flux of heat through the thermocline and thus account for the observed steadiness of the general temperature distribution; and (2) in the open ocean the mean deep flow itself is geostrophic in the strict sense that the horizontal velocity is parallel to isobars and inversely proportional to their spacing. According to the dynamics of flow on a rotating sphere, these two ideas have the remarkable consequence that deep water in the open ocean should move poleward — that is, *toward* its source regions, rather than away from them. If those ideas are true, then apparently the only way through which deep water can move equatorward, away from the source regions, is in currents narrow and swift enough to escape the strict geostrophic constraint, and these work out in the dynamics to be currents along western boundaries. In the late fifties, Stommel and Arnold Arons developed a dynamically consistent scheme of deep ocean circulation; it predicted western boundary currents to supply the deep water in all oceans, with that water then moving upward and poleward in slow geostrophic flows in the interiors of the oceans.

At the time these predictions were made, evidence already existed from hydrographic sections across the South Atlantic (*Meteor* Expedition, 1925-27) of a concentration of deep flow along the continental slope of South America. Although that body of data had not previously been discussed within the conceptual framework of boundary currents and interior flows, it nevertheless provided support for the new theory. Soon after the theory was proposed, the predicted deep western boundary current in the North Atlantic was sought, and found, by means of direct velocity measurements off the United States. This discovery, by John Swallow and Valentine Worthington, was a rare and striking example in oceanography of theory predicting the existence of a previously unknown feature of the circulation — usually theory has only rationalized observation (a difficult enough task in itself).

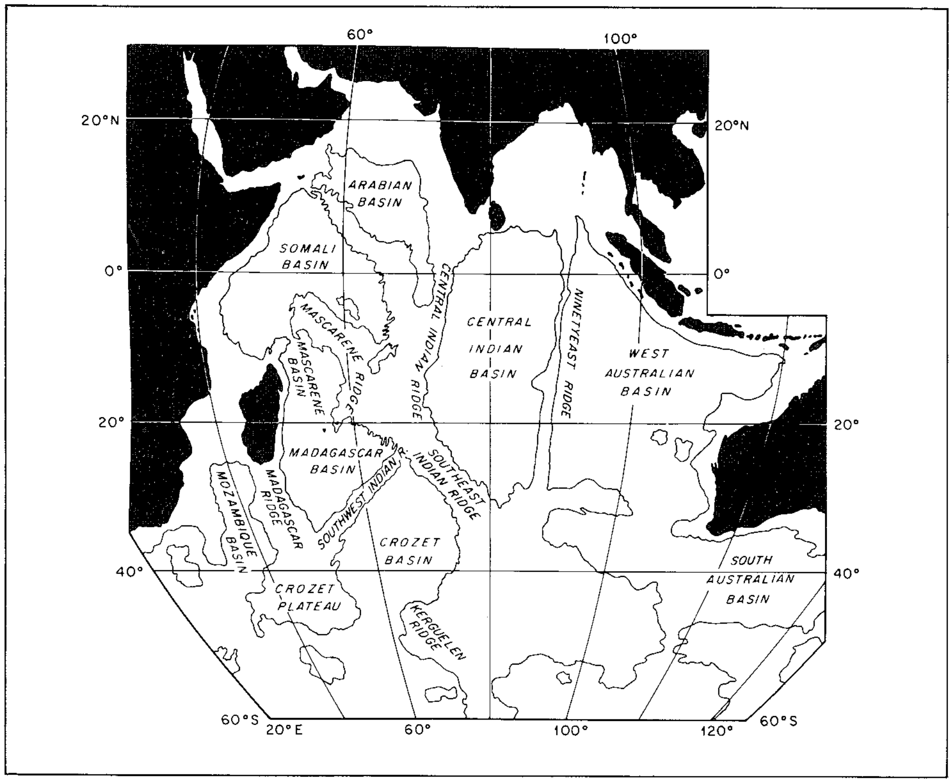
In the late sixties the deep western boundary current of the South Pacific was discovered, both through property distributions (horizontal density gradients and chemical tracers) observed at closely spaced stations and through actual current measurements. This has the largest volume transport (15 to 20 million cubic meters per second) of all the deep boundary currents, consistent with the Pacific itself being so much larger than the other oceans. To date, however, there is no convincing evidence for an extension or counterpart of this current in the North Pacific. This does not necessarily mean that the predicted current is not there; velocity measurements have simply been inadequate to tell whether one exists, and the deep North Pacific is so nearly homogeneous that circulation patterns are almost undetectable in property distributions.

Recent W.H.O.I. cruises to the Indian Ocean have provided opportunities to look for deep western boundary currents there as well. During the *Chain* cruise of 1971, the predicted northward-flowing current off Madagascar was clearly identified; it has since been shown to come from the Crozet Basin to the south, through fractures in the Southwest Indian Ridge. Its course north of Madagascar, however, is quite uncertain. An earlier set of observations indicated a pattern of deep northeastward flow close to Somalia, but those observations were taken during the Southwest Monsoon, when the Somali Current was flowing swiftly to the northeast in the upper water; the indicated deep flow might therefore represent a deep expression of the oceanic response to the monsoon, rather than a permanent boundary current.

With its several ridges and basins, the Indian Ocean has the most complicated geometry of all the oceans, and one might expect a corresponding greater complexity to its deep circulation pattern. It seems unlikely, for example, that deep water east of the Central Indian Ridge is supplied by the deep Madagascar current. One would expect the temperature of the water to increase downstream from its source, yet deep temperatures are lower in the Central Indian Basin than in the Somali and Arabian Basins, and lower still in the West Australian Basin. The Central Indian Ridge thus appears to be an effective barrier to deep flow from the west. For simplicity of presentation, the Stommel-Arons flow


PAUL MAY

Bruce Warren and Nansen bottle in Indian Ocean.



Index map identifies Indian Ocean basins and ridges and includes rough outline of the 4-kilometer isobath.

scheme took no account of such barriers and therefore allowed deep water to enter the Indian Ocean only from the southwest; Georg Wüst, however, had long ago pointed out that deep water probably entered off western Australia as well, and this eastern influx of cold water seems necessary to account for the general eastward decrease in deep temperature.

If deep water does enter the West Australian Basin directly from the Antarctic, then the dynamical arguments made by Stommel and Arons would require that it flow northward as a narrow current along the western boundary of that basin, which is the Ninetyeast Ridge. Therefore, as part of a hydrographic section made last year by *Atlantis* II along latitude 18°S, stations were made close together near the Ninetyeast Ridge, and the anticipated current was found in the property distributions at depths greater than 3,000 meters — confirming again the essential Stommel-Arons dynamics, with its idea that, in the mean, deep water moves equatorward only in western boundary currents.

In the Central Indian Basin the 18°S section is less straightforward. A preliminary interpretation of the data is that the very deepest water (deeper than 3,500 meters, say) may be supplied by the Ninetyeast Ridge current, over low-latitude saddles on the Ninetyeast Ridge, while water at lesser depths (2,500-3,500 meters, say) may enter the basin from the south in yet a third deep western boundary current flowing northward along the Central Indian Ridge. More observations are needed.

Physical Characteristics of the Benthic Boundary Layer

Laurence Armi

MANY new details of ocean currents and water property distributions are being revealed to us through the use of modern instrumental methods, many of which were developed at Woods Hole. Temperature, salinity, and light scattering by fine particles are now routinely measured with a vertical resolution of 10 centimeters — in contrast to the typical classical hydrographic station which placed a Nansen bottle approximately every 250 meters in the vertical. In effect, the increase in resolution allows us to observe the ocean along vertical lines; we no longer need *imagine* the distribution of properties between the sparsely distributed water samples.

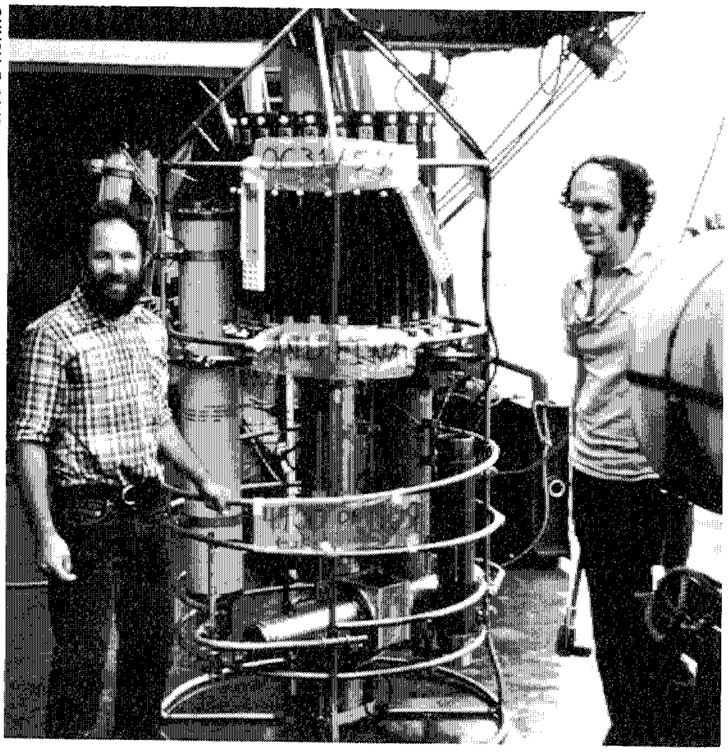
The new details observed along these lines force us to revise our ideas concerning mixing in the deep ocean. With the limited vertical resolution of the past, simple gradients were emphasized. The best guess for how properties might vary between isolated points was that they varied continuously. Mixing theories were likewise formulated using concepts for so-called quasi-homogeneous or horizontally isentropic processes. The location and characteristic signatures of perturbations to the simple gradients are, however, revealing that mixing in the deep ocean is not a homogeneous process at all. Deep ocean mixing appears to be dominated by processes occurring at the bottom boundary or in the benthic boundary layer.

An example of the information now available along these vertical profiling lines is shown in the profile on the next page, which was taken over the northern part of the Hatteras Abyssal Plain. It shows a characteristic and ubiquitous bottom mixed layer which extends in this case about 30 meters above the bottom. This is caused by the motion of the deep water over the bottom boundary. Resulting turbulence stirs the background stratification into a well-mixed bottom layer.

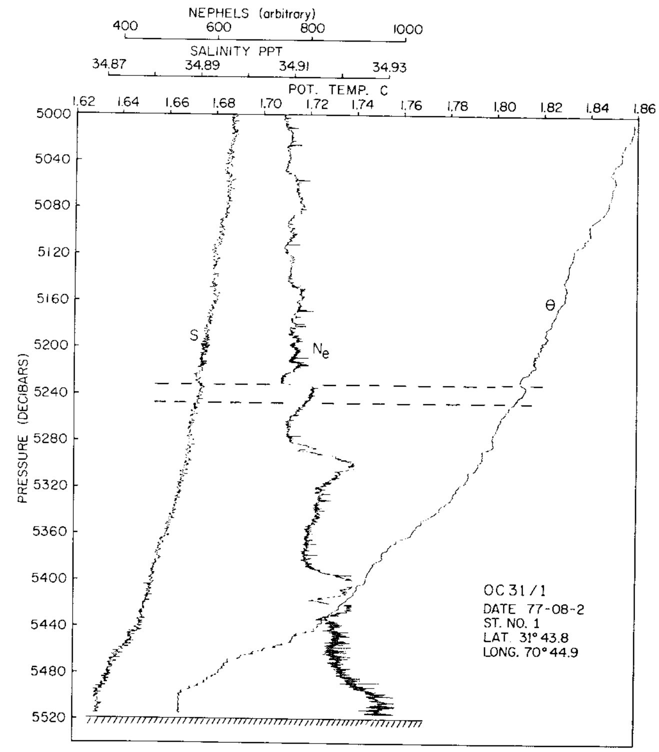
An intensive experiment was recently completed in which current meters and temperature measuring thermistors were

Ocean Bottom Processes

ERIC D'ASARO

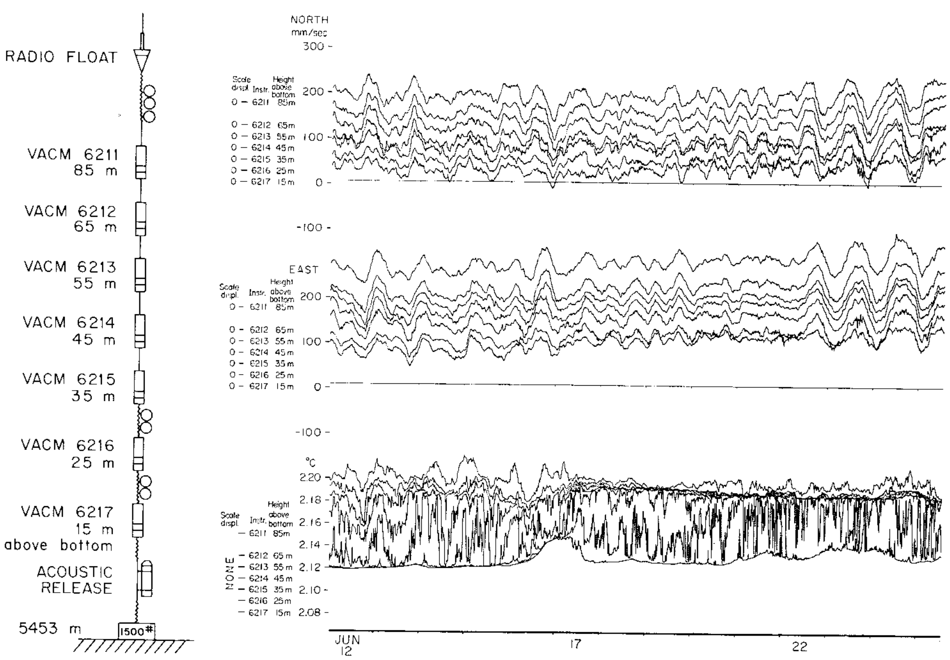


Larry Armi, left, and Peter Rhines with instrument package festooned with encouraging words for final lowering on *Oceanus* Voyage 31. Package includes conductivity, temperature, and depth sensors, a nephelometer (see right), a rosette water sampler, a pinger, and a transponder for tracking.



Profiles show salinity (S), potential temperature (θ), and amount of light scatter by particles (Ne) — *nephelo* is the Greek word for cloud, and the sensor used for this measurement is a nephelometer. Depth is displayed in units of pressure; at 5,000 decibars the depth is 4,908 meters, so a decibar is nearly equivalent to a meter.

placed at 10-meter intervals in order to span this layer. Simultaneously, profiles of temperature, salinity, particulate matter concentration, and dissolved oxygen concentration were made as close to the mooring as 100 meters. An example of



These temperature and velocity data were taken by the benthic boundary layer mooring shown in the drawing at left. The mooring was placed on the Hatteras Abyssal Plain at 28°30′N, 70°30′W for 3.5 months while Vector Averaging Current Meters (VACMs) recorded average current speed and direction and water temperature every 7.5 minutes.

the temperature and velocity record is shown above. The temperature signal of any instrument above the mixed layer contains finestructure and internal wave variability; within the layer this variability is absent. Mixed layer height is obtained by counting the number of instruments indicating the same well-mixed temperature. Note that the second half of the record shows an intermediate mixed layer intrusion with a differential motion between the warmer intermediate layer and the colder bottom layer. These intrusions or laterally advected mixed layers are also seen in the profiling data. The horizontal advection or transport of bottom boundary mixed layers originating at different depths causes vertical mixing. Little such vertical mixing appears to be taking place away from the bottom boundaries.

Some evidence for the absence of cross density mixing or stirring in the interior can be found in the persistence over large distances of a concentrated 20-meter-thick layer. This layer is also evident in the figure above at a pressure of

5,240 dB. There is a mid-water maximum in particulate matter and an anomalous temperature-salinity signal. Warm water is found beneath cold water, although the stratification is stable. This warmer, "dirtier" water is slightly saltier than the background water at this temperature. Although this profile was taken over the Northern Hatteras Abyssal Plain, this same layer can also be found some 3,000 kilometers away over the Sohm Abyssal Plain. The layer is apparently patchy, sometimes clearly present, sometimes not. What is its origin?

Cold water forms in the Norwegian Sea, sinks and flows down in a large undersea river through the Denmark Strait, under and around the Labrador Sea and past the tip of the Grand Banks off Newfoundland onto the Sohm Abyssal Plain. This large undersea river of cold Norwegian Sea Water is always flowing down through water of lower density — it could not, in fact, flow downhill except through less dense water. On the Sohm Abyssal Plain this large river of cold water, its density decreased somewhat by mixing, finally encounters water that has the same density, and it forms at this density a patchy layer which can be found throughout the basin.

There is a striking persistence of this layer over large horizontal distances from the Northern Sohm Abyssal Plain where it is fed by the Norwegian Sea Water. The existence of this thin layer some 3,000 kilometers from its source means little vertical exchange is occurring in the interior of the basin.

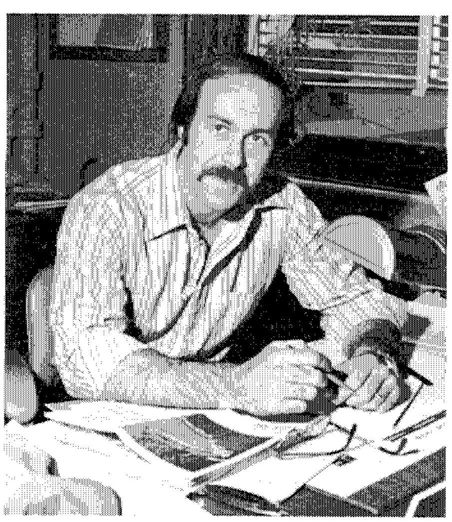
Mixing in the deep ocean is essentially the result of two processes: 1) most vertical mixing occurs within 50-to-100-meter-thick boundary mixed layers, and 2) there is horizontal advection of the layers into the interior by large eddies and the general circulation. One is reminded of arguments made some years ago by Columbus O'D. Iselin on the importance of lateral mixing to thermocline formation of waters with surface characteristics. For the deep ocean, lateral mixing is again very important, but for water with the characteristics of the boundaries. One important characteristic of a boundary is that it produces small-scale turbulence and vertical mixing.

The goal of attempting to understand mixing in the deep ocean may seem abstract, but it is closely related to pressing practical problems connected with disposal of pollutants and nuclear wastes. The understanding of dynamical processes in the bottom boundary layer itself will help in the design of structures and in predicting deposition and erosion.

Sediment Transport, Bed Forms, and Bottom Currents

William Grant

In the quest for understanding ocean bottom processes, one of the fundamental phenomena being studied is sediment transport and its relationship to the fluid forces developed by the water motion in the immediate vicinity of the seabed. The recent increase in man's use of the oceans, particularly the continental margins, has emphasized the poorly developed state of our knowledge of sediment transport processes. Ocean and coastal engineers need quantitative information about sediment transport to design submarine pipelines and offshore structures, to estimate dredging requirements at offshore and onshore port facilities, and to deal with numerous beach erosion and inlet stability problems. Scientists studying such subjects as sediment distribution in the ocean, wave energy dissipation due to bottom friction, and the environmental impact of offshore sand and gravel mining also need this information.

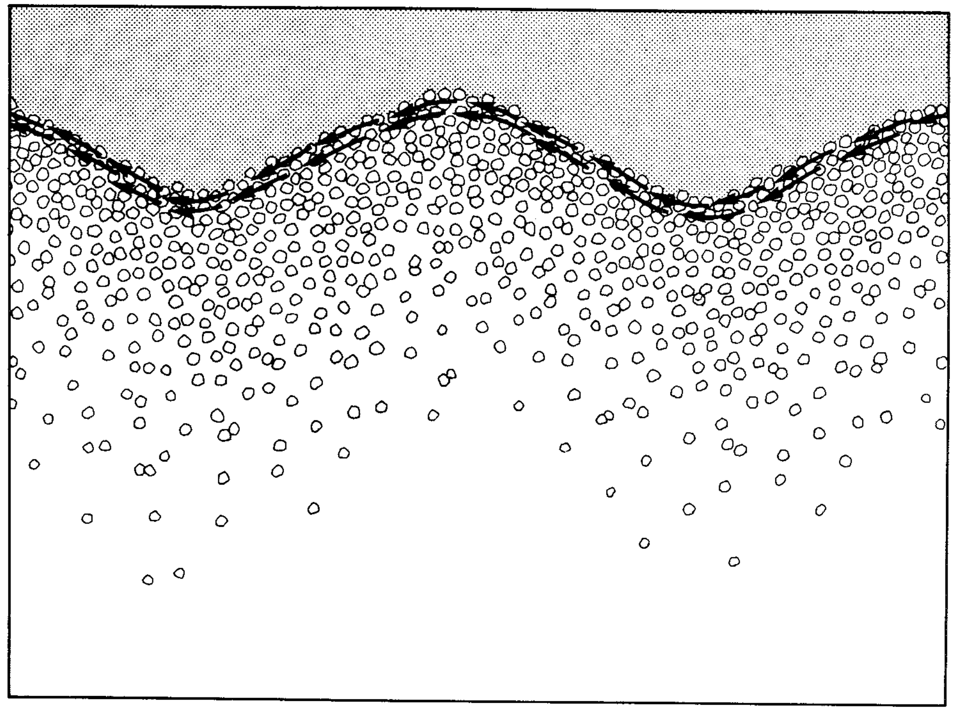

FRANK MEDEIROS

Bill Grant

The transport of sediment takes place in two physically contrasting modes generally referred to as *suspended load* and *bed load*. There are *fine* and *coarse* suspended load modes. *Fine suspended load* consists of a layer of fine-grain sediment particles moving along horizontally at nearly the mean flow velocity, essentially independent of any bottom influence. Such a layer of sediment can have quite extensive vertical dimensions and typically consists of sediment grains introduced into the water column from a distant source, such as river inflow or dredging activities, rather than from local resuspension at the bottom. *Bed load* transport occurs in the immediate vicinity of the seabed in a thin layer several sediment grain diameters thick. In this layer, the individual grains of sediment are moving along in discrete jumps, spending most of their time in contact with the bottom and moving at a rate somewhat less than that of the mean water motion. The sediment grains making up the bed load are locally entrained into the flow by fluid forces acting on the seabed. Under conditions involving highly turbulent flow, sediment grains that move only as bed load under more quiescent conditions may be locally suspended from the seabed and move in a suspended mode of transport. Since this suspended material depends directly on the bottom conditions and is directly related to the bed load, it should be distinguished from the fine suspended load described above and is therefore called *coarse suspended load*. The thickness of the coarse suspended sediment layer will also be considerably smaller than in the case of the fine grain sediments due to the greater fall velocities of the coarse sediment. In general, the mechanism of suspended load transport is much more efficient in transporting sediment over long distances than is the bed load mode. However, the volume of material transported as bed load, or as coarse suspended load, is responsible for the local erosion and deposition at the seabed. This local deformation plays a critical role in the process of sediment transport itself as well as in the determination of the nature of the water velocity profile adjacent to the seabed.

The details of the role played by the bed forms or bottom roughness in the process of fluid-sediment interaction are quite complicated, but a simple picture may be presented as follows: As water flows over a roughened seabed, it experiences resistance as part of its energy is dissipated through the generation of eddies in a process called turbulence. (These turbulent eddies are actually responsible for the movement of individual grains as bed load and also for the suspension of particles as suspended load.) Both the level of turbulence generated at the bottom boundary and hence the flow resistance increase as the bed becomes rougher. Thus the presence of bed forms causes an increase in the resistance felt by the flow over that which would be present were the seabed smooth. The flow field, in response to the increased resistance, is modified, exhibiting a steepening of the velocity profile near the bed. A corresponding change in the amount of sediment being transported by the flow also accompanies the velocity profile modification. Clearly, the process has made a full cycle, since the quantity of sediment transported influences the structure of the bed forms responsible for the boundary roughness. The mechanism of adjustment of the bed geometry and the flow field goes on continually or until an equilibrium bed profile is developed in circumstances where flow conditions at the bed remain steady.

Fluid interaction with a roughened bottom like that described above occurs throughout the ocean wherever significant water motion is present at the seabed. However, the bed forms or bottom roughness found in particular regions of the ocean differ in their characteristics depending on the sediment type, e.g., cohesive sediments or noncohesive sediments, and also on such physical processes as surface waves and currents. Our present ability to quantify in a general and basic manner the fluid-sediment interaction on a roughened bed is unsatisfactory, and research is underway to study these processes in more detail.



Sediment entrainment over wave formed ripples. Once the sediment grains from the bed load layer (arrows) are introduced into the suspended load region above, they are available for transport by mean currents.

One region of immediate concern is the inner continental shelf area of the eastern United States where many of man's present and future marine activities are planned. Surface gravity waves and currents are the dominant physical processes controlling the fluid-sediment interaction at the seabed in this physically dynamic region. Their combined presence further complicates the problem of determining the boundary roughness encountered by the flow since the presence of the unsteady oscillatory water motion at the seabed associated with the surface waves increases the level of bottom turbulence. The increased turbulence caused by the waves acts as "apparent roughness" and, in a process analogous to the effect of bed forms on the flow, increases the resistance experienced by the flow. It is important, but difficult, to distinguish the respective zones of influence of the bed form roughness and the "apparent" wave roughness.

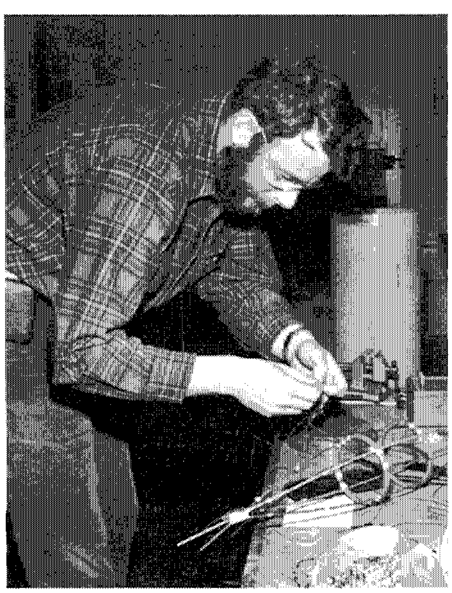
The following article by Albert J. Williams 3rd describes field studies utilizing current-measuring techniques developed at the Institution to measure bottom velocity under combined wave and current flows. These studies will advance our understanding of the fluid-sediment processes at the seabed and help improve recently developed theories for boundary layer flows under combined waves and currents.

Measurement of Bottom Boundary Layer Velocity Structure

Albert J. Williams 3rd

THE physical interaction of the ocean current with the sea floor creates ripples and erosion in the sediment and produces turbulence and mixing in the water. This aspect of the benthic boundary layer has much in common with the atmospheric boundary layer where wind interacts with the surface of the land. Both are planetary boundary layer flows. They are turbulent shear flows where the velocity increases away from the boundary, but there is often an exchange of fluid between regions near the boundary and those further from it. Very close to a smooth boundary — for example, within millimeters of a smooth fine-grained sediment — the viscosity of the fluid may be important to the flow. In this so-called viscous sublayer, the velocity varies linearly with distance from the boundary, and the fluid shear stress is proportional to this velocity gradient. The same shear stress is felt by the sediment surface, and it determines whether there will be erosion or not. Unfortunately, the actual sediment interface is almost never smooth enough for the viscous sublayer to be observed directly, and thus the technique of simply measuring the linear gradient in velocity and computing the shear stress on the sediment is rarely possible.

FRANK MEDEIROS



Sandy Williams

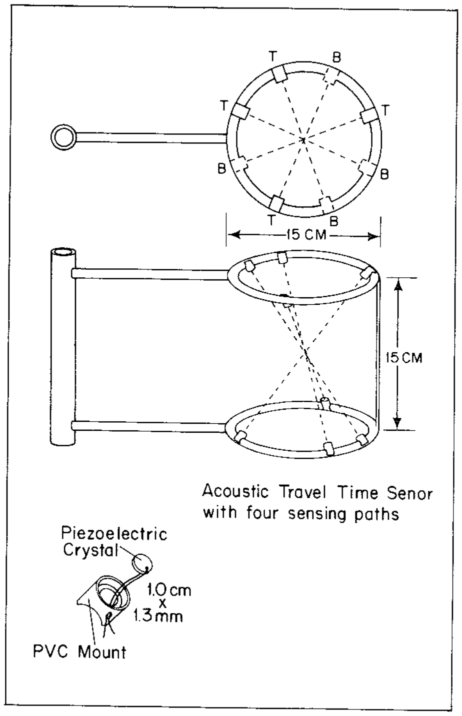
We have, therefore, turned to the following approach. If the flow is not being accelerated, all the forces on the fluid must be in balance. A layer of fluid may have pressure forces on it, as, for example, flow downstream in a river; it may have Coriolis forces on it due to the rotation of the earth; it may also have shear stresses on it from above and below. More than 10 meters from the boundary in typical deep-sea flows, the Coriolis forces are important, and the current changes direction with distance from the boundary. Pressure forces cannot be neglected in tidal flows, but they may be small in deep-sea currents. In many flows, there is a region from a few centimeters to a few meters from the boundary where the dominant forces on the fluid are the shear stresses from above and below. For these to be balanced means the stresses must be constant, and this is termed the constant stress layer. In reality, such a layer may never actually exist, and our conception must be considered as no more than an approximation to the actual conditions. Furthermore, the stresses do not balance instant by instant, and the fluid is alternately accelerated one way and another. Only on the average is the acceleration zero and are the stresses balanced. However, this allows shear stress on the sediment to be estimated by measuring the stress farther from the boundary in the constant stress layer.

Except for very close to the boundary, as mentioned before, viscous forces are not very important for carrying stress. Momentum exchange or inertial forces are the important processes in the region from a few centimeters to a few meters from the boundary. Turbulent eddies move high-velocity fluid flow toward the boundary where momentum is given up to the slower fluid there, and slow-moving fluid is carried away from the boundary to be accelerated by the flow at greater distances. It is significant that these turbulent eddies mix more than momentum. Heat, sediment particles, and chemical substances are similarly mixed away from the boundary by the turbulent flow, and the very intermittance of the flow produces peak stresses on the sediment that are considerably higher than the average. These could initiate erosion even when the mean stress is not capable of it.

A careful measurement of velocity at several points within the bottom few meters of the ocean can allow the stresses to be calculated. If the flow moves faster when it comes closer to the boundary and slower when it moves away, momentum is being transferred toward the boundary. This represents a stress called, when suitably averaged, Reynolds stress. To detect these Reynolds stresses, a velocity sensor must measure both vertical and horizontal components and must register small changes superimposed on the mean flow. The sensor must be small to resolve small-scale eddies, must sample rapidly to catch the fluctuations, and must not create turbulence itself where it is measuring the boundary layer turbulence.

Laboratory studies of such flows have used hot film or hot wire "anemometers" or velocity sensors, but they are poorly suited for unattended measurement in the sea because they become dirty and change their calibration. Small-scale propeller sensors, electromagnetic current meters, acoustic current meters, and Doppler current meters all appear capable of making these measurements in the ocean. The propeller sensors work well if there is a strong flow on which the turbulence is superimposed, but they stall at slow speeds. The electromagnetic and acoustic current meters have a linear response through zero speed, which is good, but unfortunately makes it difficult to define that zero speed with great precision. On the other hand, they are sensitive to small fluctuations even at small velocities. The acoustic meter senses flow physically removed from the hardware, so it has little likelihood of disturbing the flow. Doppler current meters measure velocity by the Doppler frequency shift of light or sound bouncing off natural particles suspended in the fluid. They represent the ultimate high-resolution velocity meters for measurements very close to the bottom and even in the viscous sublayer, if it exists.

Commercially available velocity sensors do not appear to be capable of measuring the turbulent fluctuations in the benthic boundary layer flows (although electromagnetic three-axis sensors may resolve large-scale turbulent flows). It has been necessary, therefore, for us to develop our own instruments. We have put the greatest effort into an acoustic technique that was tested last August in Vineyard Sound with a vertical array of four current sensors. Each sensor measures four velocity components — one more than needed to determine the Reynolds stress. Thus, one of the measurements may be disturbed and an accurate velocity vector still obtained. Each of the vector component determinations requires that acoustic pulses be exchanged between a pair of transducers. The pulse propagating upstream is retarded while the pulse propagating downstream is advanced, and the difference in travel time is proportional to the average velocity component along the transducer axis. In the first tests, 16 of these measurements were made and recorded in digital form every ¾ second for analysis of a tidal half cycle.



While shallow-water tidal flow in a channel does not duplicate deep-ocean flow very closely, it does generate a turbulent boundary layer and display Reynolds stress contributions to the force on the fluid. These have been recovered by breaking down the vector into downstream, cross-stream, and vertical components. Fluctuations of the vertical component are correlated to fluctuations of the downstream component; that is, all cases where the flow has a downward component at the same time as it increases its downstream speed contribute toward the correlations and represent Reynolds-stress-type fluctuations. Indeed, there was a strong Reynolds stress signal detected at each sensor. The instrument appears to have achieved its design objectives and is now ready for deployment in the deep sea.

Current Shaping of Seabed Sediments

Charles Hollister and Nicholas McCave

THE recent acceleration of interest in processes in the benthic boundary layer of the deep sea has been due largely to the realization by the oceanographic community that large areas of the deep sea floor are being strongly affected by near-bottom circulation. Some scientists believe that much of the suspended matter in the bottom nepheloid (turbid) layer is a direct result of sediment resuspension by bottom currents. It is often stated in the literature that many of the regular bed forms ranging in size from kilometers to centimeters are also the direct result of energetic motions within the benthic boundary layer of the deep sea. The genesis of these bed forms, for example furrows and mud waves, found in cohesive sediment at abyssal depths is not at all well understood.

VICKY CULLEN

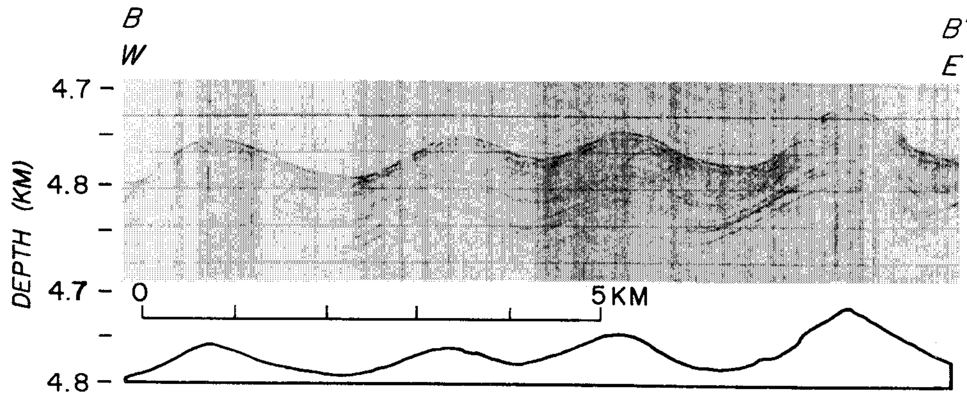
Charley Hollister and Nick McCave

In the past few years, various workshops have addressed scientific problems posed by the bottom boundary layer of the oceans. An important aspect of the conclusions of these workshops has been recognition of the fact that the shape of the boundary itself, the form of ripples, scour crescents, furrows, giant mud waves, and major topographic sedimentary ridges, is a potential source of much valuable information on flow conditions near the bed.

At the time these patterns were first observed, it was thought that the abyss was a generally tranquil region with little to disturb the gentle rain of particles from above. It did not seem possible to some that these patterns were produced by strong, near-bottom currents. There are, of course, vast areas (in the middle of great oceanic plates and beneath the major surface circulation gyres) where tranquility, perturbed only by the gentle probings of a wide variety of benthic organisms, is the rule. But recent observations, utilizing sophisticated deep-sea instruments, reveal that considerable commotion prevails near the edges of ocean basins and in the cold high latitude regions where bottom water is produced. In all oceans, strong bottom current activity is concentrated on the western side of basins. This is exactly where we find the most dramatic and most abundant current-produced abyssal bed forms; this is where the most turbid bottom water exists. The largest scale of these bed forms, such as the Blake-Bahama Outer Ridge system off the southeastern United States, indicates flow of bottom water along the same path for tens of millions of years.

A current meter record usually yields current direction and speed information which can be processed to give an indication of the average speed and the magnitude of the fluctuations. The record of sediments and bed forms promises to yield similar information if we can decipher it correctly. We already are able to map the direction of bottom currents producing ripples, lineations, scours and furrows, i.e., bottom depositional and erosional features. From the grain size of some of the bed material and its rate of deposition we can assess indirectly the current strength responsible for the bed forms. A difficulty arises here: what current speed should we consider, the mean or maximum? We have a view that deposition may be a more nearly continuous process and erosion more episodic. Clearly, if we can separate the various effects, the record of the sediments provides the basis for a natural meter with information on the direction, speed, and, perhaps, variability of deep ocean currents over much larger spatial and temporal scales than can be achieved by even the most sophisticated of current meters.

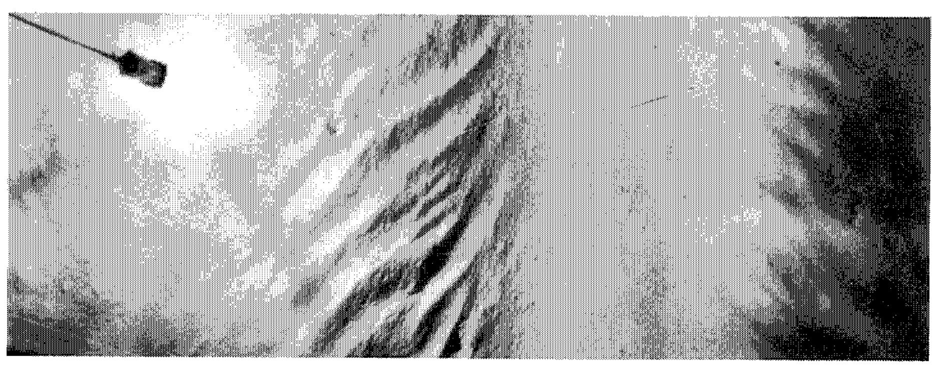
The largest scale bed forms found on the major sediment piles in the ocean are mud waves with a wavelength of a few kilometers. In general they are found down-current from regions of high sediment input. They appear to be produced by depositional processes within deep-current circulation patterns. These mud waves, which can be identified from surface ship echo-sounding profiles, are common features. Small hyperbolic echoes seen on echo soundings are generally believed to be the side-echo reflections from furrows. These are very well developed on the Blake-Bahama Outer Ridge. The furrows, an order of magnitude smaller than the mud waves,



Surface ship 3.5 kHz reflection profile of mud waves together with an echo-sounding profile obtained near the bed. The reflection profile shows the wavy surfaces are present below the seabed testifying to their permanence and demonstrating slight migration to the right.

are developed on the mud waves themselves. The furrows appear to be related to post-glacial, or modern, current activity. Near-bottom observations from the bathyscaphe *Trieste II* indicate that some furrows are presently being eroded, while others may be depositional. Small (centimeter-scale) asymmetric ripples are found on the side of depositional furrows. These ripples are developed in fine-grained cohesive sediments and appear to be in equilibrium with the present flow pattern.

These bed forms and the sediments which comprise them are the sensors of our current meter system, and, already, we can interpret them at a basic level. More detailed interpretation will only be possible when we understand more fully the processes of flow, erosion, and sedimentation responsible for these bed forms. To this end, drawing on the resources of a number of disciplines, we are working towards mounting a benthic boundary layer experiment in which current speeds and fluctuations, temperature and salinity, suspended material concentration and properties, and accurate monitoring of the form and response of the bed are all combined.



Photograph and cross section of a furrow. Ripples are shown on the furrow walls.

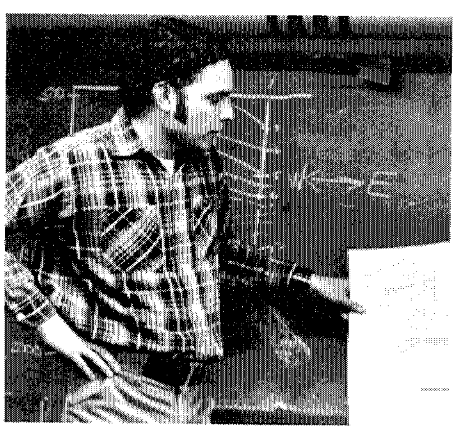
Geologic Evidence for Ocean Floor Erosion and Its Temporal Variability

David Johnson

DRY-LAND geologists are well aware of the importance of relatively infrequent events, or "storms," in producing some of the earth's most spectacular geomorphological features. Familiar examples of land forms whose initiation and subsequent development are highly episodic include landslides, alluvial fans, and the flood plains of major river systems. When considering the abyssal ocean, by contrast, it had been customary to assume that relatively steady-state conditions prevailed for long periods of time. After all, it was argued, the extreme contrasts in temperature and precipitation are most influential at the earth's surface and should be substantially, if not totally, dampened before their influence could be felt in abyssal depths. Since the mixing time of the oceans is on the order of several hundred years, daily and seasonal variations at the ocean's upper surface should have little or no influence on conditions in the interior of the ocean and on the underlying sea floor.

Within the past 25 years, geologists and oceanographers have recognized that the assumption of "steady-state" conditions at the ocean floor, even over a relatively short period of time (hours to days), is an unwarranted oversimplification. Over longer durations (years to millions of years), the abyssal ocean is apparently subjected to infrequent episodic events that are as geologically significant as the more familiar, more extensively documented terrestrial examples.

SANDY SHOR



Dave Johnson leads seminar on *Atlantis II*.

A number of difficulties are continually encountered in our attempts to document and explain precisely the temporal variability of ocean floor processes. For example:

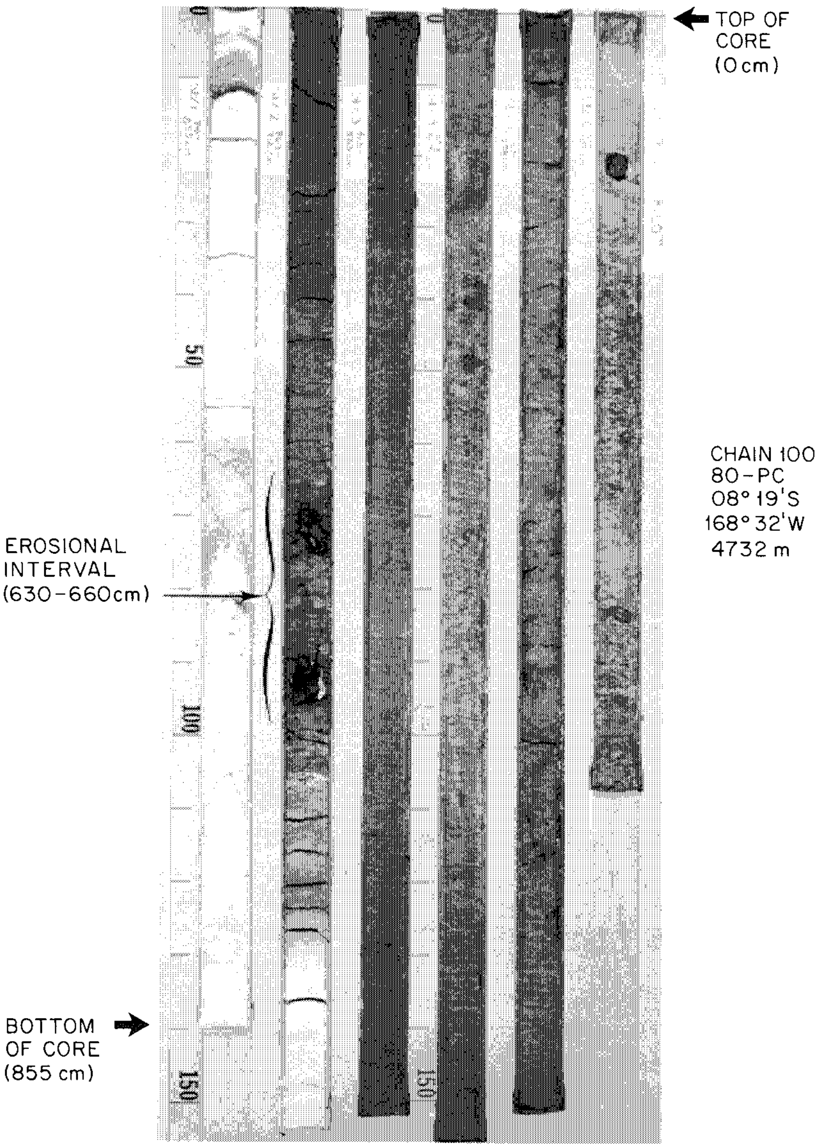
(1) Time-series observations in the benthic boundary layer have shown that much of the variability is not strictly periodic but episodic and of relatively short duration. In fact, the most geologically significant events are likely to be very infrequent, and the likelihood of observing such an event during a time-series experiment is small. Consequently there is considerable uncertainty in relating processes observed during a short-term experiment to the geological evidence that is necessarily integrative over much longer spans of time.

(2) The geologic evidence that allows precise documentation of erosional events may be largely missing. For example, the figure on the next page shows a core with 50 million years (m.y.) of sedimentary record missing. The upper part of the core (down to ~630 centimeters) is Pleistocene (<1.6 m.y.), whereas the lower portion of the core (below ~630 centimeters) is early Tertiary (>55 m.y.). Separating these two units is a manganese pavement representing a long period of erosion or nondeposition. The event(s) which produced this hiatus could have begun at any time between ~55 m.y. and ~1.5 m.y. before present, and the information from this core alone does not allow us to determine when they began. As another example, the widespread erosion of hundreds of meters of carbonate sediment in the equatorial Pacific may be due to chemical dissolution, but the critical pieces of evidence documenting this explanation have been largely dissolved away.

(3) Even when the geologic record can be pieced together from a number of different cores that collectively contain a fairly complete record, very precise stratigraphic resolution is needed to correlate satisfactorily between cores and to establish the timing and causes of erosional and nondepositional events. Biostratigraphic correlation uses skeletal remains of widespread planktonic organisms which evolve and change with time. Many of these evolutionary changes occur approximately synchronously. As a consequence, this technique has a precision of 0.5 m.y. to 1 m.y. and is sufficient for documenting major events of long duration. But for those variations of shorter duration (e.g., glacial/interglacial climatic events), a much more refined technique for stratigraphic correlation is required.

Recently a new technique has been introduced. During the glacial and interglacial periods of the late Pleistocene (<m.y.), the ratio of the stable oxygen isotopes (^{18}O and ^{16}O) in the ocean changed in response to the climatic changes. Organisms growing in the ocean reflected these changes and measurement of the oxygen isotope ratios in the remains of these organisms now provides us with a very powerful technique for stratigraphic correlation.

Explanations for the causes of episodes of ocean floor erosion are generally related to either (a) global tectonics or (b) variations in the earth's climate. On a time scale of tens to hundreds of millions of years, changing configurations of continental masses and changing geometries of the ocean basins lead to shifting patterns of flow for both surface and abyssal waters. For example, the opening of the Drake Passage about 22 m.y. ago and the separation of Australia



Deep-sea sediment cores including one with a 50 million year erosional interval.

from New Zealand about 50 m.y. ago were critical events in controlling the routes of Circumpolar Water and Antarctic Bottom Water into the major ocean basins. On a time scale of thousands to a few million years, climatic changes appear to be the most important factors controlling the rates of production of bottom waters in polar latitudes. Ocean-floor variations on a scale of years to thousands of years fall into a largely unknown region: too long to measure directly, yet too short to be reliably documented in the geologic record. Some of the variations observed on a time scale of days to years may be explained in terms of the dissipation of tidal energy on the ocean floor or the migration of eddies in the overlying water column; by and large, however, most of the variability on a short time scale is unexplained.

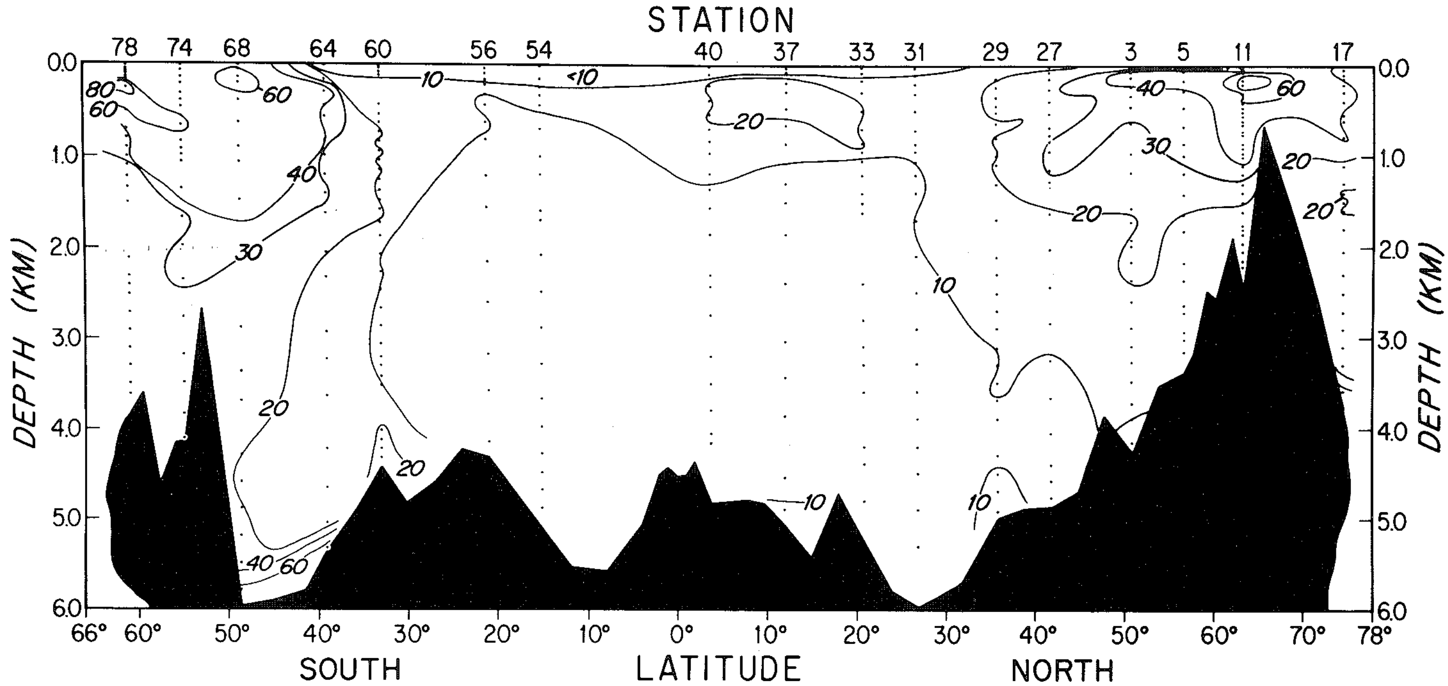
One of the most critical future problems is the establishment of a definitive correlation between the geologic evidence in modern sediments and properties of the overlying water. We need to determine with more certainty whether or not a particular patch of ocean floor is "in equilibrium with" conditions in the water column. And we need to identify those sedimentary components and bed forms that are quantitatively related to the properties and/or flow characteristics of water in the benthic boundary layer. Only through the establishment of such correlations can we begin to derive precise and quantitative interpretations of paleocirculation from the available geologic evidence.

Chemical Fluxes to the Bottom Boundary Layer

Peter Brewer

CHEMICAL fluxes to the bottom boundary layer take place principally through the sinking of particles. Some direct adsorption of ions from seawater to the sediments, or the cloud of suspended material frequently found near the sediment-water interface, takes place, but this is of importance only for a few highly reactive and easily hydrolyzed chemical species. Oceanographers have long realized that the diversity of the remains of pelagic organisms found in deep-sea sediments matches that occurring in the euphotic zone several thousand meters above and have postulated that rapid sinking of particles might occur, most probably through zooplankton grazing on fine particles and excreting fecal pellets. This mechanism provides a direct coupling of the sea surface and the sediments beneath, and is of great interest to marine scientists.

Our initial investigation of the chemical composition of marine particulate matter on GEOSECS samples in the Atlantic and Pacific Oceans has yielded information on the abundance of particulate material and its elemental composition. The figure overleaf shows the distribution of particulate barium, in nanograms of



Barium in nannograms per kilogram in the western Atlantic.

barium per kilogram of seawater, along a section through the western Atlantic Ocean from 78°N to 66°S. Barium appears to be taken up by siliceous organisms, which tend to be more abundant in cooler waters, and the poleward enrichments of particulate barium can be plainly seen. Beneath the euphotic zone the tongues of particulate barium extend downward and toward the equator reflecting sinking, dissolution, and dilution by mixing. By combining data such as this with Stokes Law calculations, or with radio-isotopic data, it is possible to arrive at a settling velocity and a flux to

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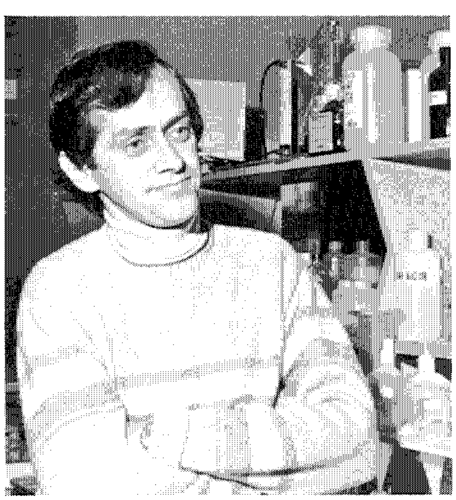


Peter Brewer

the sediments. Data of this kind are not biased in any way, since an element of seawater is trapped in a sampling bottle and completely filtered; however, the probability of catching a large and fast-sinking particle is quite small, and the estimate of the flux is indirect.

The direct measurement of the flux to the sediments comes from the use of sediment traps. We have successfully carried out several such experiments using a sediment trap designed in the form of a cone with a 1.5 m^2 collection area fitted with a 25 cm cell size honeycomb to spoil turbulence. The cone angle of 60° permits particles falling into the trap to roll down and into a Lucite collection cup containing a bactericide to retard spoilage. A timer controls closure of a door over the cup at the end of the experiment. These traps are deployed on a taut mooring at several depth horizons, and they are recovered by activating an acoustic release. In a 75-day experiment at 31°34′N, 55°03′W in the Sargasso Sea, we observed a mean total particulate flux of 1.68 $\pm$0.79 $mg/cm^2/yr$, at a depth of 5,367 meters. The trapped material consisted of about 50 percent clay, 20 percent calcium carbonate, 20 percent silica, and 5 percent organic matter. From elemental and isotopic investigation of the samples, we conclude that much of this material is derived from the nepheloid layer and represents resuspended sediments. Only 5 percent of the clay, most of the calcium carbonate, and 90 percent of the organic matter were contributed by rapidly settling particles from above. In particular, green fecal pellets derived from the euphotic zone contributed the greater part of the flux of the biophilic elements carbon, calcium, strontium, and iodine.

In one sense, the ocean floor acts as the ultimate sediment trap, and cores can reveal much of the historical record of the particulate flux. However, because of many effects, such as bioturbation, there are many questions that cannot be answered by direct examination of sediments. How does recent particulate material differ from ocean sediments, and what chemical transformations are required to transform one into the other? What is the rate of supply of organic carbon as food for benthonic organisms? Does sinking particulate material adsorb chemical elements during transit, thereby cleansing the water column? How will the industrial pollutant signal of the twentieth century be recorded on the ocean floor? We hope to answer some of these questions in our continuing work.

Dissolution of Carbonate Particles in the Deep Ocean

Susumu Honjo

LARGE portions of the deep oceanic water column are undersaturated with calicite and aragonite. The manifestation of this undersaturation on the sea floor is a narrow transition zone separating calcium carbonate rich sediments above from calcium carbonate poor sediments below. This transition zone is called the CCD (calcite compensation depth) and is believed to represent a narrow depth range where rate of dissolution equals rate of supply, causing accumulation rates of calcium carbonate to be very low. The CCD can be represented as a subhorizontal surface occupying a depth of 4.5 to 5.5 kilometers in the major ocean basins.

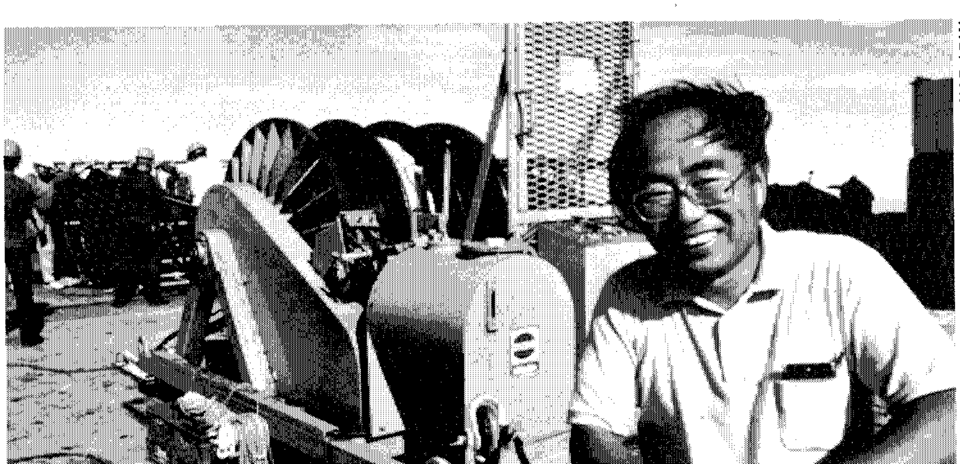
In most places the CCD does not coincide with the depth at which seawater becomes undersaturated with calcite. This depth is considerably shallower than the CCD in both the Atlantic and the Pacific. Furthermore, below 2 kilometers the extent to which the water is undersaturated with calcite decreases almost linearly with depth while percent of carbonate and the degree of preservation of planktonic foraminifera decrease at a much faster rate. The position of the CCD is determined by the rate at which calcium carbonate is supplied to the ocean floor, dilution by noncarbonate sediments, and the rate at which calcium carbonate dissolves. Production of calcium carbonate in the surface ocean by plankton (mainly coccoliths, planktonic foraminifera tests, and pteropod shells) by far exceeds the supply of calcium and carbonate from rivers. Therefore, most of the calcium carbonate produced must dissolve if the chemical composition of seawater is to remain constant. Dissolution of carbonates in the ocean also regulates the pH of seawater (at least over an oceanic mixing time scale). Thus, changes in pH caused by addition of carbonate to the atmosphere through combustion of fossil fuels will be buffered by calcium carbonate dissolution in the ocean. Accurate dissolution rates of carbonates are therefore essential to any attempt to understand calcium carbonate related phenomena and to prediction of the earth's health regarding ever-increasing levels of atmospheric carbon dioxide.

Estimates of dissolution rates from carbonate sediments and from laboratory experiments have proven unsatisfactory for many reasons. *In situ* experiments in which calcium carbonate particles were suspended for several months in cages or permeable containers at different depths in the water column have been more useful. Dissolution rates were estimated from the weight loss during the experimental period. Perhaps the most important result of these experiments is that at a certain depth level (4 to 5 kilometers) the rate of dissolution shows a sharp increase with depth. This depth is above the CCD and is referred to as the chemical lysocline. One important problem with these *in situ* experiments was that the free exchange of seawater was interrupted by the container, and therefore accurate rates of dissolution may not have been obtained. In addition, the coccoliths, which are the major constituent of biogenic carbonates in the ocean, are much too small to handle easily.

Utilizing the Institution's highly developed deep-sea mooring engineering capability, we have moved *in situ* measurement a step forward with fully automated instrumentation to measure the dissolution rate of oceanic particles at any water depth. The significance of the ISWAC II (*In Situ* Water Circulation Mark II) system is that 16 fine-grained samples can be exposed simultaneously to *in situ* water for several months with minimum mechanical loss and without stagnation. A sample is placed in a Lucite cylinder 3.3 centimeters long and 2.4 centimeters in diameter. Both ends of the cylinder are protected by filters with pore sizes of 0.6 to 0.4 micrometer. Seawater in the chamber is replaced every 20 minutes by pumping water through the chamber at a rate of 0.6 cubic centimeters per minute, a rate that will prevent stagnation even at very high rates of dissolution.

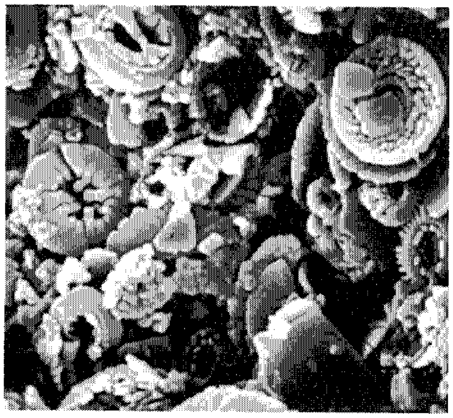
Three ISWAC II instrument packages were deployed at depths of 3,598 meters, 4,799 meters, and 5,518 meters along the taut line of a sediment trap mooring in the Sargasso Sea at 32°22.0'N and 55°00.8'W where the water depth is 5,581 meters. The samples were exposed to seawater for 79 days beginning 20 October 1976. To avoid contamination by biogenic and man-made organic matter in surface water, the interior volume (including chambers, tubing, pumps, and prefilter) was filled with artificial seawater, and pumping began three hours after the anchor was set.

At 3,600 meters and 4,800 meters no weight loss was detected for the calcite samples, but aragonite samples showed significant dissolution. All the samples



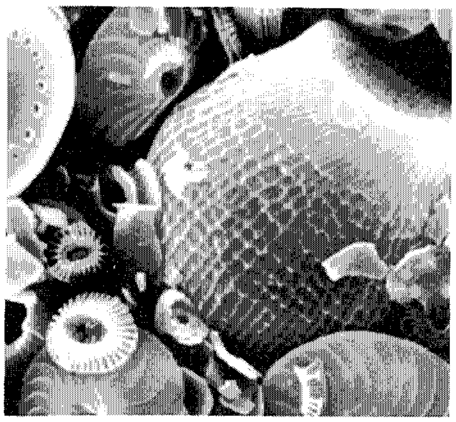
LAURENCE ARMI

Sus Honjo on deck of *Knorr* with sediment traps being deployed in the background.



MARGARET GOREAU

The photo above shows coccoliths considerably dissolved after exposure at 5,200 meters in the Sargasso Sea for 80 days. They are magnified about 3,000 times. In the control sample below, which was moored at 400 meters, the dissolution susceptible species have completely disappeared, and diversity has been reduced to only a few species.

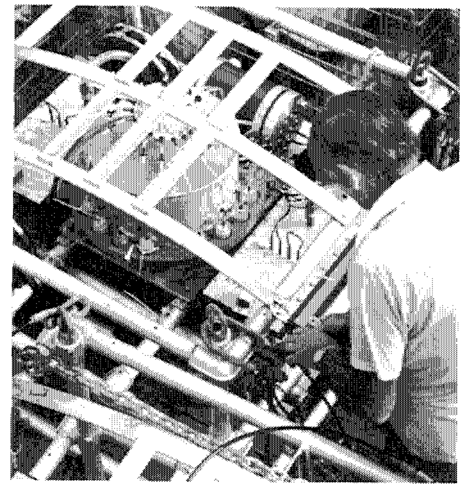


MARGARET GOREAU

deployed at 5,518 meters were significantly dissolved as shown in the table below, and the percent weight loss varied widely. The pteropod and synthetic aragonite samples dissolved most, 72.8 percent and 72.2 percent respectively. Reagent calcite lost 57.5 percent; the foraminiferal assemblage lost 30.4 percent; individual species of foraminifera ranged from 23 to 36 percent; and cultured coccoliths (several grams of "pure" coccoliths were produced in our laboratory from a ton of laboratory culture media) lost only 11.3 to 14.5 percent. The bleached *E. huxleyi* coccoliths dissolved twice as much as the unbleached sample.

One might expect that the specific dissolution rate (weight loss/specific surface area/unit time) should be equal for all calcite particles. Yet the specific dissolution rates we measured for different kinds of particles differed by more than two orders of magnitude. The coccoliths, with the largest specific surface area, showed the lowest weight loss, while reagent calcite, with very small specific surface area, showed the highest weight loss. Foraminifera, with intermediate specific surface area, showed higher weight loss than coccoliths but lower weight loss than the reagent calcite.

Recent sediment trap experiments have shown that biogenic carbonates may reach the floor of the deep Atlantic without undergoing significant dissolution. Thus, much of the dissolution may take place on the ocean floor before the particles are buried. The time required for complete dissolution of a particle can be calculated from the dissolution rates measured during our experiment. When the accumulation rate is known, the time a particle spends on



SUSUMU HONJO

This *in situ* water circulation system exposes 16 fine-grained samples to seawater for several months for measurement of calcium carbonate and silicate dissolution rates.

Summary of Measurements from ISWAC II Experiment at 5,500 m

Material	% Weight Loss in 79 days	% Weight Loss per year	Complete Dissolution Time (days)	Initial (SSA*) m^2/g	Final (SSA*) m^2/g	Sp. Dissolution Rate (Init. SSA*) $mg/cm^2/yr$	Sp. Dissolution Rate (Final SSA*) $mg/cm^2/yr$	Sp. Surface Area Increase (%)
Reagent Calcite	57.5	266	137	0.36	–	0.74	–	–
Large Calcite Crystals	2.2	10	3591	0.013	–	0.78	–	–
Synthetic Aragonite	72.2	333	109	1.53	–	0.22	–	–
Foraminifera assemblage	30.4	140	260	1.51	3.33	0.09	0.042	121
Bleached Foram. assemblage	36.5	169	216	1.50	5.18	0.11	0.033	245
G. sacculifera	36.3	168	218	3.44	8.19	0.05	0.021	138
G. bulloides	23.0	106	343	2.67	3.72	0.04	0.029	40
G. pachyderma	31.1	144	254	1.41	1.88	0.10	0.076	34
E. Huxleyi	11.3	52	699	10.4	11.5	0.005	0.005	10
Bleached *E. huxleyi*	24.0	111	329	10.4	12.3	0.011	0.009	18
C. neohelis	14.5	67	545	9.86	–	0.007	–	–
Pteropod assemblage	72.8	336	108	2.17	3.09	0.15	0.11	42
Diatom, *coscinnodiscus* sp.	12.0	55	658	6.50	17.5	0.009	0.003	169

*SSA: Specific Surface Area

the sediment-water interface before burial can be estimated for different sized particles. It is assumed that once a particle is buried, its dissolution rate is strongly retarded. If the time required for complete dissolution is longer than the time a particle spends on the sediment/water interface, it has a good chance of being preserved in the geological record. Obviously, other factors like bioturbation, resuspension, and changes in accumulation rates, including those caused by dissolution, must be taken into account in more elaborate models of carbonate dissolution at the water/sediment interface. Yet, application of this model to the data we collected reveals useful information.

A sedimentation rate of 3 millimeters per thousand years (0.008 micrometer per day) is a conservative estimate for the central Sargasso Sea where the ISWAC was deployed. The average size of a pteropod is above 2,000 micrometers, and the corresponding time before burial is more than 240,000 days. The complete dissolution time is 108 days. Thus, no pteropods should be found in the sediments at our station. The time before burial of foraminifera with an average diameter of 150 millimicrons is more than 18,000 days, and their complete dissolution time is 260 days; hence, there is only a very small chance that foraminifera will last long enough on the interface to be buried. The time before burial of coccoliths with an average height of 5 millimicrons is 600 days, while their complete dissolution time is about 700 days. Thus, coccoliths may be expected to be found in the bottom sediments of the deep Northwest Atlantic.

A surface sediment sample collected using a box corer at the Sargasso Sea station consists of fine red clay containing approximately 10 percent calcium carbonate by weight. No pteropods or foraminifera were found, the carbonate fraction is mostly coccoliths, and small siliceous diatoms are also found. As expected, both coccoliths and diatoms are partially dissolved because their burial time is shorter than their complete dissolution time by only 100 days. These observations are in good agreement with the predictions of the simple model presented above.

Organic Diagenesis at the Bottom Boundary

John Farrington, Robert Gagosian, Cindy Lee

ORGANIC geochemistry in ocean science is the study of physical, chemical, geological, and biological processes acting upon organic compounds entering, leaving, and residing in the ocean system. Organic matter in sediments is a major source of energy for benthic ecosystems, and the metabolism of organic matter is closely coupled to nutrient regeneration. Metabolism of organic compounds also influences chemical reaction conditions in the sediment. Understanding the biochemical and geochemical reactions of organic compounds can provide insight into the biological and geochemical processes controlling the carbon cycle and nutrient regeneration.

The physical properties of sediments are also influenced by their organic content. In nearshore areas and apparently to a lesser extent in the deep sea, organic matter can act as a "glue" holding together mineral grains of sand, silt, or clay. The response of the "organic matter/mineral" particles to erosion and transport processes is different from that of the minerals by themselves, and this is important to understanding sediment dynamics and properties for engineering applications.

We can interpret the history of ancient sediments from studies of contemporary surface sediment composition and changes occurring during early diagenesis. When we know which reactions took place immediately after deposition and which ones occurred thousands or millions of years later, we can describe sources of organic matter deposited to ancient sediments and infer types of organisms living in and contributing to organic matter in sediments. One application of this knowledge is a better understanding of how and where fossil fuels are formed. Organic matter in surface sediments of the benthic boundary layer undergoes early reactions that yield material which may react thousands of years later under certain conditions to form fossil fuels.

Organic compounds in the benthic boundary sediments are important not only of themselves but also to the processes controlling the distributions of many inorganic chemicals.

For several reasons, our initial investigations have focused on lipids, a group of compounds that form some of the chief structural components of living cells: methods for detailed elucidation of lipid structure are available; lipids have been studied in ancient sediments, and their geochemistry is related to fossil fuel formation; several of the lipid class compounds, such as fatty acids and sterols, are important biochemicals in a wide range of organisms; several organic pollutants are in the lipid class compounds; and these compounds exhibit a range of biochemical reactivities.

A portion of our data set from a station in Buzzards Bay, Massachusetts, gives an example of our approach. The concentrations of a few of the lipid compounds at various depths in cores and their molecular formulas are given in the figure overleaf. The n-alkane hydrocarbons, including n-C_{29}, were derived from land plants or marsh grasses. The fairly constant concentration of these n-alkanes with depth in the core indicates that these compounds are not being converted to other compounds or metabolized to any appreciable extent. The fatty acids 16:0 and 16:1 decrease in concentration with increasing depth (time) in the core indicating that they are reactive or are

FRANK MEDEIROS

Bob Gagosian, John Farrington, and Cindy Lee

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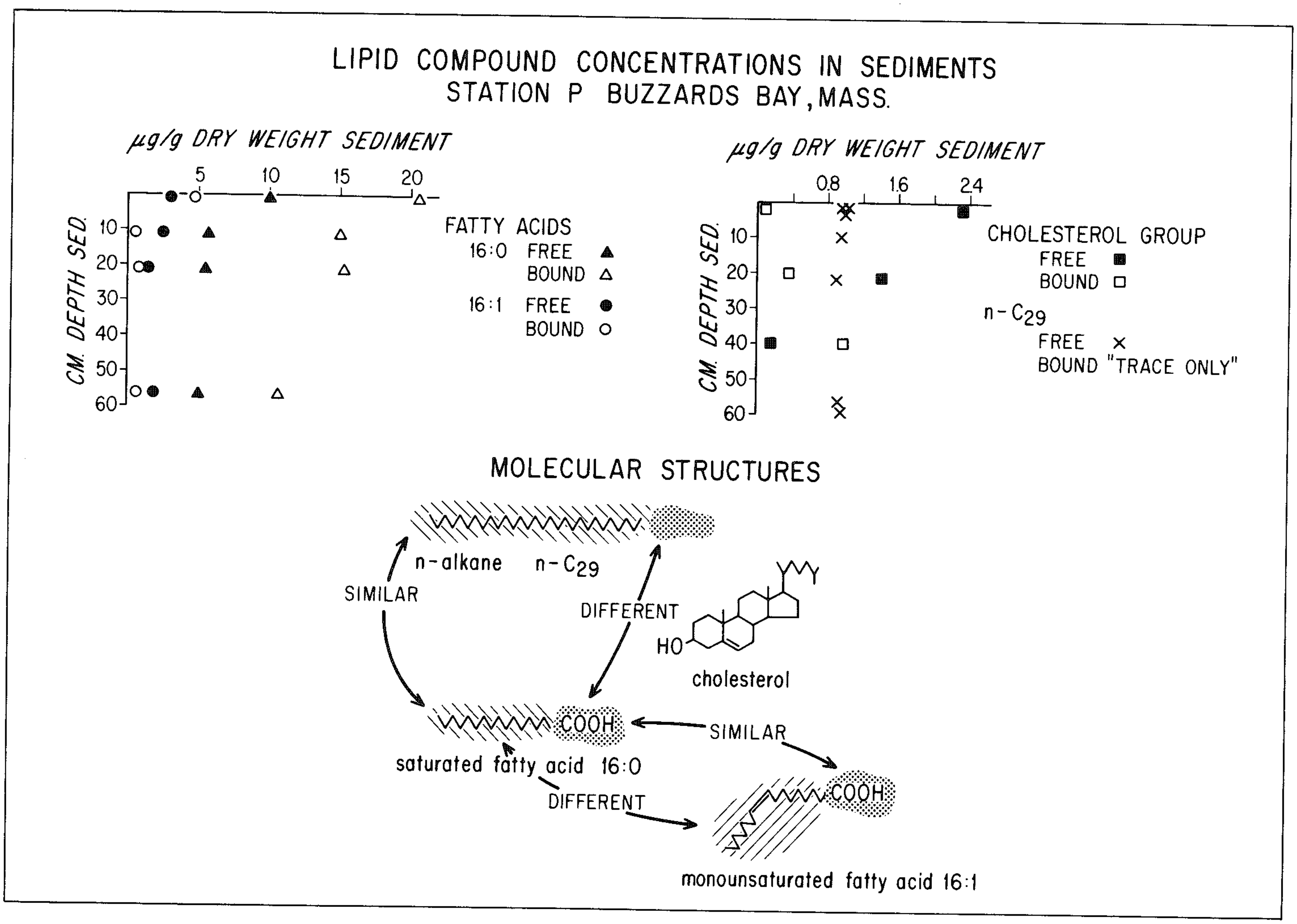
John Farrington reaches for corer.

being metabolized. There are two groups of fatty acids, one extracted easily by organic solvents and called "free," another extracted by chemical hydrolysis after the organic solvent extraction and called "bound." There was little, if any, bound hydrocarbon. Thus, the carboxyl group (COOH) imparts at least two different geochemical properties to the fatty acids compared to hydrocarbons: 1) they react or are utilized after deposition, and 2) a portion are bound in the sediment and require chemical hydrolysis to release them.

The depth profile of cholesterol and the cholesterol formula are given in the figure. Note that unlike the fatty acids the bound cholesterol increases with increasing depth in the core. The free cholesterol decreases in concentration similar to the free fatty acids.

Thus, for n-alkanes and fatty acids having similar structures in one part of the molecule, there are major differences in reactions. Sterols, even though they are lipid class compounds, have some different geochemical properties compared with both the hydrocarbons and fatty acids. We have found many other major and minor differences in the depth distribution of the fatty acids, sterols, and hydrocarbons.

We are now analyzing cores of surface sediments from a number of different depositional environments to investigate the influence of different sources of organic matter deposited to sediments and of subsequent water circulation, mineral interactions, and benthic organisms on the geochemistry of organic compounds. We focus much of our attention on concentrations and on the exact molecular structures of the organic compounds. Major and minor changes in molecular structure provide important information about sources of and reactions of organic matter and, by inference, other processes operating in the benthic boundary layer.



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Professor of Science and Public Policy
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Public Affairs
Mail Code BO 31
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After graduating from the University of Delaware in 1916, Homer Ewing worked briefly for the Ingersoll Rand Company and the Krebs Pigment and Chemical Company. In 1918, he joined E. I. duPont de Nemours and Company, with whom he remained until his retirement in 1960, spending the last 10 years on assignments in Europe. He served as a Research Advisor to the University of Delaware and was a Trustee of the National Security Industrial Association and the Communications Research Institute of St. Thomas, V.I. He was a Member of the Munitions Board, the Technical Advisory Committee of the Air Force Armament Center at Eglin Air Force Base, and the American Chamber of Commerce in London. He was Secretary of the National Investors' Council.

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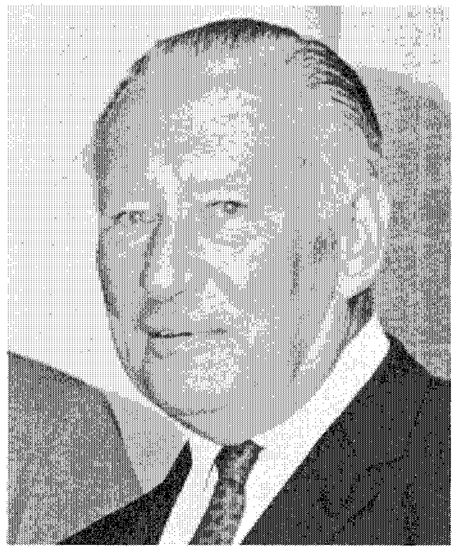

He gave much pleasure to his friends as an accomplished pianist, a skill which he first developed as an organist for silent movies in his college days, and which livened up many evenings associated with Woods Hole meetings. Homer Ewing's universal friendliness and loyalty to the Institution will be hard to match in years to come.

L. Hoyt Watson

Elizabeth Perkins Bigelow

26 June 1881 — 23 Nov. 1977

Resolution of the Board of Trustees and Members of the Corporation:

THAT the Official Boards of the Woods Hole Oceanographic Institution at their meeting on January 17, 1978, express their deep sorrow at the passing of Mrs. Elizabeth Perkins Bigelow on November 23, 1977, beloved wife of the founding Chairman and first Director of the Woods Hole Oceanographic Institution, Dr. Henry Bryant Bigelow.

Let it be recorded in the minutes of this Joint Meeting of our Board of Trustees and Corporation Members that we sincerely appreciate the many contributions and moral support she provided the founding fathers of our Institution.

We recognize and note with gratitude the kind and wise guidance provided us by Dr. and Mrs. Bigelow; especially do we gratefully acknowledge with love and affection the many years of her gentle influence.

Be it further resolved, that this resolution be transmitted to her son, Dr. Frederick S. Bigelow, a Member of the Corporation, and her daughter, Mrs. Lamar Soutter, as an indication of our affection and sympathy.

Statement of Changes in Fund Balances for the years ended December 31, 1977 and 1976

	Current Fund					Plant Fund	
1976	Restricted	Unrestricted	Total	Endowment and Similar Funds	Annuity Fund	Invested in Plant	Unexpended
Balances at December 31, 1975	$ 1,357,272	$1,663,476	$ 3,020,748	$30,483,731	$44,376	$18,303,394	$ 482,460
Increases:							
Gifts and grants received	11,345,714	355,460	11,701,174	35,345		1,850	2,420,546
Transfers from restricted to unrestricted (Note F)	(234,393)	234,393					
Contract revenues earned	8,837,708		8,837,708				
Endowment and similar funds investment income	1,143,602	292,668	1,436,270				
Other		674,476	674,476		8,108		2,439
Net increase in realized and unrealized appreciation				4,224,115			
Decreases:							
Expenditures (including $432,410 of depreciation)	(21,236,077)	(820,630)	(22,056,707)				
Unfunded depreciation (Note A)						(263,228)	
Net loss on disposal of plant fund assets						(904)	
Other						(2,439)	
Transfers – additions (deductions):							
Transfers to endowment fund	(137,083)	(269,303)	(406,386)	2,906,386			(2,500,000)
Transfers to plant fund		(125,000)	(125,000)				125,000
Invested in plant						182,951	(182,951)
Funded depreciation						(432,410)	432,410
Balances at December 31, 1976	1,076,743	2,005,540	3,082,283	37,649,577	52,484	17,789,214	779,904
1977							
Increases:							
Gifts and grants received	11,393,467	606,401	11,999,868	186,588			50,000
Contract revenues earned	9,861,468		9,861,468				
Endowment and similar funds investment income	1,244,855	447,128	1,691,983				
Other		825,693	825,693			7,544	
Decreases:							
Expenditures (including $441,737 of depreciation)	(22,531,534)	(1,260,935)	(23,792,469)				
Unfunded depreciation (Note A)						(263,228)	
Net loss on disposal of plant fund assets						(352)	
Other					(7,323)		
Net decrease in realized and unrealized appreciation				(2,985,966)			
Transfers – additions (deductions):							
Transfers to endowment fund	(5,143)	(275,000)	(280,143)	430,143			(150,000)
Transfers to plant fund		(275,000)	(275,000)				275,000
Invested in plant						374,958	(374,958)
Funded depreciation						(441,737)	441,737
Balances at December 31, 1977	$ 1,039,856	$2,073,827	$ 3,113,683	$35,280,342	$45,161	$17,466,399	$1,021,683

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

Statement of Current Fund Revenues, Expenses and Transfers for the years ended December 31, 1977 and 1976

Revenues	**1977**	**1976**
Sponsored research:		
Government	$19,894,748	$18,576,747
Nongovernment	1,673,916	1,669,813
	21,568,664	20,246,560
Education funds availed of	962,870	989,517
Total restricted	22,531,534	21,236,077
Unrestricted:		
Fees	257,272	199,796
Endowment and similar fund income	447,128	292,668
Gifts (Notes F and G)	606,401	589,853
Tuition	262,928	234,091
Other	305,493	240,589
Total unrestricted	1,879,222	1,556,997
Total revenues	**24,410,756**	**22,793,074**
Expenses and Transfers		
Sponsored research:		
Salaries and fringe benefits	6,574,110	6,332,583
Ships and submersibles	5,409,160	4,600,610
Materials and equipment	4,030,287	3,826,308
Laboratory overhead	1,336,920	1,330,639
Other	1,595,999	1,653,942
	18,946,476	17,744,082
Education:		
Faculty expense	224,779	222,672
Student expense	522,757	533,850
Other expense	116,524	141,082
	864,060	897,604
Institutional research	656,009	274,832
Other unrestricted activity	505,730	449,593
General and administrative:		
Allocated to sponsored research	2,622,188	2,502,478
Allocated to education	98,810	91,913
Allocated to other	99,196	96,205
	2,820,194	2,690,596
Total expenses	**23,792,469**	**22,056,707**
Nonmandatory transfers:		
To quasi-endowment fund (Note F)	275,000	269,303
To plant fund, unexpended	275,000	125,000
Total expenses and nonmandatory transfers	**24,342,469**	**22,451,010**
Net increase in unrestricted current fund (Note G)	**$ 68,287**	**$ 342,064**
Designated for:		
Income and salary stabilization	149,044	97,556
Ocean industry program (Note G)	(62,918)	234,393
Working capital and contingency	(17,839)	10,115
	$ 68,287	$ 342,064

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

Notes to Financial Statements

A. SUMMARY OF SIGNIFICANT ACCOUNTING POLICIES:

Fund Accounting

In order to comply with the internal and external limitations and 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 a nominal value of $1. Income from such investments is not significant.

Net investment income is distributed to all funds in the year received and for pooled investments, income 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.

The Institution follows the accrual basis of accounting except that 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 generally recognized as related costs are incurred.

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 5% on buildings, 3⅓% on Atlantis II and 5% to 33⅓% on equipment. Depreciation expense on Institution-purchased plant assets amounting to $441,737 in 1977 and $432,410 in 1976 has been charged to operating expenses. Depreciation on certain government funded facilities (Atlantis II, Laboratory for Marine Science and the dock facility, amounting to $263, 228 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.

Annuity Funds

On the date of receipt of annuity fund gifts, and 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.

B. ENDOWMENT AND SIMILAR FUND INVESTMENTS:

The cost and market value of separately invested and pooled investments are as follows:

	December 31, 1977		December 31, 1976	
	Cost	Market	Cost	Market
Separately invested:				
Government and government agencies	$ 2,272,239	$ 2,213,000	$ 1,628,438	$ 1,662,000
Bonds	2,200,977	2,181,500	3,184,714	3,289,500
Common stocks	11,905,661	11,865,650	11,482,615	12,864,975
Savings deposits	1,052,200	1,052,200	875,000	875,000
Cash	6,074	6,074	256,699	256,699
Total separately invested	**$17,437,151**	**$17,318,424**	**$17,427,466**	**$18,948,174**
Pooled investments:				
Pool A				
Government and government agencies	1,598,363	1,575,000	1,408,468	1,452,000
Bonds	1,995,499	1,977,650	3,560,884	3,617,120
Preferred stocks	59,704	23,000	59,704	27,000
Common stocks	8,169,123	8,159,681	7,129,057	7,909,563
Savings deposits	970,295	970,295	401,000	401,000
Real estate	44,126	44,126	45,152	45,152
Cash	(385)	(385)	118,741	118,741
Other assets	7,000	7,000	7,000	7,000
	12,843,725	**12,756,367**	**12,730,006**	**13,577,576**
Pool B				
Government and government agencies	1,622,552	1,573,000	922,520	939,000
Bonds	1,070,448	1,040,000	1,759,108	1,784,600
Common stocks	2,202,812	2,162,650	1,725,064	1,852,100
Savings deposits	429,500	429,500	538,000	538,000
Cash	22,249	22,249	7,844	7,844
	5,347,561	**5,227,399**	**4,952,536**	**5,121,544**
Total pooled investments	**$18,191,286**	**$17,983,766**	**$17,682,542**	**$18,699,120**

On July 1, 1977 Pool B was established principally from funds which had previously been separately invested. Accordingly, the December 31, 1976 balances have been reclassified for comparative purposes.

C. POOLED INVESTMENTS UNITS:

The value of a pooled investment unit was as follows:

	Pool A	Pool B
December 31, 1976	$.9027	$.8982
December 31, 1977	$.8361	$.8373

The pooled investment income per unit was as follows:

	Pool A	Pool B
1976	$.0401	–
1977	$.0423	$.0426

D. ENDOWMENT AND SIMILAR FUND INCOME:

Income of endowment and similar funds consisted of the following:

	1977	1976
Dividends	$ 761,502	$ 612,772
Interest	995,723	883,236
Other	3,479	2,994
	1,760,704	1,499,002
Investment management costs	(68,721)	(62,732)
Net investment income	$1,691,983	$1,436,270

E. RETIREMENT PLAN:

The Institution has a noncontributory 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 $1,513,700 in 1977 and $1,137,800 in 1976, including $39,700 and $37,800, respectively, relating to expenses of the retirement trust.

The adoption of a cost-of-living feature for benefit payments has caused annual pension expense to increase approximately $265,000 over the past two years. The full impact of this charge was not reflected in pension costs until 1977 and caused 1977 pension expense to increase $180,000 as compared to 1976.

At the most recent valuation date (January 1, 1977), the actuarially computed value of vested benefits exceeded the assets of the trust by approximately $893,000. At that date unfunded prior service costs, which will be funded through future annual accruals, approximated $6,600,000.

F. CURRENT YEAR GIFTS:

In 1977 the Institution sold a sport fishing boat which it had received as a gift in 1976 and assigned a nominal value of $1. The net proceeds of the sale ($140,000) have been reflected as a 1977 unrestricted gift.

In 1976, the Institution sold its 100% ownership of Deep Sea Marina, Inc. The net proceeds of the sale ($269,303) were reflected as a 1976 unrestricted gift, and were then transferred to quasi-endowment funds.

G. OCEAN INDUSTRY PROGRAM:

On December 31, 1976, the unexpended balance of the Ocean Industry Program Fund ($234,393) was reclassified from unexpended balances of restricted funds to unrestricted gift income in recognition of a revised interpretation of the terms of the related gifts. Beginning in 1977, activity associated with these funds is recorded in the unrestricted current fund. Had activity in this program been accounted for on an unrestricted basis in prior years, the 1976 net increase in the unrestricted current fund would have been $68,759, instead of $342,064 reported in the Statement of Current Fund Revenues, Expenses and Transfers.

H. DEFERRED SUBSCRIPTION REVENUES:

Prior to 1976, subscription revenue for Oceanus Magazine was recognized on a cash basis. In 1976 the Institution adopted the accrual basis of accounting for such revenue in recognition of its growing significance to unrestricted operations. Accordingly, $70,000 of subscription revenue received but not earned was deferred at December 31, 1976. Had similar accounting been used at December 31, 1975, $30,000 would have been deferred at that date.

FRANK MEDEIROS

Dr. and Mrs. Steele and Mrs. Fye greet visitors at Fenno House summer reception.

ON 27 April the Board of Trustees selected Dr. John H. Steele of Aberdeen, Scotland, to become the fifth Director of the Woods Hole Oceanographic Institution. Dr. Steele, who was Deputy Director of the Marine Laboratory of the Department of Fisheries for Scotland, has had a long association with the Institution. In 1958 he was a visiting research fellow in Woods Hole and between 1959 and 1961 he took part in the Institution's studies of the Sargasso Sea. He has twice served on the scientific visiting committee for the Department of Biology. In recent years he has worked with Institution scientists on a number of international oceanographic experiments including investigations of the transport of deep water from the Norwegian Sea into the North Atlantic in cooperation with Valentine Worthington, studies of the productivity of pelagic systems in the North Sea (FLEX), and the Controlled Ecosystem Pollution Experiment in British Columbia (CEPEX). A mathematician who has applied his skills to the physical and biological processes of the oceans, Dr. Steele's professional reputation embraces many fields, including physical, chemical, and biological oceanography. His numerous publications include models of the physical and chemical environment in relation to the production of the oceans, of marine pollution, and of environmental quality. He was awarded the prestigious Alexander Agassiz Medal by the National Academy of Sciences in 1973.

VICKY CULLEN

Ruth and Paul Fye at Ruth and Paul Fye Day.

On 25 June more than 500 employees, students, visiting investigators, and guests joined Paul and Ruth Fye at a summer reception on the grounds of the Fenno House to welcome John and Evelyn Steele, who were visiting from Scotland. They returned to Woods Hole 3 October when Dr. Steele assumed the responsibilities of Institution Director.

Dr. Fye, who is continuing as President of the Corporation, has moved to a waterfront office in the Bigelow Laboratory. The third of August was designated Ruth and Paul Fye Day. Some 700 employees and friends gathered at the Fenno House in the afternoon for a colloquium and clambake to honor the Fyes. Following discussions of Paul Fye's 19 years as Director by Dr. Burr H. Steinbach, Dr. Kenneth O. Emery, and Dean F. Bumpus, a series of presentations were made by employees. These included a book of messages to the Fyes from people at the Institution, a certificate entitling Paul Fye to boating privileges at the Institution's small craft facility, and a plaque to be placed in a garden dedicated to Ruth Fye. The creation of two awards honoring the Fyes was announced: contributions from more than 600 employees funded the $100 Ruth and Paul Fye Award for Excellence to be presented annually for the year's best student paper, and the Paul McDonald Fye Graduate Student Fellowship is

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K. O. Emery addresses Ruth and Paul Fye Day assembly on Fenno lawn.

supported by gifts from more than 75 Trustees, Corporation Members, and friends of the Fyes.

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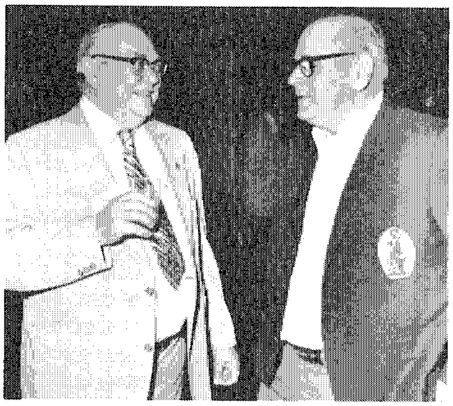

Buck Ketchum and Jack Lindon at retirement party.

Associate Director Bostwick H. Ketchum and Senior Scientist Dean F. Bumpus retired from the Institution in May with a total of 82 years of service. Buck Ketchum came to the Institution as an undergraduate student at Harvard with Dr. Alfred C. Redfield as mentor and advisor, and Dean Bumpus came in 1937 as a biological observer.

FRANK MEDEIROS

Dean Bumpus hands out cake at retirement party.

Dr. Robert A. Frosch, Associate Director for Applied Oceanography, was appointed Director of the National Aeronautics and Space Administration by President Carter in June.

Several Institution staff members received distinguished awards during 1977. Associate Scientist Robert D. Ballard received the Compass Distin-

MTS

MTS President James Rikard presents Compass Award to Bob Ballard.

guished Achievement Award from the Marine Technology Society for achievements in marine geology and ocean engineering related to the use of manned submersibles. Dr. Paul M. Fye received the U.S. Navy Department's Distinguished Public Service Award, the highest award made to a civilian by the Navy, and he received the annual achievement award from the Boston Chapter of the Association of Government Accountants "for his outstanding leadership in the management of the facility at Woods Hole." Senior Scientist Kenneth O. Emery received the Illini Achievement Award, a prize given annually to three graduates of the University of Illinois. He was also invited to join the Swedish Academy of Sciences this year. Senior Scientist Gabriel T. Csanady was the first recipient of the Chandler Misener Award from the International Association for Great Lakes Research for his paper entitled "Circulation Diffusion and Frontal Dynamics in the Coastal Zone." Senior Scientist Allyn C. Vine received the David B. Stone Award from the New England Aquarium for "distinguished service to the environment and community."

A $50,000 grant received this year from the Fleischmann Foundation along with $25,000 of Institution funds will be used to construct a biological specimens collection building on the Quissett Campus near the GEOSECS building.

The interior of the first floor, west wing of the Clark Laboratory was finished in April. The United States Geological Survey has leased the space for three years.

The 53-foot sports fishing boat *Dodo,* donated to the Institution by Elmer Bobst of Palm Beach, Florida, was sold in November for $155,000. This money is designated for replacement of *Asterias.*

It was a heavy traffic year at the Institution pier. The entire fleet was in port for the first time in five years during the Labor Day weekend and again for the holidays in December. A total of 68 calls were made at the pier by 27 non-Institution vessels including five foreign ships participating in cooperative projects with the National Marine Fisheries Service.

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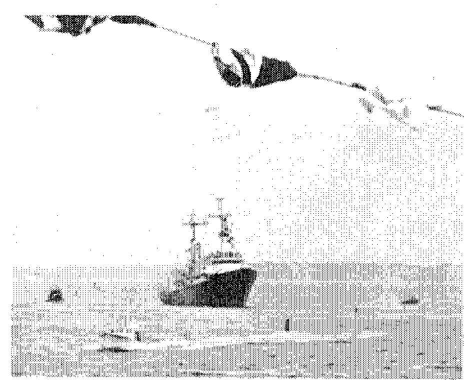


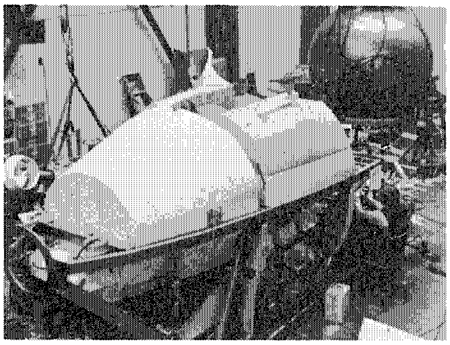
Atlantis II steams into Woods Hole after long cruise.

FRANK MEDEIROS

Atlantis II arrived in Woods Hole 21 May at the end of the Indian Ocean voyage to a gala reception marking the longest cruise ever made by an Institution ship. She flew the flags of 13 countries visited during Voyage 93. The ship steamed nearly 80,000 miles in 573 days away from home port. A total of 187 scientists participated in the expedition: 80 Institution staff, 30 guest investigators, and 67 foreign observers.

Later in the year, on Voyage 96, *Atlantis II* rescued all 11 crew members of the 150-foot Costa Rican freighter *Ensenada* some 350 miles east of Cape Hatteras about midnight 8 December. *Atlantis II* was heading north on the last leg of the cruise, a geological and geophysical survey of the Kane Fracture Zone southeast of Bermuda, when she

VICKY CULLEN



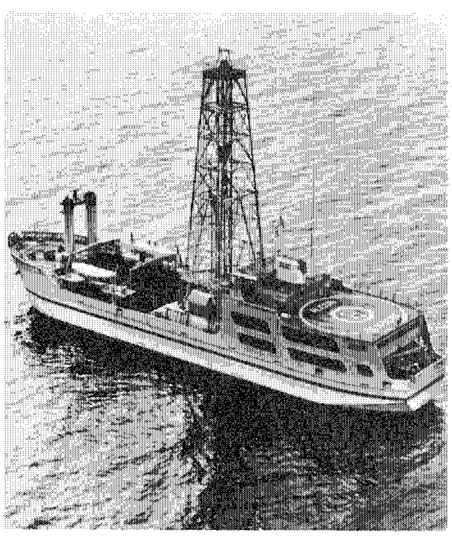
Alvin is separated into many pieces for overhaul.

answered a distress call from *Ensenada*, eventually picking up the nine Colombians and two Americans from life rafts shortly before their ship disappeared from the radar. The survivors, all in good condition, had many words of praise for *Atlantis II* captain and crew both for their efficient rescue and for monitoring emergency radio channels on the open sea.

Alvin completed her first 100-dive season in September and started the annual overhaul period, which includes replacement of the aluminum frame with a stronger titanium frame. The new frame is two feet longer for future accommodation of a fourth battery pack to allow a 30 percent increase in endurance.

The Institution entered an agreement with Aluminum Company of America (Alcoa) for operation of *Alcoa Seaprobe* as a specialized research vessel. The 243-foot aluminum ship, constructed in 1970, is unique in its capability to maintain precise positioning while lowering and retrieving heavy instrument arrays through a center well on as much as 10,000 feet of semirigid pipe. *Alcoa Seaprobe* arrived in Woods Hole 10 July for summer tests and operations.

ALCOA



R/V *Alcoa Seaprobe*

Seaprobe carried the Institution's first woman crew member when she departed for a 24 July cruise. By summer's end, three women crew members had served aboard *Seaprobe* and one aboard *Lulu*.

Among the many visitors to the Institution during 1977 were Massachusetts Governor Michael S. Dukakis, who talked 31 January with scientists involved in cruises to study the aftermath of the *Argo Merchant* oil spill, and 12th District Congressman Gerry E. Studds, who spent a half day 16 April discussing questions of current interest with members of the Woods Hole scientific community. Archbishop Jean Jadot, the Apostolic Delegat to the United States visited the Institution while in Falmouth to dedicate Saint Elizabeth Seton Church in North Falmouth.

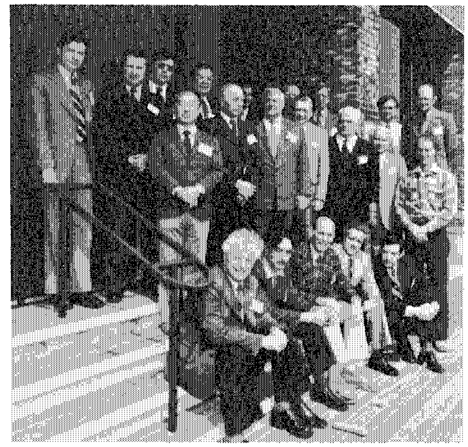
FRANK MEDEIROS

Sea Grant Coordinator David Ross welcomes Gov. Dukakis.

Thirteen members of the US/USSR Joint Committee on World Ocean Studies attended lectures, toured the laboratories, and dined with Institution staff members 21 April.

The Executive Committee of the International Federation of Institutes for Advanced Study (IFIAS), of which the Institution is a charter member, met at Woods Hole for three days in March to discuss the organization's next five-year program.

FRANK MEDEIROS



Russian visitors and hosts on Clark Lab balcony.

Dr. Fye discussed "The Oceans: Common Heritage of Mankind?" at the annual Associates dinners in Boston, New York, and Woods Hole in April. He was joined at the podium by Dr. Robert D. Ballard, who reported on discoveries made on the February-March *Knorr* cruise to the Galápagos Rift (see page 27).

Corporation Members, Associates, and guests watched the second of the 1977 America's Cup series aboard *Alcoa Seaprobe* 15 September. Although it was not officially a race since time ran out due to lack of wind, it was a beautiful day with excellent visibility. Alcoa Corporation was host 13 September to a special guest list for the first race between the Australian contender *Australia* and the US defender *Courageous*.

The annual Associates' Day of Science brought about 100 people to Woods Hole 7 October for a morning of lectures by staff members, lunch on the Fenno House lawn, and afternoon tours and a film showing.

The upstairs of Endeavour House was transformed into an exhibit center for the summer months so that visitors could see photographic displays and a 10-minute narrated slide presentation about Institution activities.

The Institution's Matamek Research Station on the north shore of the Gulf of St. Lawrence in Quebec, Canada, celebrated its 10th anniversary this year. Scientists from this Institution as well as the Universities of Waterloo, Manitoba, Quebec, and Sherbrooke in Canada have conducted research at the station.

Support Staff

Departmental Assistants

Biology Department

Austin, Robert G.
Belastock, Rebecca A.
Bowker, Paul C.
Boyd, Steven H.
Brown-Leger, L. Susan
Butler, Norma Y.
Connell, Thomas R.
Debusk, Thomas A.
Dennett, Mark R.
Ellis, Elaine M.
Gunning, Anita H.
Hammar, Terrence R.
Harrison, Karen S.
Hoar, Peter R.
Hoercher, Susan J.
Konnerth, Andrew, Jr.
Lancaster, Bruce A.
*Lawrence, Sarah A.
Manganini, Steven J.
McAlister, Vicki L.
Molyneaux, Stephen J.
Moore, Karen E.
Morse, Linda S.
Peterson, Jane M.
Quinby, Helen L.
Sherman, Albert C.
Stanley, Helen I.
Stenberg, Richard W.
Taylor, Rodman E., Jr.
Volkmann, Suzanne B.
Whoriskey, Frederick G., Jr.
Williams, Isabelle P.
Woodward, Bonnie L.

Chemistry Department

Alford, Jane
Andrews, John E., III
Bates, Peter P.
Blakesley, Barbara A.
Boudreau, Richard D.
Brady, Lynette
Brockhurst, Barbara J.
Carey, Anne E.
Casso, Susan A.
Chase, Elsa M.
Clarke, William R.
Davis, Alan C.
Fleer, Alan P.
Gordon, Allan G.
Goudreau, Joanne E.
Graham, Linda B.
Hayward, Nancy A.
Jacobson, Helen A.
Johnson, Christine
Lavoie, Robert G.
Livramento, Joaquim B.
Michael, Anne M.
Nigrelli, Gale E.
Olson, Brenda L.
Olson, Charles A.
Palmieri, Julianne
Ross, Edith H.
Schneider, David L.
Shafer, Deborah K.
Smith, C. L. Roy
Sulanowski, Margaret M.
Surprenant, Lolita D.
True, Mary B.

Geology & Geophysics Department

Akens, John J.
Allison, Donna F.
Berry, Mary E.
Broda, James E.
Bullen, Thomas D.
Connell, John F.
Davies, Rodman F.
Dean, Carolyn J.
Edwards, Anne S.
Farmer, Harlow G., III
Galbraith, Nancy R.
Gately, Ellen M.
Gegg, Stephen R.
Gever, David H.
Goreau, Margaret
Gove, Leon A.
Grant, Carlton W., Jr.
Handy, Robert E.
Hays, Helen C.
Hindley, Pamela E.
Keith, Darryl J.
Kroll, Jane D.
Mooney, Robert C.
O'Brien, Thomas F.
Peters, Christopher S.
Porteous, John
Ruiter, Robert G.
Saunders, Pamela L.
Scheer, Catherine O.
Scheer, Edward K.
Shaughnessy, Daniel R., III
Sousa, Angela J.
Toner, Lois G.
Tonge, Sandra M.
Witzell, Grace M.
Wooding, Christine M.

Ocean Engineering Department

Bardsley, Brian L.
Bartlett, Arthur C.
Beatty, Keith W.
Clay, Peter R.
Cole, Bruce R.
Collins, Aganoris
Cressy, Steven A.
Crook, Thomas
Crowell, Donald N.
Deane, Stanley R.
Denton, Edward A.
Evans, Emily
Fairhurst, Kenneth D.
Francis, Keith A.
Freund, William F., Jr.
Gibson, George W.
Gunderson, Allen C.
Gustafson, Carl W.
Hilliard, Channing N., Jr.
Kucharski, William M.
Letendre, William J.
Lowe, Robert G.
Mason, David
McElroy, Marguerite K.
Meier, George A.
Morehouse, Clayton B.
Morton, Alfred W.
Muzzey, Charlotte A.
O'Malley, Patrick
Pettigrew, Patricia M.
Pires, Clara Y.
Pires, Karen M.
*Polloni, Christopher F.
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Woods Hole Oceanographic Institution
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Royal Institute of Technology, Sweden
Francis P. Bretherton
National Center for Atmospheric Research
George Buzyna
Florida State University
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Woods Hole Oceanographic Institution
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Scripps Institution of Oceanography
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Woods Hole Oceanographic Institution
Massachusetts Institute of Technology
Charles W. Van Atta
Scripps Institution of Oceanography
Pierre Welander
University of Washington
John A. Whitehead, Jr.
Woods Hole Oceanographic Institution

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Donald W. Forsyth
Brown University
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University of Miami
Francis P. Shepard
Scripps Institution of Oceanography
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Institute of Oceanographic Sciences, England
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Yale University
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Southern California Coastal Water Research Project

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McGill University, Canada

Christopher R. Johnson
Bureau of Mineral Resources, Australia

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Field Museum of Natural History, Illinois

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Influence of Marine Sediments on the Chemistry of the Oceans

Frederick Sayles

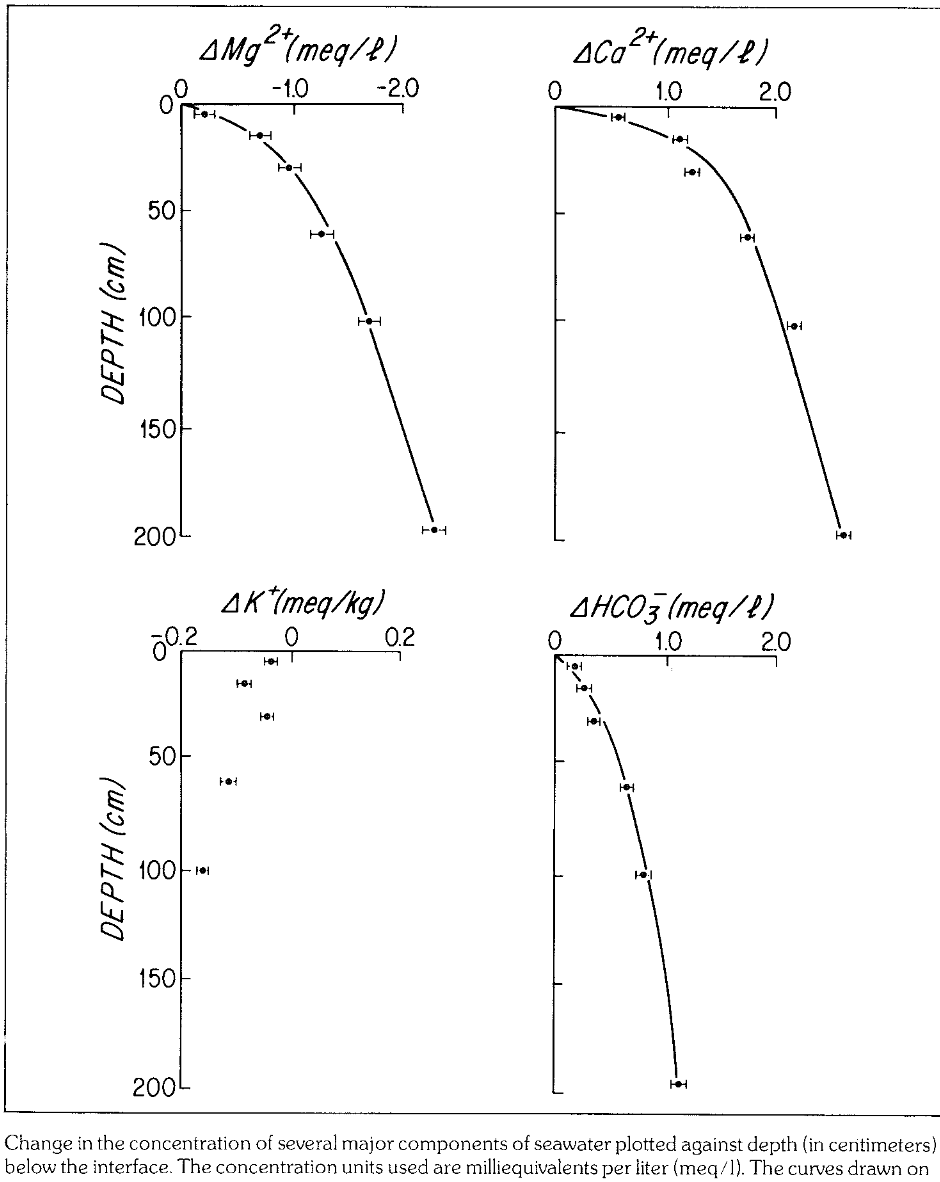
THE floor of the ocean is often thought of as a relatively well-defined boundary between the solid earth and the overlying water of the oceans, with the exception that a few organisms inhabit the upper few centimeters of sediment. Recent studies have shown, however, that sea-floor sediments play a critical role in controlling the chemistry of the ocean. On purely thermodynamic grounds it can be predicted that many components of sediments *should* react with one another and with seawater to modify the composition of both, but the nature of the reactions and their significance to the ocean has only recently begun to be understood, in large part through studies at Woods Hole.

The reaction of materials within the sediments of the sea floor is commonly referred to as diagenesis. As a consequence of these reactions, the chemistry of the solutions that fill the interstices between the solid grains (usually 70 to 90 percent of the bulk sediment by volume) is modified from its original seawater composition. Soluble products of reaction become enriched while reactants are depleted. These changes in concentration establish a chemical gradient between the interstitial solutions of the sediment and the overlying seawater. Diffusion occurs in response to the gradient, acting to eliminate the differences in concentration, or, more accurately, chemical potential. The overlying seawater serves as a source for reactants taken up from interstitial solutions in the sediments while the soluble products diffuse out of the sediment to enrich seawater. Under most circumstances encountered in the deep sea, the rate of transfer of material across the interface can be quite simply related to the chemical gradient at the interface by the expression:

$$F_i = D_i \left. \frac{\partial c_i}{\partial x} \right|_{x=o}$$

F_i is the flux of species i (mass per unit per unit time); D_i is the diffusion coefficient of i, a constant for a given sediment; and $\frac{\partial c_i}{\partial x}$ is the chemical gradient of i. In shallow waters, the activities of organisms dwelling in or on the bottom may stir the sediments at rates such that advection due to stirring is comparable to D_i, but in the deep sea, such mixing rates are far slower, permitting the use of the simple relation above.

In studying the influence of diagenetic reactions upon the major element chemistry of seawater, we have collected samples of interstitial solutions at stations in the North and South Atlantic, the Caribbean, and the Antarctic Ocean. Analysis of the solutions yields profiles of the concentrations of various components as a function of depth below the interface over the 2-meter interval sampled. Typical examples of the profiles are presented in the figure below; the raw data are shown as points in the figure, the uppermost data point being at a depth of 5 centimeters below the interface. The flux across the interface is determined by the gradient at the interface, i.e., at depth=0. This cannot be sampled for practical reasons, and some means of estimating $\frac{\partial c_i}{\partial x}$ at x=o it needed to deter-



Change in the concentration of several major components of seawater plotted against depth (in centimeters) below the interface. The concentration units used are milliequivalents per liter (meq/l). The curves drawn on the figure are the fit of a mathematical model to the raw data.

Ocean Bottom Processes

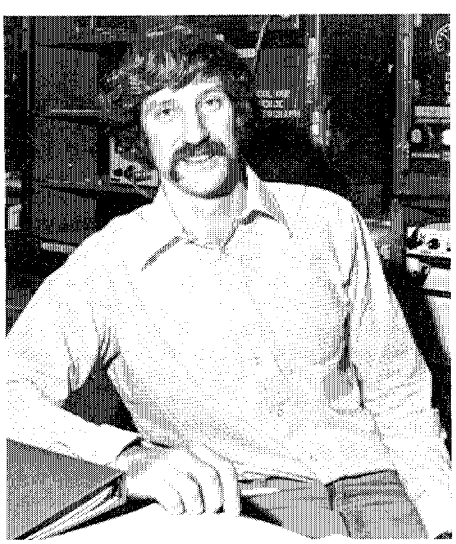
Comparison of River Fluxes of Dissolved Species with Estimate Fluxes Across the Water/Sediment Interface (+ = Addition to Seawater, − = Removal)

Component	Flux Across the Water/Sediment Interface (10^{16} meq/yr.)	Fluxes from Rivers (10^{16} meq/yr.)
Mg^{2+}	−1.3	+1.1
Ca^{2+}	+1.7	+2.4
K^+	−0.12	+0.19
HCO_3^-	+0.8	+3.2

mine F_i. One approach is to find a mathematical expression which accurately describes the available data (concentration/depth relations) and use the derivative of the expression evaluated at x=o. This method has been used in these studies employing the relation

$$C_i = a_1(1-e^{a_2 x}) + a_3^x,$$

a saturating exponential with a linear term to account for sources or sinks well below the sampled interval. The curves of the figure are generated by a fit of the raw data to the above equation in the cases of calcium (Ca^{2+}), magnesium (Mg^{2+}), and bicarbonate (HCO_3^-). For potassium (K^+) the data are sufficiently noisy that the uncertainties in calculating the coefficients of the above equation are large. Consequently, fluxes of K^+ have been calculated by assuming a linear gradient between the interface and 5 centimeters — an underestimate, doubtless, but this is about all the treatment that the data warrant.



FRANK MEDEIROS

Fred Sayles

A summary of the estimated fluxes across the seawater/sediment interface is given in the table at left along with estimates of the fluxes from rivers (the major source of supply to the oceans) for reference. The calculations assume that the Atlantic, Antarctic, and Caribbean data are representative of the world oceans generally. From the data listed, it is quite apparent that diagenetic reactions within the sediments are a major factor in chemical budgets of the oceans. Virtually all of the river-supplied Mg^{2+} can be balanced by uptake in the sediments (the difference between 1.3 and 1.1 is not significant). A major portion of the K^+ entering the oceans annually is also removed through diagenetic reactions. For Ca^{2+} and HCO_3^-, diagenesis significantly enhances the total amount supplied to the oceans in solution.

The relationship between Ca^{2+} and HCO_3^- warrants further comment. While both Ca^{2+} and HCO_3^- are added to the oceans by diffusive fluxes, they are not added in stoichiometric proportions (equivalent for equivalent). The rate of addition of Ca^{2+} is about double that of HCO_3^-. From the total CO_2 and the HCO_3^- data, it is clear that the HCO_3^- (and at least some of the Ca^{2+}) are derived from dissolution of $CaCO_3$ in response to the addition of acid (H^+) from another reaction. In effect, alkalinity is transported to and accumulated into the sediments as particulate $CO_3^=$ in $CaCO_3$. Some $CaCO_3$ is solubilized and returned to the oceans as Ca^{2+} and HCO_3^-, undoubtedly to reenter the biogenic $CaCO_3$ cycle. Since a mole of $CO_3^=$ equals two equivalents of alkalinity and HCO_3^- is only one equivalent, the sediments must be a net sink for seawater alkalinity over and above the amount of $CaCO_3$ buried. This is true despite the fact that considerable quantities of HCO_3^- (alkalinity) diffuse out of the sediment into seawater. The quantity of alkalinity consumed in this fashion (net loss) is given by the difference between Ca^{2+} and HCO_3^- fluxes.

The magnitude of the imbalance between the fluxes of Ca^{2+} and HCO_3^- out of the sediments indicates that these diagenetic reactions are the most important control of alkalinity in the oceans save for the biogenic precipitation of $CaCO_3$. It is estimated that about 70 percent of the alkalinity supplied to the oceans annually by rivers (essentially as HCO_3^-) is removed in the precipitation and burial of (Ca, Mg) CO_3, almost entirely of biogenic origin. From the table, the difference between Ca^{2+} and HCO_3^- fluxes is 0.9 x 10^{16} meq/yr. or 28 percent of the total river HCO_3^- flux. Hence, essentially all of the HCO_3^- not eliminated by $CaCO_3$ precipitation can be accounted for in the fashion described above.

Profiles such as those in the figure on the previous page provide a means of determining where in the sedimentary column the reactions producing fluxes occur. This can be done quantitatively using the second derivative of the mathematical expression relating concentration to depth given above. Such an analysis applied to the data available demonstrates that, in general, at least half of the material diffusing across the interface is released or taken up from the uppermost 15 centimeters of sediment. The remainder of the reactions are largely (>90 percent) spread out over the interval 15 to 100 centimeters. This has important consequences regarding investigation of solid phases for the products of these diagenetic reactions. Much of the reaction that occurs is confined to the zone of sediment subject to biological mixing. Sedimentation rates in most of the deep sea are such that despite low mixing coefficients, the solids of this zone are well mixed. Consequently, it would appear to be fruitless to search for evidence of reaction in chemical trends in the solids as a function of depth (for example, increased Mg^{2+} in the solids to reflect the Mg^{2+} taken up from solution). The zone of principle uptake is so well homogenized over the time scale of reaction that solid phase trends are obliterated. This would seem to explain the general absence of unambiguous proof of diagenetic reactions in studies of the chemistry of the solids of marine sediments near the seawater/sediment interface.

The sea floor, then, cannot be envisaged as a definitive boundary of the ocean. Quite the contrary. Chemical and biological processes occurring in the sediments exert a strong, critical influence on the composition of the oceans. This has been shown for the recycling of nutrients as well as of the major elements of seawater. Further investigation will provide more details of the importance of this zone in cycling of many other substances, including trace metals and organic compounds. Such information will be critical to our understanding of the pathways and fate of pollutants added to the ocean.

Warm Water Vents on the Galāpagos Rift

Robert Ballard

THE emanation of warm water from vents is not known to be a common phenomenon on the deep-ocean floor, but it apparently plays a significant role in certain areas. Warm-water vents were the object of investigation on an early-1977 expedition to the Galāpagos Rift, the third major investigation with submersibles of plate tectonic spreading centers in recent years. (Project FAMOUS — French-American Mid-Ocean Undersea Study — was conducted on the Mid-Atlantic Ridge in 1973 and 1974, and the Cayman Trough was explored in 1976 and 1977.)

Scientists from this Institution and from the Scripps Institution of Oceanography first investigated unusually high temperatures in the seabed and overlying water of the Pacific Ocean near the Galāpagos Islands in 1972. During Project FAMOUS when we had our first look at spreading center topography from submersibles, we found clues that later helped to explain the high heat flow found in the Pacific. Fissures in the pillow-lava terrain, which we now consider typical of spreading centers, seemed the most likely avenue for convective heat flow to the sea-floor surface.

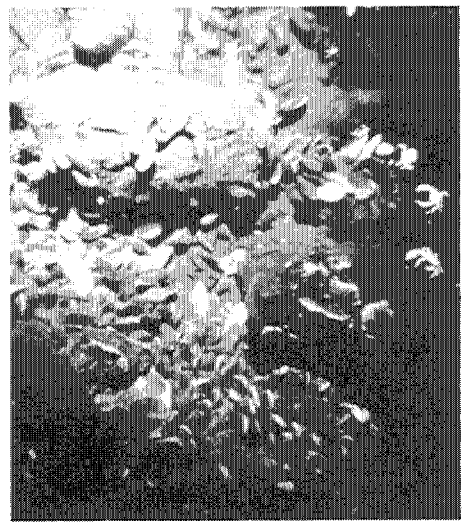
The idea that warm water was apparently flowing springlike out of the earth's crust was substantiated by analysis at Scripps of a 1976 deep water sample taken at the site of a Galāpagos Rift water temperature anomaly. The presence in the sample of natural tracers in the form of primordial gases, primarily helium isotopes, indicated that the temperature anomaly marked the possible location of a spring of water heated by the earth's molten interior.

Investigators from Woods Hole, Scripps, Oregon State University, the Massachusetts Institute of Technology, and Stanford University made up the scientific party that left Panama in early February with the research vessels *Knorr*, *Lulu*, and *Alvin*. The first days of the expedition were devoted to delineating the region for intensive study, installing a precision navigation system, and reconnoitering the area with ANGUS, a color camera and temperature measuring system towed by *Knorr*. On the first lowering of the W.H.O.I.-developed ANGUS, a temperature anomaly one degree higher than normal was recorded along the central ridge axis. Subsequent processing of the ANGUS color film showed an unusual accumulation of marine life in the area of the anomaly

ROBERT BALLARD

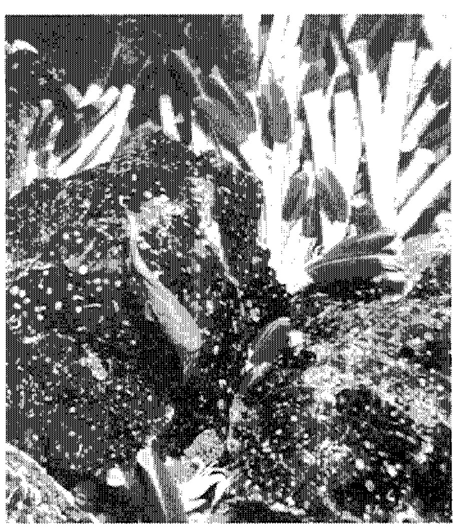
Alvin's arm picks up one of the giant clams found in the warm water vent Galāpagos Rift colonies.

ANGUS



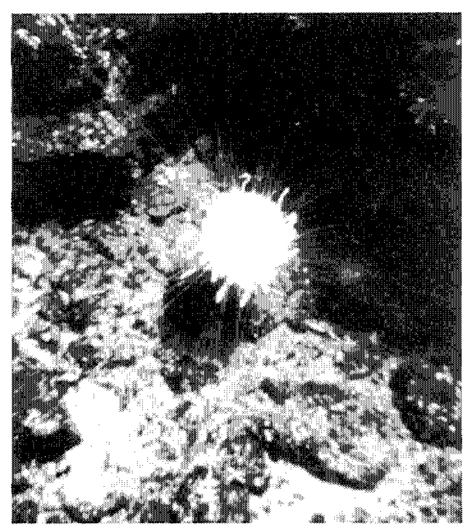
This photo illustrates the abundance of life around the vents. Clams, mussels, and crabs can be seen.

JOHN EDMOND

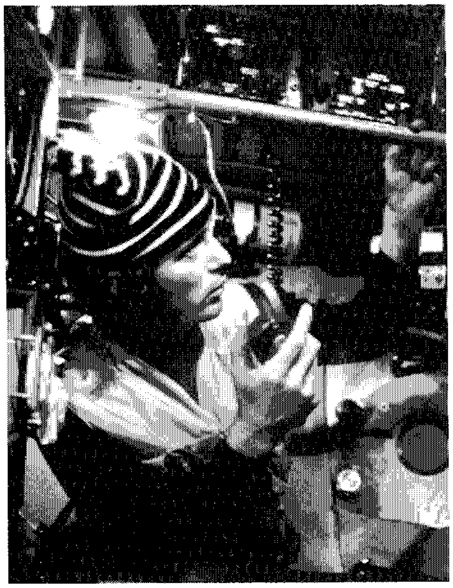


Unusually large tubeworms as well as limpets, crabs, and seaworms were found in one vent colony.

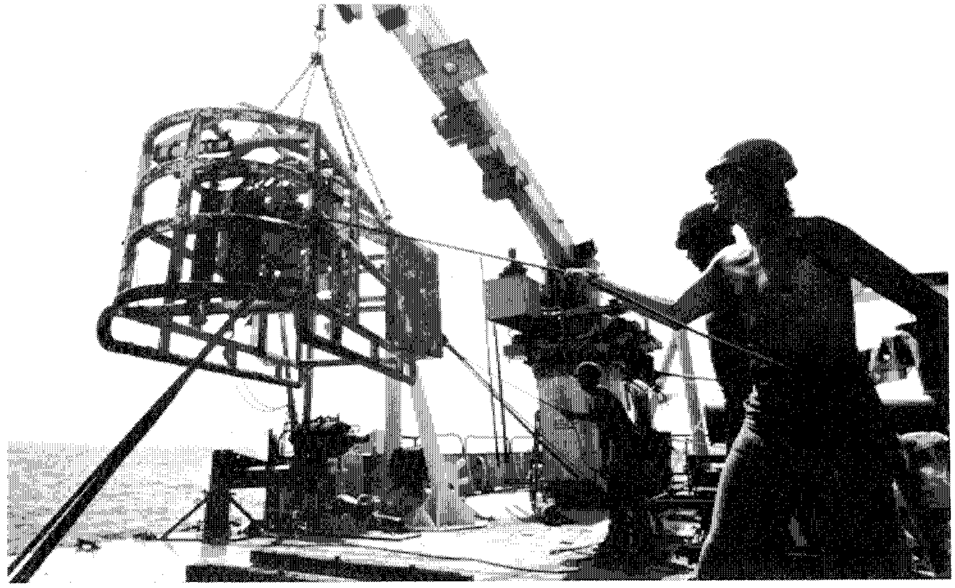
JOHN CORLISS



This organism, which has not been identified, was dubbed "dandelion" because of its appearance.



Bob Ballard in *Alvin*



ANGUS camera rig is launched from *Knorr* for survey run.

NATIONAL GEOGRAPHIC SOCIETY

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rather than the normally barren seascape. Using the same navigation system that tracks ANGUS, *Alvin* could subsequently dive 2,500 meters directly to the spot where the water anomaly and dense marine life were located.

There the diving scientists observed a cloudy plume of water emerging from a vent about 12 centimeters across surrounded by a dense colony of large clams, mussels, gastropods, and worms. This "oasis" was about 50 to 80 meters in diameter and surrounded by the common desertlike terrain of the deep sea. In a total of 21 dives on the rift, we encountered four more similar oases. One was inactive and marked by a dense accumulation of dead clams and empty mussel shells, but the other four were hydrothermally active, and each appeared to have evolved its own unique biological community. As this expedition was planned by geologists, geophysicists, chemists, and physical oceanographers, specific identification of the unexpected biological find had to wait for our return to home bases: we had not a biologist among us.

Water temperatures up to 17°C were recorded in the vents, while the usual temperature for these depths is about 2-3°C. Analysis of the warm water indicated a high concentration of hydrogen sulfide as well as other chemicals. Subsequent culturing of the gut content of some of the organisms showed high concentrations of chemolithotropic sulfur oxidizers and heterotrophic bacteria. Living and multiplying in total darkness, these small organisms appear to be the basis of a food chain which culminates in the larger organisms we observed. The exact reasons for the occurrence, size, and diversity of the biological communities along with numerous other questions pertaining to the biology, chemistry, geology, and geophysics of these active hydrothermal vents are presently being sought through analysis of the samples, photographs, and visual observations made during this expedition. Plans are now being made to return — with biologists — to the Galāpagos Rift in early 1979 to expand this work.

The development of the technology for ANGUS survey followed by overnight processing of its film and immediate dive targeting from the newly-developed film allowed maximum use of the submersible as an observational tool. It was not, therefore, necessary to consume valuable submersible time in reconnaissance, as we had on previous expeditions. This form of teamwork will be most important to the scientific output of future cruises.

Manned Deep Submersible Operations

Lawrence Shumaker

THE Deep Submergence Research Vehicle *Alvin* had a banner year in 1977. Carried aboard the Research Vessel *Lulu,* the submersible ventured into both the Pacific Ocean and the southern hemisphere for the first time, visiting two U.S. possessions and four foreign countries in the course of traveling nearly 10,000 miles. Far more significant, however, is the fact that 101 dives were made in 1977 (a record in itself), and 96 produced scientific information. With an average time of about 5 hours per dive on the sea floor carrying 2 scientific observers, this amounts to nearly 1,000 observer hours on the sea floor.

The Galāpagos Rift expedition was the most spectacular program of the year and one in which the submersible proved most durable. On the first diving leg, a record 11 dives in 11 days were made, but that record stood only until the second diving leg when 13 dives were made in 13 days. Specialized equipment developed both at Woods Hole and at other institutions for studying and sampling the warm water vents supplemented the usual *Alvin* package of instrumentation.

The scientific findings of the expedition are described by Robert Ballard elsewhere in this report.

Early in the year a cruise was made in the Bahamas to make firsthand observations on the biology of deep water benthic fishes and larger invertebrates and to take qualitative and quantitative data by visual and photographic methods. During the course of 8 dives, 35 species of benthic and benthopelagic fishes were observed, and behavioral studies were made on several species. At least a dozen species of holothurians and 6 species of echinoids were also observed.

Five dives in 1975 to look at and take selective samples on the sea floor in the Tongue of the Ocean in the Bahamas led to six more dives in 1977. The combination of direct observation of sediment and rock samples *in situ* and the laboratory analysis of these same samples has resulted in some exciting discoveries regarding the composition, diagenesis, and emplacement of the boulder beds found in various canyons in that area.

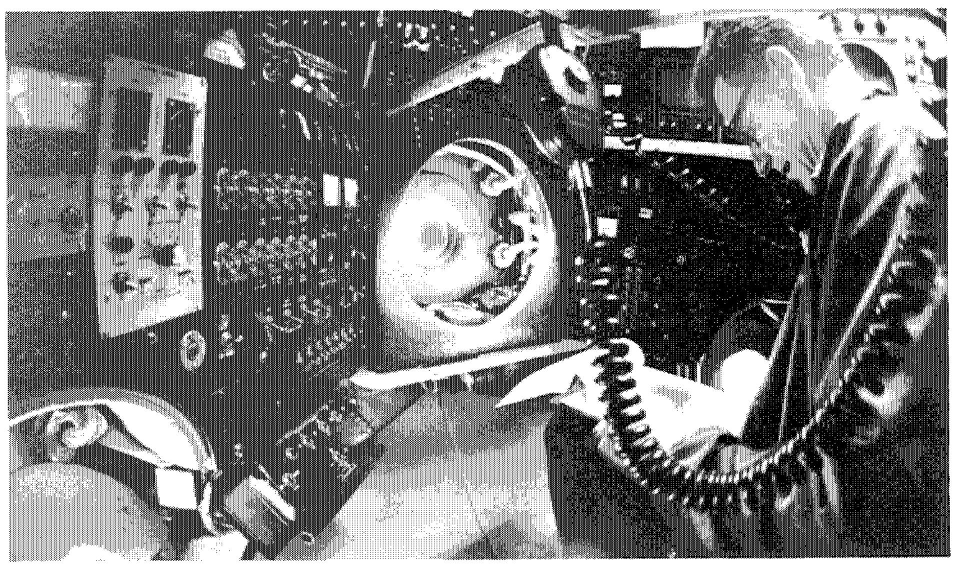
Other biological and geological studies were made on the continental margins off the Middle and North Atlantic States and a cruise to the Cayman Trough area of the Caribbean allowed selective geological sampling to fill in gaps left in the knowledge of that area following analysis of data and samples taken during 15 dives in 1976.

Better than any previous year, the 1977 season has underscored the importance of direct observation to oceanographic scientists. Dreams of using submersibles to make direct observations that would supplement and verify samples and data taken from the surface date, at least in mythology, to Alexander the Great. In more recent history, as oceanography grew into a modern science, there was an increasing desire for a means of direct observation, particularly at the sea-floor/water interface, now known as the benthic boundary layer. When *Alvin* was constructed by the United States Navy and delivered in 1964 to the Woods Hole Oceanographic Institution for operation, the means for direct observation in the deep sea began to become a reality. The early years of the submersible were largely devoted to finishing engineering touches and familiarization with a new tool. Gradually, however, a core of experienced users began to assemble. As the pilots developed skill in maneuvering and operating the sub, scientists began to understand its capabilities for their purposes, and the ratio of testing to scientific dives has steadily moved heavily toward the scientific.

Alvin's capabilities include:

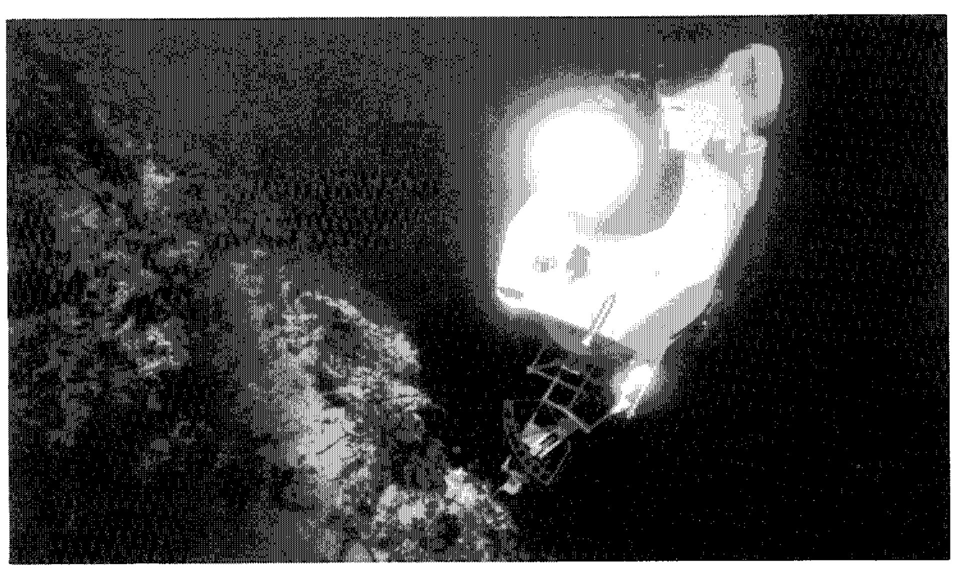
1) Operation at any depth from the surface to 3,658 meters at speeds of 0 to 3.5 kilometers per hour while carrying one or two observers and various internal and/or external instrumentation and tools.
2) Performance of scientific or engineering tasks.
3) Maneuverability within 30 centimeters of slopes or other bottom topography.
4) Performance of tasks while resting on the bottom.
5) Hovering at neutral buoyancy.
6) Ability to remain submerged for periods up to approximately 10 hours (with 72 hours of emergency life support).

Perhaps the major recent development toward productive scientific utilization of *Alvin* was the design and construction of a deep ocean acoustic navigation system. This system, developed by engineers at Woods Hole, allows the submarine to be precisely positioned



VICKY CULLEN

Larry Shumaker inside *Alvin*'s personnel sphere



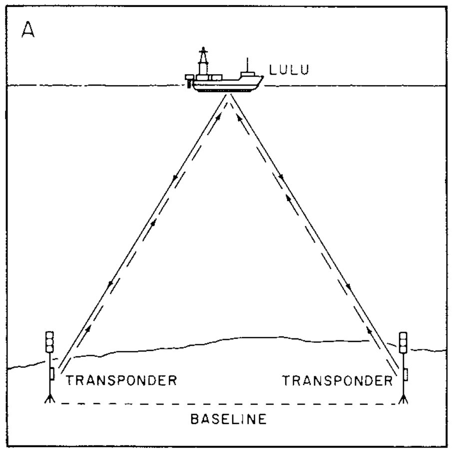
DAVID DOUBILET, NATIONAL GEOGRAPHIC SOCIETY

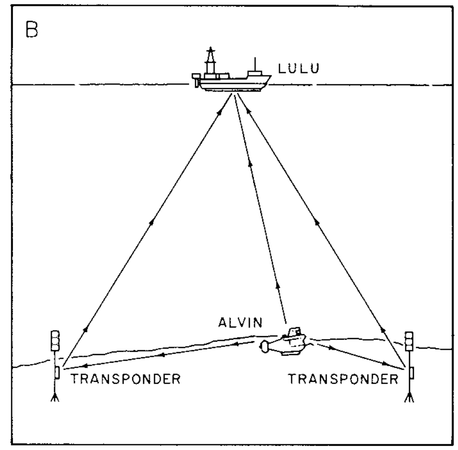
Alvin explores submarine cliff near Andros Island.

within a given area with relation to a set of bottom mounted acoustic transponders. Any feature within the area can then be related in space to any other feature, allowing very detailed maps of geological and topographical features to be produced.

This system had its first full scale use during the French-American Mid-Ocean Undersea Study in 1974 when 18 dives were made on the Mid-Atlantic Ridge. In a much improved version, it was used this year in the Galāpagos Rift not only to relate all dive observations to each other but also to relate the many kilometers of towed camera photographs to each other and to the dive observations.

The addition of improved cameras, which record time, depth, altitude, and submarine heading on each photograph, and the installation of an automatic analog data recording system have further improved the ability of the scientist





At left, *Lulu* interrogates transponders for her own position. At right, *Alvin* interrogates transponders, and the answers are received on *Lulu*. The position fixes calculated on *Lulu* are available at 30 to 40 second intervals.

to correlate direct observations with photographs and data gathered from other sensors.

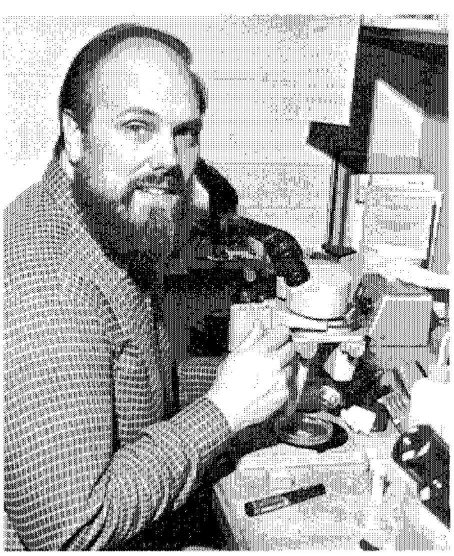
For the future, *Alvin* is receiving a major refit which will give her added payload for more sensors and will provide space for additional batteries that may allow even longer dives. During 1978, we also expect to add a color television camera and recording system and a digital data logging system with greatly increased data capacity.

Colonization and Patchiness in Deep-Sea Sediments

Frederick Grassle

THE deep sea was once thought inhospitable to life, but recent assessments have begun to show that although most deep-sea organisms are small, their variety rivals that of rain forests and coral reefs. A single square meter of bottom may contain over 200 species of macrofauna.

FRANK MEDEIROS



Fred Grassle

The deep sea is a vast area of relatively constant climate. There is little input of energy, and the topography is basically simple. As we cannnot yet simulate deep-sea conditions in the laboratory, experiments must be done on the sea floor. Many of them take years to complete including periodic returns to the same spot in submersibles. We have used *Alvin* to place, manipulate, and retrieve experiments at permanent bottom stations established at 1,800 and 3,600 meters off the northeastern United States and at 2,000 meters in the Bahamas.

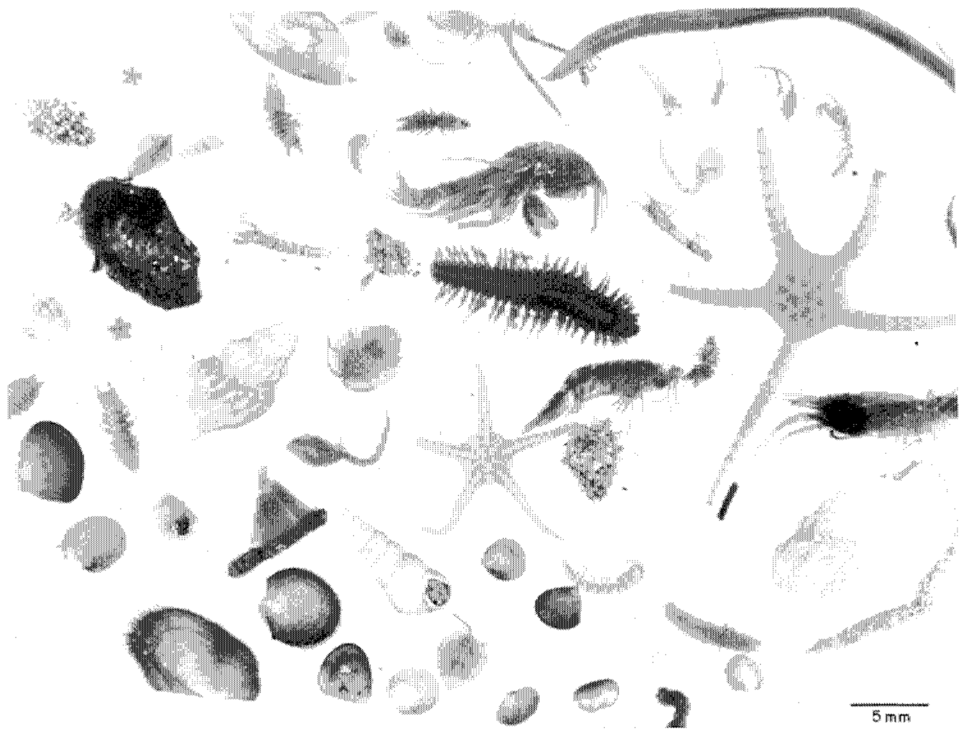
Some experiments have involved the use of unoccupied sediments which are placed on and later collected from the deep seabed to assess rates of colonization and growth. Trays of sediment are opened on the bottom and left for periods ranging from two months to three years. Immediately after retrieval, the contents of each tray and also of control samples from the surrounding sediments are gently washed over fine screens. The material retained on the screens is then sorted under a microscope, a process that may take months for a single sample. (The use of fine screens and closing doors on trawls now results in single samples with many times more animals than were collected on the entire Challenger Expedition.)

Results to date clearly indicate very low rates of colonization in comparison with shallow water. Even after two years, densities are an order of magnitude lower in the experimental trays than in surrounding sediments, and most of the animals settling in the trays are juveniles with one notable exception, a species of polychaete worm belonging to the genus *Capitella*. These animals are well-known for their ability to increase following disturbance, though they are normally rare in the deep sea.

The growth rates of the remaining fauna for the most part indicate time-to-maturity of longer than two years. One of the deep-sea relatives of the sea squirts, *Polycarpa delta*, and the most common of the slope-dwelling bivalves, *Nucula cancellata*, have times-to-maturity of about two years. At the other extreme, we have collected from the continental rise a different species of bivalve, *Tindaria callistiformis*, which has a time-to-maturity of about 50 years, with the oldest age class living to about 100 years.

Although these data on the potential for population increase appear contradictory at first glance, they provide remarkable support for current theories on the evolution of life history features. Large numbers of eggs and short maturation times are characteristics of relatively opportunistic species, which are well-adapted for life in short-lived habitats. Most species withstand environmental changes through physiological and behavioral responses that are part of the adaptive equipment of every individual. Sudden catastrophic changes in the environment are not within the tolerance of every individual and thus require population adjustments for the species' survival. Species adapted to short-lived habitats must have the ability to increase rapidly under favorable conditions and release sufficient young to colonize new areas as the local environment becomes uninhabitable. If disturbance is a frequent feature of the environment, a premium is placed on local increase in numbers.

The results obtained with *Alvin* provide the first direct information on how the whole community functions to allow the coexistence of such an enormous variety of species. Although disturbance is infrequent in the deep sea, when it does occur a few species colonize slowly, and the disturbed area remains different from the surrounding environment for periods of time measured in years. This is in sharp contrast to high latitude shallow-water environments where recovery occurs in periods of months or less. The very slow rates of colonization in the deep sea mean that an environmental mosaic is created. Each small patch will differ depending on the length of time elapsed following disturbance and the particular species which happen to find each spot. The infrequent disturbances affecting small areas, such as mud slumps, activities of larger animals (fish and invertebrates), and large objects settling from the surface (especially carcasses of surface animals, sargassum weed, and pieces of wood), are the



FRANK MEDEIROS

Collection of tiny organisms that inhabit bottom sediments shows the wide diversity of their development.

sources of environmental heterogeneity. They occur so infrequently that the patchiness they produce is seldom demonstrated in quantitative samples.

Our studies of diversity and the preliminary information on life histories indicate that the deep sea is an extremely fragile ecosystem. Having evolved in a relatively unchanging environment, most species are ill-adapted to disturbance. Environmental changes of a magnitude that would have little or no effect on land or in shallow water severely affect deep-sea communities. Our measurements of rates of response of populations to disturbance will be of practical value in predicting the effects of such human perturbations as dumping of wastes or deep-sea mining. More accurate prediction of the rates of recovery following such disturbances and the rates at which organisms facilitate the spread of toxic wastes will require further experimentation on the sea floor.

Deep-Sea Animal Distribution and Ecology

Richard Haedrich

In 1970, Gilbert Rowe, Pamela Polloni, Hovey Clifford, and I undertook an investigation of the distribution and ecology of the large animals living on the deep ocean floor south of New England. This community of large animals, usually referred to as the megafauna, had received only little attention. We were anxious to find out if the accepted generalities concerning life in the deep sea, derived almost entirely from study of the macrofauna — the small worms and clams living in the sediments — would apply as well to the megafauna. Another area of interest was to compare the fauna living on the open continental slope with that found in large submarine canyons at similar depths. The canyons are themselves a rather special environment, and we expected them to be populated by a unique fauna.

We adopted the 40-foot Gulf of Mexico shrimp trawl as our standard sampling gear. Fitted with 80-foot bridles, this net performed very well even to depths near 5,000 meters, the mouth being held open by steel doors specially designed for use in deep water. The net had to be set and retrieved rather slowly, with the result that a single deep-water tow could occupy as much as 8 hours, and considerable ship time has been needed for the over 100 trawls we have made to date. To augment and to complement our trawl collections, for these are not without their biases, we used deep-sea cameras and, whenever opportunity availed, dives in the submersible *Alvin*.

The major megafaunal groups are the shrimps and crabs, the starfish, brittlestars, sea urchins, and sea cucumbers, and the fishes. These groups occur with the greatest regularity in our collections, but others, for example sea anemones, octopuses, quill worms, sea spiders, and solitary corals, can be locally abundant. As has been shown for all oceanic life, there is a pronounced, approximately logarithmic decline in numbers and biomass with increasing depth.

Interesting anomalies occur at about 2,000 meters. Here, where the fairly steep continental slope meets the more gentle continental rise, greater numbers and biomass of animals are encountered than would be predicted. At these sites the accumulation of organic-rich sediments eroded from shallower depths could provide the basis for the observed increase in life. In most groups, there is a tendency for the numbers of species present to increase with depth, but this increase in diversity generally reaches a maximum, then declines at greater depths. Diversity in fishes is greatest at deep slope depths; in crustaceans it is greatest on the mid and upper slope; in echinoderms it is greatest near the slope base and top of the rise; and in the small animals living in the sediments it is greatest near the middle of the rise. The diversity maximum in echinoderms appears to exist in areas with the greatest heterogeneity in bottom type, and, thus, presumably with the greatest number of microhabitats.

In examining the changes in species composition with depth, we have noticed, as have others, that distributions are zoned, and our data show that zonation is more than just a species phenomenon. It extends to entire faunas as well. For the megafauna between 200 and 5,000 meters, 7 broad regions replace one another with increasing depth. For the small animals in the sediments, there are about 6 zones between 32 and 3,600 meters. The fauna within a zone is distinct and fairly homogeneous and can be characterized in terms of overall abundance, biomass, diversity, and dominant species. The boundaries between zones are defined by a general and relatively rapid pattern of species replacement. In a very approximate way, the zonation patterns follow the topographic regime. Where the depth gradient is the steepest, on the continental slope, zones appear to be the most clearly defined. Across the more gradual incline of the continental rise, zonation is not as marked. Canyons, contrary to one of our early hypotheses, do not seem to harbor distinct faunas; the faunal zones of the slope cut right through them at the appropriate depths.

In an attempt to determine the underlying causes in the patterns of zonation, we began studies of the ecology of certain dominant species. We have focused first on the fish, with emphasis on the feeding of the abundant rattails, but have looked at other groups as well. Other than the fact that a multitude of life styles

Dick Haedrich

seems to be present in the deep ocean, little in the way of firm generalizations about deep-sea life is emerging from this time-consuming work. There are some species which seem to spawn year-round, but there are others, even in the presumed absence of seasonal cues, that spawn at only one time of year. Some species appear to have specialized diets, while others are quite generalized. Some species assemble rapidly to the bait we lower with our cameras, but others

HOVEY CLIFFORD

A skate, a few brotulids, and a number of grenadiers gather at a feast of two tunas and a shark provided by a baited camera experiment at 3,640 meters. The tunas were consumed in two weeks, and the fish were beginning on the shark at the end of the 17-day experiment. Photographs were taken every 30 minutes.

ignore it completely. The patterns we see in parasite infestation and life histories and in the degree of genetic polymorphism of deep-sea populations differ but little, if at all, from those observed in shallow waters.

The basic food supply drives any ecosystem. For the deep ocean, where no primary production is thought to take place, this food material must come from outside. As reflected in the logarithmic decline in abundance with depth and in the various feeding strategies observed, food supply to the deep sea must vary considerably in both type and rate of input. It is the nature of these two factors, we feel, that ultimately produces faunal zonation. For this reason, we have been very interested in the current attention being given to the measurement of particle flux into the deep ocean. Sediment traps in deep water suggest that fecal pellets produced by near-surface plankton are a major source of organic matter. A model based on feeding relations in the upper water column predicts that this should be true, but also suggests that falls of very large particles, the bodies of dead fishes and whales, should not be discounted. Appreciation of this fact helps us to understand the "bigger-deeper" phenomenon, whereby the mean size of bottom-living fishes in the deep ocean increases significantly with depth. Large size is necessary for these animals, which live mostly by scavenging, to cover sufficient territory to find the relatively rare but rich food source represented by such a large particle.

Food Sources and the Cycling of Organic Matter in Deep-Sea Communities

Gilbert Rowe

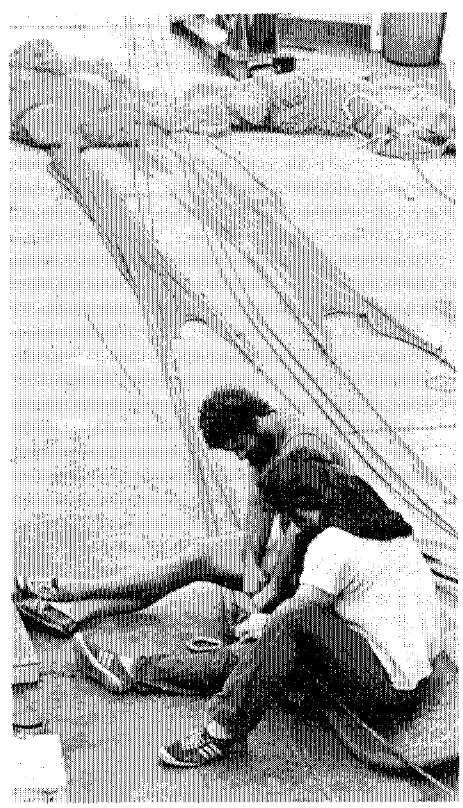
THE biota of the sea floor, so distant from the phytoplankton of the sunlit surface water, depends for its food on the importation of organic detritus from above. The abundance, biomass, and structure of deep-sea communities are dependent on the composition, quality, and quantity of the descending food resources. The little-understood mechanisms for this flux of organic energy present biological oceanography with some of its most difficult and important questions.

The traditional assumption that "organic detritus" reaches remote depths in a "rain of small particles," that is, sinking of dead plankton and fecal pellets of live surface-dwelling animals, led us to deploy arrays of sediment traps in the deep North Atlantic and in the Pacific upwelling region off Peru. Large cylinders were strung along anchored vertical moorings for extended periods (up to 16 days) to collect the rain of particles much as a rain gauge in the air catches rainfall. A study completed with Joint Program student Wilford Gardner, now at Lamont, indicated that about 4 grams of organic carbon per meter square per year reaches continental rise depths in the North Atlantic.

A simplified budget of the fate of settling organic matter in the deep sea can be represented by a diagram relating vertical flux into the deep ecosystem to utilization by organisms, burial, and resuspension. In general, for the North Atlantic continental rise, the infaunal and microbial respiration are equal to one-fourth of the primary input, in terms of organic carbon, whereas burial or accumulation on the bottom is slightly greater than one-fourth of the primary flux. An unaccounted-for fraction is indirect evidence that a significantly large community of scavenging organisms lives just above the bottom.

There may be other important sources of food. Recent experiments with baited cameras have shown that many fish and invertebrates assemble to devour the large bait. Richard Haedrich, Holger Jannasch, and I were surprised to find, however, that in a long-term (17-day) baited camera deployment, the bait was consumed much more slowly than we had thought it would be. Whether such falls occur in nature is not known, but we believe we would see much more evidence of the phenomenon if it were widespread and important. It is possible that material of this kind never reaches the bottom, but is consumed as the carcass slowly sinks from the surface, taking weeks to reach really deep water in a much-altered form.

Catastrophic downslope movement in slumps or turbidity flows could move shallow water sediments, relatively rich in organic matter, into the deep sea (or such events could instead decimate bottom communities by burying them). To test the hypothesis that these landslidelike currents are food sources, numerous short cores (20 to 60 centimeters) were taken with *Alvin* and from surface vessels on the continental slope, rise, and abyssal plain in the North



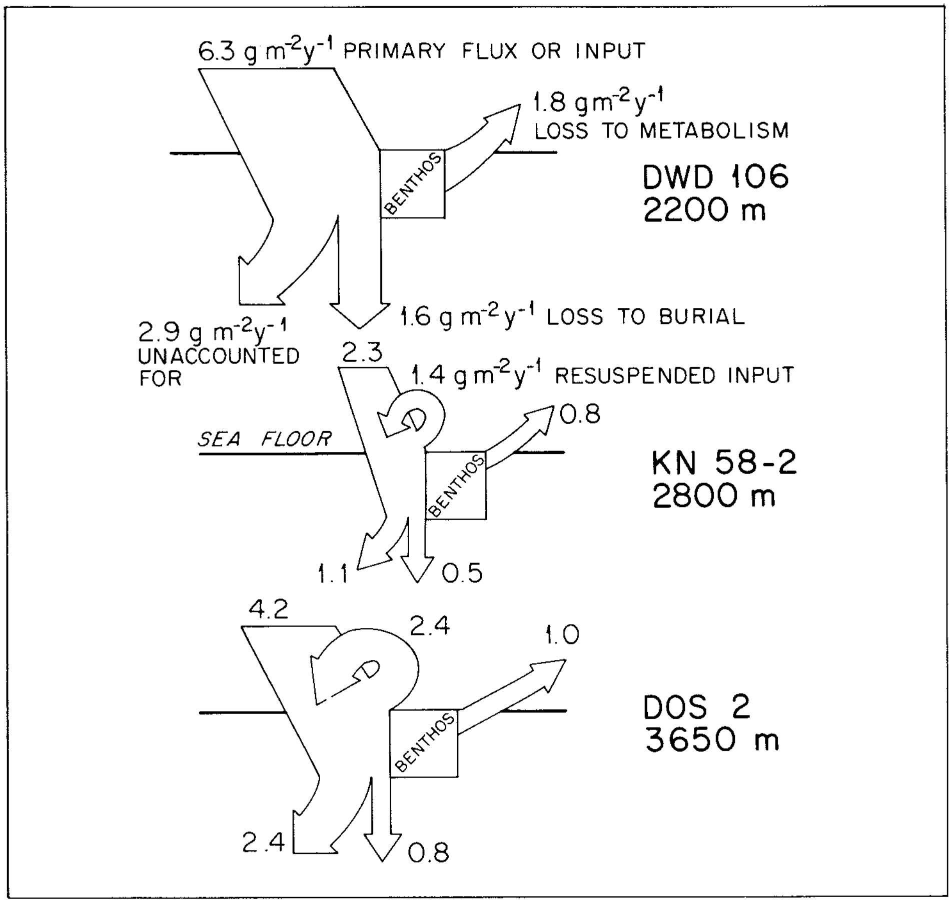
VICKY CULLEN

Gil Rowe and Nick Staresinic prepare shrimp trawl.

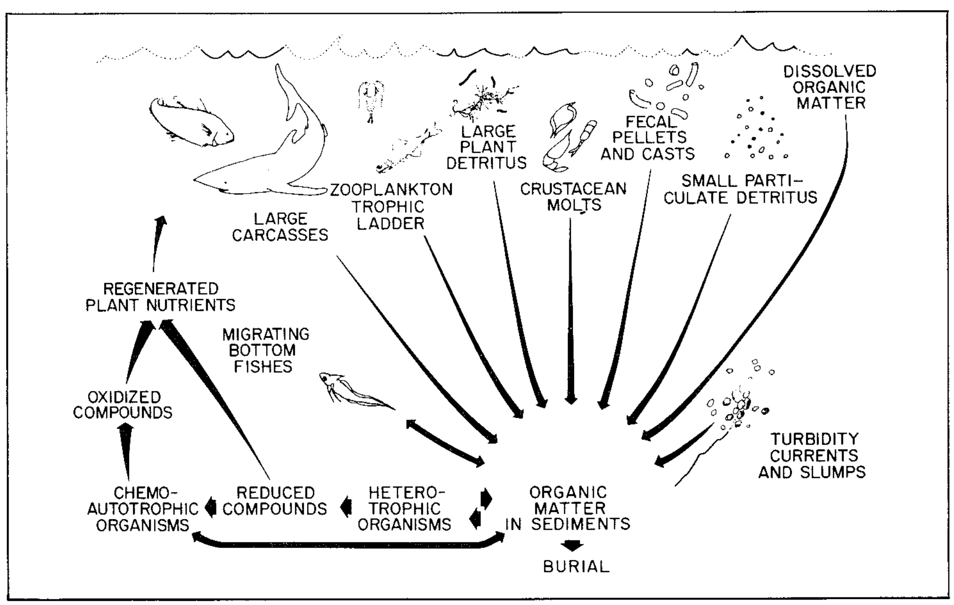
Atlantic. Care was taken to sample in the central axes of submarine canyons, known to contain periodic sediment movements, and on the abyssal plains at various distances from where turbidity currents are known to debouch onto abyssal plains. Geologists use shelf-derived mineral grains and shells of shelf-living animals to trace these flows, and it was our intention to look in their paths for high concentrations of organic matter or metabolic byproducts, such as ammonia, in sediment pore water. We found sediment grain size and composition changed radically from coarse sand-sized particles in the canyons and valleys to fine silt and clay-sized material outside canyons, but the concentrations of organic matter were inversely correlated with percent sand and not related to any presumed proximity to sediment flow from shallow water. Organic carbon in the deep Hudson continental rise valley was about half that at equivalent depths nearby, but outside the canyon.

Ammonia is utilized by nitrifying bacteria as an energy source to produce organic matter, with nitrate and nitrite as byproducts. While the concentration ratio of ammonia to nitrate and nitrite is about 5 to 1 in most shallow sediments, on the distal abyssal plain off Cape Hatteras there is about a 1 to 1 correspondence between the concentrations of the 2 compounds, indicating that nitrification is somewhat higher there than at lesser depths. In sediments of the shallow waters of the continental shelves, we believe that the diffusion of ammonia and nitrate back into the water column from the sediments is an important source of nitrogen for photosynthetic organisms. Although at great depths this would seem less important, because the bottom is so removed from the surface waters, there is the possibility that the conversion of ammonia to nitrate is indirectly acting as a source of food for organisms because the energy liberated allows the chemoautotrophic organisms to synthesize cell material. These microbes can then be consumed by larger organisms. If this synthesis of organic matter from CO_2 is very efficient, it may mean that a key to understanding early diagenesis lies with the synthesizing capabilities of a few relatively restricted taxonomic groups of bacteria.

Continuing work with similar approaches will concentrate on regions of high productivity instead of depauperate oceanic waters. Major emphasis will change somewhat from studies of total fluxes to the biological mechanisms responsible for transferring organic energy to great depths.



Flow diagrams of organic carbon flux at three depths on the continental rise in the northwest Atlantic Ocean.



Conceptual model of the potential sources and transport mechanisms of organic matter to the deep sea.

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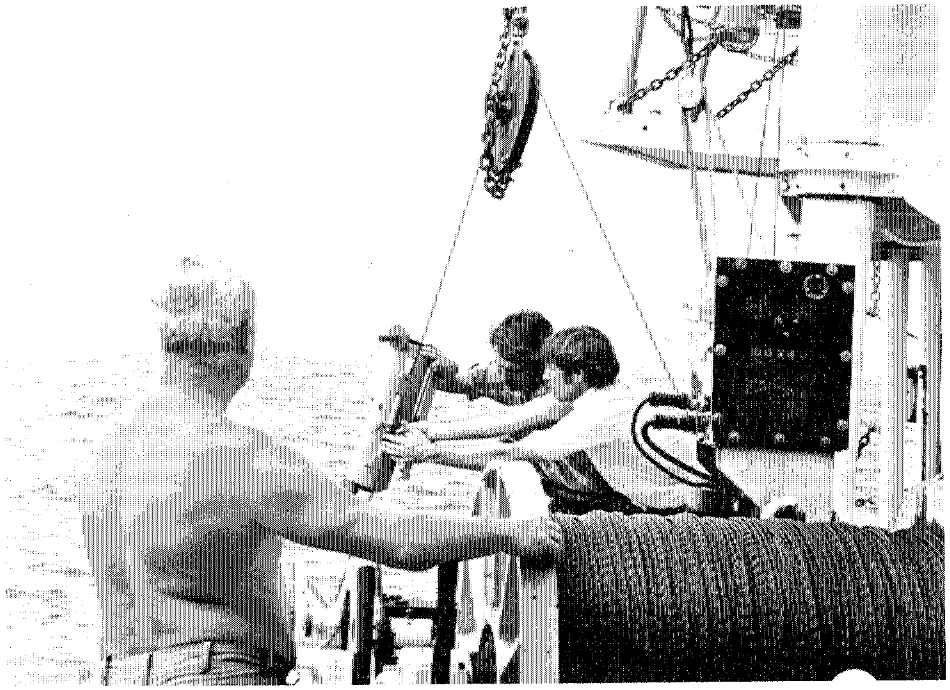


Geology graduates Ed Laine (1977) and Wilf Gardner (1978) attach sample bottle to *Atlantis II* hydrowire.

Dean's Report

OUR educational programs operated at a vigorous pace in 1977. In every category — undergraduate summer fellows, guest students, graduate students, postdoctoral fellows — the number of students was equal to or greater than that of any previous year.

In 1977 the Institution awarded 14 doctorates jointly with the Massachusetts Institute of Technology. The names of these graduates together with their fields and thesis topics are given overleaf. All of the recent graduates have obtained employment in suitable research or teaching positions.

Eighty-one students were enrolled in our graduate programs during the year, the same number as in 1976. Twenty new students joined the graduate program in 1977. These were selected from 184 applicants, a decrease of about 10 percent from the levels of the previous 3 years.

It is worth commenting on certain trends in our joint graduate program since 1970 when the new program was expanded to include biological oceanography. Although the total number of applicants rose dramatically after opening the program to biologists, the total number of applicants has remained at about 200 for the past several years. The most dramatic feature of our applicant distribution has been the imbalance that has persisted between biology and the other fields. Over half of our applicants are biologists but only about 5 percent are offered admission in that field.

While the enrollment in physical oceanography has been reasonably constant over the years (at about 20), the number of applicants to that field steadily declined from 1970 to 1976. This trend has been of concern since the joint strength of W.H.O.I. and M.I.T. in physical oceanography is unmatched anywhere in the world. Fortunately this decline in applicants was arrested in 1977. The pool of applicants in physical oceanography probably will continue to remain small, although fortunately the quality of students has remained high.

Applicants in geology and geophysics grew steadily between 1970 and 1975 to the present level of about 35. Enrollment has now leveled off at about 20. Although the program in marine chemistry has remained small, it is reasonably selective. The program in engineering has also remained small over the years. Applicants each year have rarely exceeded 20 and enrollment has remained at about a dozen. Recently the joint program has been broadened to include most of the M.I.T. engineering departments, but it is too early to see to what degree this will increase the number of students.

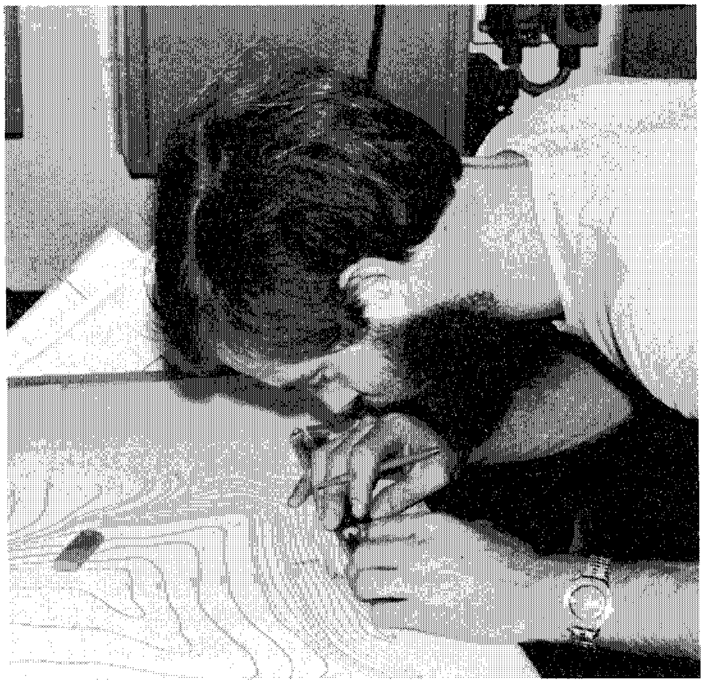
Since 1970 there have been significant shifts in the relative roles played by W.H.O.I. and M.I.T. in the joint program. Not surprisingly, as the program has grown, the Oceanographic Institution has played an increasingly larger relative role. Indeed, the growth in the program since 1970 (from 54 students to 81) has taken place almost entirely at Woods Hole. This is indicated most clearly by the statistics on student residency. Students may be resident at either institution; the choice usually reflects where the students' activities are centered. In 1970, 33 students were resident at M.I.T. and 21 students were resident at Woods Hole. In 1977, 35 students were resident at M.I.T. but 45 were resident at Woods Hole. The more than doubling of the number of students resident at Woods Hole has necessitated a significant increase in the commitment of staff time to educational activities. Because student financial assistance also is primarily determined by the place of residence, the growth of the program since 1970 has been financed largely by funds from W.H.O.I. sources, government-supported research grants as well as endowment funds and private grants.

The summer fellowship program enrolled 18 undergraduate students in 1977. I am happy to report this year that 8 of these summer fellowships were provided by special gifts from Associates.

The number of postdoctoral fellows at the Institution was at a record high in 1977. Eight fellows were selected for our program in the marine sciences and engineering, and 11 fellows were selected for our program in Marine Policy and Ocean Management. We are most happy that strong financial support from the private sector (endowment funds and foundation grants) has allowed us to maintain such strong postdoctoral programs.

ROBERT W. MORSE

Education



ALAN DRISCOLL

ALAN DRISCOLL

Geology & Geophysics students Sandy Shor, charting bathymetry, and Mary Jo Richardson, wielding pencil, work aboard *Atlantis II* Voyage 94.

DEGREE RECIPIENTS — 1977

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

Doctor of Science

JAMES K. B. BISHOP
B.S., University of British Columbia, Canada
Special Field: Chemical Oceanography
Dissertation: *The Chemistry, Biology and Vertical Flux of Oceanic Particulate Matter*

ALAIN COLIN de VERDIERE
Engineer Degree, Ecole Supérieure de Physique et de Chimie, France
Special Field: Physical Oceanography
Dissertation: *Quasigeostrophic Flows and Turbulence in a Rotating Homogeneous Fluid*

Doctor of Philosophy

CHARLES C. ERIKSEN
A.B., Harvard University
Special Field: Physical Oceanography
Dissertation: *Measurements and Models of Fine-structure, Internal Gravity Waves and Waves Breaking in the Deep Ocean*

CHARLES N. FLAGG
B.S., Cornell University
Special Field: Physical Oceanography
Dissertation: *The Kinematics and Dynamics of the New England Continental Shelf and Shelf/Slope Front*

PETER J. HENDRICKS
A.B. and Sc.B., Brown University
Special Field: Oceanographic Engineering
Dissertation: *Finestructure and Turbulence in the Deep Ocean*

SUSAN E. HUMPHRIS
B.A., University of Lancaster, England
Special Field: Chemical Oceanography
Dissertation: *The Hydrothermal Alteration of Oceanic Basalts by Seawater*

EDWARD P. LAINE
B.A., Wesleyan University
Special Field: Marine Geology
Dissertation: *Geological Effects of the Gulf Stream System in the North American Basin*

STEVEN J. LEVERETTE
B.A., Gettysburg College
Special Field: Ocean Engineering
Dissertation: *Data Adaptive Velocity/Depth Spectra Estimation in Seismic Wide Angle Reflection Analysis*

CHARLES G. PARIS
B.S., Rensselaer Polytechnic Institute
Special Field: Biological Oceanography
Dissertation: *Studies on the Metabolism of Tryptophan in* Klebsiella aerogenes: *Enzymology and Regulation*

JOHN W. PEIRCE
A.B., Dartmouth College
Special Field: Marine Geophysics
Dissertation: *The Origin of the Ninetyeast Ridge and the Northward Motion of India, Based on DSDP Paleolatitudes*

JAMES G. RICHMAN
B.S., Harvey Mudd College
Special Field: Physical Oceanography
Dissertation: *Kinematics and Energetics of the Mesoscale Mid-Ocean Circulation: MODE*

BARRY R. RUDDICK
B.S., University of Victoria, Canada
Special Field: Physical Oceanography
Dissertation: *Observations of Interaction Between the Internal Wavefield and Low Frequency Flows in the North Atlantic*

MARY I. SCRANTON
B.A., Mount Holyoke College
Special Field: Chemical Oceanography
Dissertation: *The Marine Geochemistry of Methane*

KENNETH B. THERIAULT
S.B., M.S., E.E., Massachusetts Institute of Technology
Special Field: Electrical Engineering
Dissertation: *Accuracy Bounds on Normal Incidence Acoustic Structure Estimation*

Sources of Support for Research & Education

Amoco International Oil Company
Associates of the Woods Hole
  Oceanographic Institution
Atlantic Richfield Company
Atlantic Tuna Club
Australian National University
Bermuda Anglers Club
Boston University
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Continental Oil Company
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Duke University
Exxon Corporation
  Exxon Company, U.S.A.
Field Enterprises Educational Corporation
The First National Bank of Boston
Max C. Fleischmann Foundation
Freeport Tuna Club
Getty Oil Company
Globe Newspaper Company
Green Harbor Tuna Club
Gulf Oil Foundation of Delaware
The John A. Hartford Foundation, Inc.
Harvard University
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International Light Tackle
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George B. H. Macomber Company
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Marlin Conservation Club
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McGill University
Andrew W. Mellon Foundation
Memorial University, Newfoundland
Mobil Foundation, Inc.
Mobil Oil Corporation
New England Farm & Garden Association
New Orleans Big Game Fishing Club
Nova University
Ocean City Light Tackle Club
Ocean City Marlin Club, Inc.
Pew Memorial Trust
Phillips Petroleum
Port Aransas Rod and Reel Club
Research Corporation
Sailfish Club of Florida, Inc.
St. Joe Minerals Corporation

The Schaefer Foundation
Scaife Family Charitable Trusts
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  of America
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Textron Charitable Trust
Union Oil Company of California
U.S. Atlantic Tuna Tournament
United States
  Air Force Department
  Army Department
    Army Corps of Engineers
  Commerce Department
    National Marine Fisheries Service
    National Oceanic & Atmospheric
      Administration
  Energy Department
  Environmental Protection Agency
  General Services Administration
  Health, Education & Welfare Department
    National Institutes of Health
  Interior Department
    U.S. Geological Survey
  National Aeronautics & Space
    Administration
  National Science Foundation
  Navy Department
    Naval Air Development Center
    Naval Air Systems Command
    Naval Electronics Systems Command
    Naval Facilities Engineering Command
    Naval Research Laboratory
    Naval Undersea Center
    Naval Underwater Systems Center
    Naval War College
    Office of Naval Research
  State Department
  Transportation Department
    Coast Guard
University of Alaska
University of California
University of Cambridge, England
University of Delaware
University of Gothenburg, Sweden
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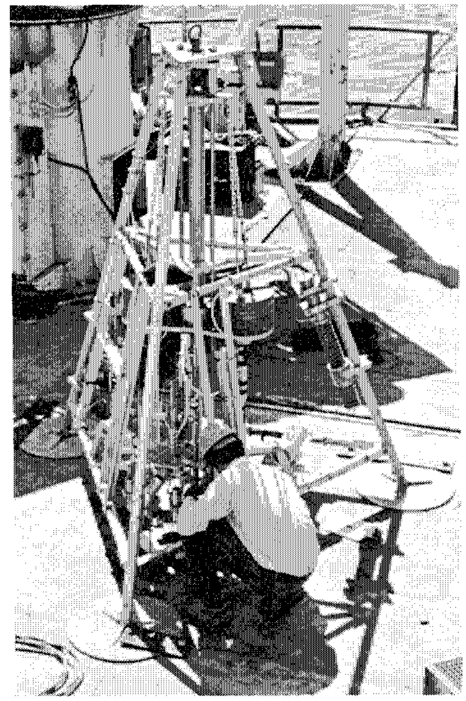
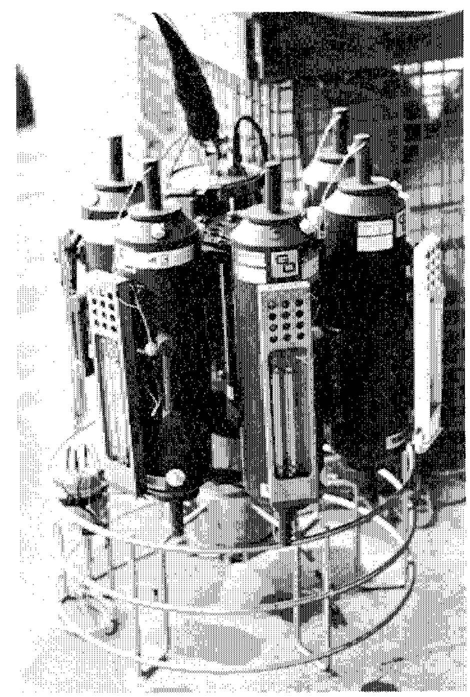
University of Miami
University of New Hampshire
University of Rhode Island
Woman's National Farm &
  Garden Association
Yale University



Tripod supports apparatus for studies of water contained in sediments



Rosette water sampler is mounted on conductivity, temperature, and depth instrument.

Voyage Statistics

R/V Atlantis II

Total Nautical Miles for 1977 — 45,071
Total Days at Sea — 298

Voyage	Cruise Period	Principal Objectives, Area of Operations	Port of Call	Chief Scientist
93-XV	(12 Dec)–10 Jan	Physical oceanography in Indian Ocean along equator from 90°E to 50°E; underway survey of currents; recovery of 7 moorings	(Singapore) Goa, India	Tupper
93-XVI	13 Jan–1 Feb	Study of the chemistry and microbiology of oxygen-depleted waters of eastern and northern Arabian Sea	Karachi, Pakistan	Deuser
93-XVII	7 Feb–26 Feb	Examine chemical mass balance in the Persian Gulf and its outflow, sample rocks along Owen Fracture Zone	Bandar 'Abass, Iran	Brewer
93-XVIII	3 Mar–26 Mar	Persian Gulf to Gulf of Oman. Geological structure of a colliding plate, plankton and neuston studies	Djibouti, FTAI	Ross
93-XIX	29 Mar–17 Apr	Geological, chemical, and microbiological studies of Red Sea hot brines; study of rift valley, Gulf of Aqaba	Suez, Egypt	Ross
93-XX	19 Apr–26 Apr	Coring and large volume water sampling for International Laboratory of Marine Radioactivity (ILMR)	Valetta, Malta	Elder (ILMR)
93-XXI	30 Apr–21 May	XBTs and continuous magnetic measurements across Mediterranean and North Atlantic	Woods Hole	Sheer
94-I	14 Jun–12 Jul	Study of contour and turbidity current processes on Iceland Insular Rise	Reykjavik, Iceland	Johnson
94-II	16 Jul–3 Aug	Heat flow and coring at 56°N–29°W	Woods Hole	Denham
95	9 Aug–1 Sep	Investigation of structure of Laurentian Fan and adjacent deep sea with 6-channel seismic system	Woods Hole	Uchupi
96-I	14 Sep–26 Sep	Seismic refraction studies of Kane Fracture Zone and adjacent flanks of Mid-Atlantic Ridge; gravity/bathymetry across Ridge and gravitational edge effect across Fracture Zone; reconnaissance dredging in Fracture Zone; extensive seismic reflection studies; sedimentological studies in western Sohm Abyssal Plain with sediment traps	St. George's, Bermuda	Bunce
96-II	28 Sep–25 Oct		St. George's, Bermuda	Bunce
96-III	1 Nov–2 Dec		St. George's, Bermuda	Purdy
96-IV	5 Dec–13 Dec		Woods Hole	Purdy

R/V Knorr

Total Nautical Miles for 1977 — 24,400
Total Days at Sea — 267

Voyage	Cruise Period	Principal Objectives, Area of Operations	Port of Call	Chief Scientist
63	3 Jan–18 Jan	Recover Parflux mooring, sampling, and coring near Nashville Seamount	(Woods Hole) Woods Hole	Honjo
64-I	26 Jan–10 Feb	Coring for paleomagnetic studies on Blake-Bahama Outer Ridge	Panama	Denham
64-II	11 Feb–1 Mar	Geological, geophysical, and chemical studies on the Galāpagos Rift, escort for *Alvin-Lulu* diving operations	Galāpagos Islands	Von Herzen
64-III	5 Mar–24 Mar		Panama	Ballard
	28 Mar–3 Apr	Transit	Miami	
65	9 Apr–1 May	Multidisciplinary studies of cold core Gulf Stream ring at 36°30′N–69°30′W	Woods Hole	Wiebe
66-I	10 May–22 May	Deploy 7 POLYMODE moorings, conduct CTD surveys	St. George's, Bermuda	Bradley
66-II	26 May–24 Jun	Deploy 10 POLYMODE moorings, recover 4 POLYMODE moorings and 3 additional moorings	St. George's, Bermuda	Tupper
66-III	28 Jun–13 Jul	Recover 10 POLYMODE moorings, deploy satellite-tracked drifter buoys	Woods Hole	Bradley
67	14 Jul–29 Jul	East Boston Shipyard	Woods Hole	

68-I 68-II	4 Aug–17 Aug 18 Aug–30 Aug	Examine food chain dynamics south of Long Island and possible development of anoxia off New Jersey for Brookhaven National Laboratory	Governor's Island Woods Hole	Walsh Whitledge (Brookhaven)
69-I 69-II	7 Sep–21 Sep 24 Sep–7 Oct	Chemical sampling for studies of factors controlling transfer pathways and reactions of trace metals, organic compounds, and radionuclides in marine environment	Halifax, NS Woods Hole	Farrington Burke
70	12 Oct–16 Oct	Test gear and collect interstitial water samples for chemical studies near 36°N–68°50′W	Woods Hole	Sayles
71	22 Oct–18 Nov	Multidisciplinary studies for Gulf Stream ring work at slope station, Gulf Stream, and in ring	Woods Hole	Richardson
72	22 Nov–4 Dec	Water column and bottom sediment studies near Georges Bank and Nantucket Shoals for Energy Resources Company, Inc. (ERC)	Woods Hole	Courant (ERC)

R/V Oceanus

Total Nautical Miles for 1977 — 33,506
Total Days at Sea — 229

Voyage	*Cruise Period*	*Principal Objectives, Area of Operations*	*Port of Call*	*Chief Scientist*
21	12 Jan–3 Feb	Deployment of POLYMODE SOFAR floats down 70°W to Bahama Escarpment, extensive CTD work north to 30°N	(Woods Hole) Woods Hole	Rhines
22-I	19 Feb–26 Mar	Transit	Bridgetown, Barbados	
22-II	5 Mar–30 Mar	Diving stations for studies of salp population dynamics in tropical and equatorial waters	Bridgetown, Barbados	Harbison
23	2 Apr–14 Apr	Bathymetric surveys, dredging, and escort for *Alvin-Lulu* in Cayman Trough	Georgetown, Cayman Islands	Thompson
24	25 Apr–4 May	Newport, RI, Shipyard	Woods Hole	
25	18 May–23 May	Deep-sea microbiological sampling at 37°N–68°W, environmental physiology of marine phytoplankton	Woods Hole	Wirsen
26	31 May–4 Jun	Biological sampling and nutrient analysis in New York Bight near sewage sludge dump	Woods Hole	Teal
27	8 Jun–14 Jun	Geophysical work for USGS on continental shelf off New Jersey, Delaware, Maryland	Woods Hole	Twichell (USGS)
28	22 Jun–30 Jun	Deep-sea biological sampling on Gay Head–Bermuda transect and northeast Bermuda Rise	Woods Hole	Grassle
29	6 Jul–13 Jul	Sediment transport measurements on continental shelf for USGS	Woods Hole	Butman (USGS)
30	17 Jul–26 Jul	Deployment of Parflux sediment trap at 31°32′N–55°W and environmental measurements in area of deployment	Woods Hole	Honjo
31	30 Jul–23 Aug	Physical oceanography of western boundary undercurrent and bottom layer observations on Blake-Bahama Outer Ridge, Hatteras Plain	Woods Hole	Armi/Rhines
32	27 Aug–2 Sep	Multidisciplinary program to study internal waves and their interactions with plankton in Massachusetts Bay	Woods Hole	Haury
33	6 Sep–19 Sep	Diving stations for studies of salp populations in western North Atlantic slope water	Woods Hole	Madin
34	21 Sep–4 Oct	Current regime studies in Hudson Canyon	Woods Hole	Wunsch (MIT)
35	18 Oct–24 Oct	Water sampling for microbial studies, collection of Sargasso Sea phytoplankton	Woods Hole	Wirsen
36-I	7 Nov–21 Nov	Deployment and recovery of Parflux moorings	Bridgetown, Barbados	Honjo Andersen (NSF)
36-II	25 Nov–21 Dec	Study of flow of Antarctic Bottom Water into North Atlantic basin in equatorial Atlantic (3–4°N, 35–40°W)	Woods Hole	Worthington

Voyage Statistics

R/V Lulu and DSRV Alvin

The submersible Alvin is a Navy-owned national oceanographic facility supported by NSF, ONR, and NOAA and operated by this institution.

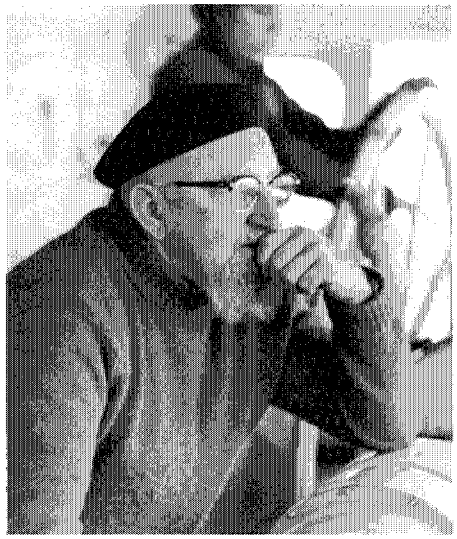
Total Nautical Miles for 1977 — 9,890
Total Days at Sea — 195
Total Dives — 101

Lulu Voyage	*Cruise Period*	*Principal Objectives, Area of Operations*	*Port of Call*	*Chief Scientist*
90-IV	3 Jan–12 Jan	1 training dive, 8 dives for quantitative estimates of benthic fishes and large invertebrates of the deep sea in the Bahamas	(Andros Island) Andros Island	Cohen (NOAA)
90-V	14 Jan–25 Jan	4 dives to study geology of Puerto Rico Trench	St. Croix	Heezen (LDGO)
90-VI	27 Jan–3 Feb	2 dives continuing work in Puerto Rico Trench, 3 dives for Naval Air Development Center	St. Croix	Heezen (LDGO)
90-VII	4 Feb–9 Feb	Transit	Panama	
90-VIII-IX	13 Feb–1 Mar	11 dives to study hydrothermal processes on Galāpagos Rift	Galāpagos Islands	Corliss (Oregon State Univ.)
90-X	5 Mar–25 Mar	13 dives continuing study of hydrothermal processes on Galāpagos Rift	Panama	Corliss (Oregon State Univ.)
90-XI	29 Mar–3 Apr	Transit	Cayman Islands	
90-XII	5 Apr–14 Apr	6 dives to investigate crustal layers exposed along fault scarps of Mid-Cayman Rise	Cayman Islands	Fox (SUNY-Albany)
90-XIII	18 Apr–27 Apr	Transit and 2 dives to Florida current bottom boundary layer	Nassau	Wimbush (Florida State Univ.)
90-XIV	30 Apr–6 May	6 dives for work on comparative morphology of erosional and depositional platform slopes around the Tongue of the Ocean	Andros Island	Schlager (Univ. of Miami)
90-XV	8 May–14 May	5 dives for *in situ* experiment to study recruitment, growth, and mortality of deep-sea benthic populations in the Tongue of the Ocean	Nassau	Grassle Turner (Harvard)
90-XVI	19 May–24 May	4 dives to study continental margin sedimentary processes in Great Abaco Submarine Canyon	Grand Bahama Is.	Kofoed (NOAA)
90-XVII	27 May–1 Jun	5 dives to study lithified biohermal structures in northeast Straits of Florida	West Palm Beach	Neumann (Univ. of N.C.)
90-XVIII	4 Jun–17 Jun	Transit and 3 dives in Baltimore Canyon for shelf slump physiography	Woods Hole	Malahoff (NOAA)
91	14 Jul–23 Jul	5 dives for selective sampling and experiment placement for study of cycles of organic matter through the deep-sea benthic ecosystem on continental rise off Cape Cod	Woods Hole	Wirsen
92	28 Jul–6 Aug	6 dives for *in situ* experiments to study recruitment, growth, and mortality of deep-sea benthic populations at Deep Ocean Station 2	Woods Hole	Grassle Turner (Harvard)
93	12 Aug–16 Aug	Newport, RI, Shipyard		
94	23 Aug–1 Sep	7 dives to study processes of sediment transport and erosion in outer portions of Georges Bank canyons	Woods Hole	Ryan (LDGO)
95	6 Sep–15 Sep	4 dives to study biology and geology of New England continental shelf submarine canyons	Woods Hole	Cooper (NOAA)
96	20 Sep–29 Sep	5 dives for *in situ* experiment to study recruitment, growth, and mortality of deep-sea benthic populations at Deep Ocean Station 2	Woods Hole	Grassle Turner (Harvard)
	3 October	1 test dive	Woods Hole Harbor	

VICKY CULLEN

Atlantis II album: Relief Mate Bill Dowd . . .

ALAN DRISCOLL

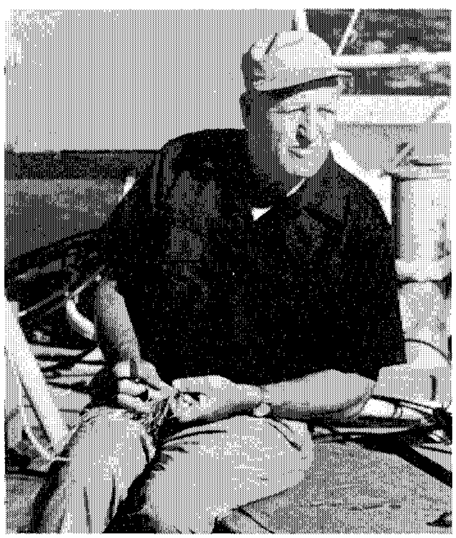


. . . Chief Mate Bob Munns . . .

VICKY CULLEN

. . . Bosun Eddie Pierce . . .

CAROLYN DEAN



. . . Chief Engineer Ray Rioux . . .

VICKY CULLEN

. . . Captain David Casiles being welcomed home from Indian Ocean cruise by Dr. Fye.

R/V Alcoa Seaprobe

Total Nautical Miles for 1977 — 3,411
Total Days at Sea — 59

Voyage	*Cruise Period*	*Principal Objectives, Area of Operations*	*Port of Call*	*Chief Scientist*
1	4 Jul–10 Jul	Transit to Woods Hole	(Charleston, SC) Woods Hole	Donnelly
2	24 Jul–24 Jul	Sea Trial in Vineyard Sound		
3	24 Jul–2 Aug	Transit and Sea Trials	New London, CT	Donnelly
4	9 Aug–1 Sep	North Atlantic work for Naval Underwater Systems Center, New London, CT	Woods Hole	NUSC
5	11 Sep–12 Sep	Sea Trial in Vineyard Sound		
6	13 Sep–13 Sep	America's Cup Race	Woods Hole	
7	15 Sep–15 Sep	America's Cup Race	Woods Hole	
8	22 Sep–30 Sep	Testing of ANGUS camera sled and related instrumentation	Woods Hole	Ballard
9	20 Oct–25 Oct	Survey for lost equipment	Woods Hole	Donnelly

Scientific and Technical Staff

As of 31 December 1977

Directorate

JOHN H. STEELE
Director
ARTHUR E. MAXWELL
Provost
ROBERT W. MORSE
Dean of Graduate Studies and Associate Director
FERRIS WEBSTER
Associate Director for Research
JOSEPH KIEBALA, JR.
Assistant Director for Finance and Administration
ALFRED C. REDFIELD
Senior Oceanographer (Emeritus)
Professor of Physiology (Emeritus), Harvard University
H. BURR STEINBACH
Dean Emeritus

Biology Department

George D. Grice, Jr., Department Chairman, Senior Scientist
Richard H. Backus, Senior Scientist
Judith M. Capuzzo, Assistant Scientist
Francis G. Carey, Associate Scientist
George L. Clarke, Marine Biologist
nonresident
Professor of Biology, Emeritus, Harvard University
Charles H. Clifford, Research Associate
Nathaniel Corwin, Analytical Chemist
James E. Craddock, Marine Biologist
Associate in Ichthyology, Harvard University
R. John Gibson, Assistant Scientist
Victoria R. Gibson, Research Associate
Joel C. Goldman, Associate Scientist
J. Frederick Grassle, Associate Scientist
Robert R. L. Guillard, Senior Scientist
Richard L. Haedrich, Associate Scientist
Associate in Ichthyology, Harvard University
George R. Hampson, Research Associate
G. Richard Harbison, Associate Scientist
Loren R. Haury, Assistant Scientist
Edward M. Hulburt, Associate Scientist
Holger W. Jannasch, Senior Scientist
Privat Docent in Microbiology, University of Göttingen
Advisory Board, Environmental Affairs, Boston College Law School
Adrianus J. Kalmijn, Associate Scientist
John W. Kanwisher, Senior Scientist
Senior Fellow, Columbia University
Visiting Professor, Harvard College
*Thomas J. Lawson, Jr., Research Associate
Laurence P. Madin, Assistant Scientist
Roger L. Mann, Assistant Scientist
John M. Mason, Jr., Research Associate
Frank J. Mather III, Associate Scientist, Retired
Lynda S. Murphy, Assistant Scientist
Pamela T. Polloni, Research Associate
Gilbert T. Rowe, Associate Scientist
John H. Ryther, Senior Scientist
Howard L. Sanders, Senior Scientist
Research Affiliate of the Marine Sciences Research Center, State University of New York, Stony Brook; Associate in Invertebrate Zoology, Harvard University
*Rudolf S. Scheltema, Associate Scientist
William E. Schevill, Biological Oceanographer, *nonresident*
Associate in Mammalogy, Museum of Comparative Zoology, Harvard University
John J. Stegeman, Associate Scientist
Craig D. Taylor, Assistant Scientist
John M. Teal, Senior Scientist
Ralph F. Vaccaro, Associate Scientist
Frederica W. Valois, Microbial Chemist
William A. Watkins, Bioacoustic Engineer
Stanley W. Watson, Senior Scientist
Peter H. Wiebe, Associate Scientist
Carl O. Wirsen, Jr., Marine Microbiologist

Chemistry Department

Derek W. Spencer, Department Chairman, Senior Scientist
Michael P. Bacon, Assistant Scientist
Donald C. Bankston, Research Associate
Instructor, Mathematics, Cape Cod Community College
**Max Blumer, Senior Scientist
Vaughan T. Bowen, Senior Scientist
Visiting Lecturer in Radiobiology, AIBS-AEC, several campuses
Peter G. Brewer, Associate Scientist
John C. Burke, Research Associate
Werner G. Deuser, Associate Scientist
John W. Farrington, Associate Scientist
Nelson M. Frew, Analytical Mass Spectrometrist
Robert B. Gagosian, Associate Scientist
John M. Hunt, Senior Scientist
David J. Hydes, Assistant Scientist
William J. Jenkins, Assistant Scientist
Cindy Lee, Assistant Scientist
Hugh D. Livingston, Analytical Radiochemist
Don R. Mann, Research Associate
Zofia J. Mlodzinska, Research Associate
Michael J. Mottl, Assistant Scientist
Edward T. Peltzer III, Research Associate
Peter L. Sachs, Research Associate
Richard M. Sawdo, Research Associate
Frederick L. Sayles, Associate Scientist
Brian W. Schroeder, Research Associate
Geoffrey Thompson, Associate Scientist
Research Associate, Department of Mineral Sciences, Smithsonian Institution
Bruce W. Tripp, Research Associate
Jean King Whelan, Research Associate
Oliver C. Zafiriou, Associate Scientist

Geology & Geophysics Department

John I. Ewing, Department Chairman, Senior Scientist
Robert D. Ballard, Associate Scientist
John C. Beckerle, Associate Scientist
William A. Berggren, Senior Scientist
Visiting Professor, Brown University; Adjunct Docent, University of Stockholm
Carl O. Bowin, Associate Scientist
Wilfred B. Bryan, Associate Scientist
Elizabeth T. Bunce, Senior Scientist
Raymond E. Davis, Research Associate
Charles R. Denham, Associate Scientist
Henry J. B. Dick, Assistant Scientist
Alan H. Driscoll, Research Associate
William M. Dunkle, Jr., Research Associate
Jeffrey P. Ellis, Research Associate
Kenneth O. Emery, Senior Scientist
Henry Bryant Bigelow Oceanographer
Robert G. Goldsborough, Research Associate
Robert C. Groman, Research Associate
Bilal Ul Haq, Associate Scientist
Adjunct Docent, University of Stockholm
James R. Heirtzler, Senior Scientist
Charles D. Hollister, Associate Scientist
Susumu Honjo, Associate Scientist
Adjunct Professor, Syracuse University
David A. Johnson, Associate Scientist
Sydney T. Knott, Hydroacoustics Engineer
Donald E. Koelsch, Electronics Engineer
George P. Lohmann, Associate Scientist
John D. Milliman, Associate Scientist
Nonresident Staff Member, West Indies Laboratory, Fairleigh Dickinson University
Kenneth E. Prada, Electronics Engineer
Graham M. Purdy, Assistant Scientist
David A. Ross, Associate Scientist
Visiting Instructor, Fletcher School of Law and Diplomacy; Visiting Instructor, Massachusetts Institute of Technology

*Leave of Absence
**Deceased, 11 February 1977

Hans A. Schouten, Associate Scientist
Rudolf C. Tjalsma, Assistant Scientist
Elazar Uchupi, Associate Scientist
Allyn C. Vine, Senior Scientist
Keith von der Heydt, Research Associate
Richard P. Von Herzen, Senior Scientist
*David Wall, Associate Scientist
Warren E. Witzell, Sr., Hydroacoustics Engineer
Earl M. Young, Research Associate

Ocean Engineering Department

Earl E. Hays, Department Chairman, Senior Scientist
Lincoln Baxter II, Applied Physicist
Stanley W. Bergstrom, Research Associate
David S. Bitterman, Jr., Research Associate
Paul R. Boutin, Research Associate
Albert M. Bradley, Research Associate
Clayton W. Collins, Jr., Research Associate
Kenneth W. Doherty, Research Associate
James A. Doutt, Research Associate
Willard Dow, Electronics Engineer
Robert G. Drever, Electronics Engineer
George V. Frisk, Assistant Scientist
Roger A. Goldsmith, Research Associate
William D. Grant, Assistant Scientist
Frederick R. Hess, Electronics Engineer
David S. Hosom, Research Associate
Mary M. Hunt, Research Associate
Maxine M. Jones, Research Associate
Peter E. Kallio, Research Associate
Richard L. Koehler, Electrical Engineer
William S. Little, Jr., Research Associate
James W. Mavor, Jr., Mechanical Engineer *Lecturer, Dept. of Ocean Engineering, M.I.T.*
Paul C. Murray, Research Associate
Richard T. Nowak, Acoustics Engineer
Marshall H. Orr, Assistant Scientist
Kenneth R. Peal, Research Associate
George H. Power, Computer Analyst
Melvin A. Rosenfeld, Manager, Information Processing Center, Senior Scientist
Richard M. Sawdo, Research Associate
Arnold G. Sharp, Research Associate
Woollcott K. Smith, Research Statistician
Robert C. Spindel, Associate Scientist
Jesse H. Stanbrough, Jr., Research Physicist
Constantine D. Tollios, Computer Engineer
*Barrie B. Walden, Research Associate
Robert G. Walden, Manager, Ocean Structures Moorings & Materials Section, Electronics Engineer
Douglas C. Webb, Manager, Instrument Section, Electrical Engineer, Senior Research Specialist
Jacqueline H. Webster, Computer Analyst
Albert J. Williams 3rd, Associate Scientist
Valentine P. Wilson, Research Associate
Clifford L. Winget, Electromechanical Engineer
Warren E. Witzell, Jr., Research Associate

Physical Oceanography Department

Valentine Worthington, Department Chairman, Senior Scientist
Laurence D. Armi, Assistant Scientist
Robert C. Beardsley, Associate Scientist
Keith F. Bradley, Research Associate
Alvin L. Bradshaw, Applied Physicist
Melbourne G. Briscoe, Associate Scientist
John G. Bruce, Jr., Research Associate
Harry L. Bryden, Assistant Scientist
Andrew F. Bunker, Associate Scientist
Gabriel T. Csanady, Senior Scientist
C. Godfrey Day, Research Associate
Jerome P. Dean, Sr., Electronics Engineer
John H. Dunlap, Research Associate
Gifford C. Ewing, Senior Scientist, Emeritus
Nicholas P. Fofonoff, Senior Scientist *Gordon McKay Professor of the Practice of Physical Oceanography, Harvard University; Associate of the Center for Earth & Planetary Physics, Harvard University*
Frederick C. Fuglister, Senior Scientist, Retired
*Robert H. Heinmiller, Buoy Engineer
Nelson G. Hogg, Associate Scientist
Terrence M. Joyce, Associate Scientist
Eli J. Katz, Associate Scientist
James R. Luyten, Associate Scientist
John A. Maltais, Research Associate
Gerard H. Martineau, Research Associate
Michael S. McCartney, Assistant Scientist
Charles H. McComas III, Assistant Scientist
James R. McCullough, Instrument Engineer
William G. Metcalf, Associate Scientist
Robert C. Millard, Jr., Research Associate
Arthur R. Miller, Associate Scientist
Berthold H. G. Pade, Research Associate
*Charles E. Parker, Research Associate
Richard E. Payne, Research Associate
Peter B. Rhines, Senior Scientist
Philip L. Richardson, Assistant Scientist
Thomas B. Sanford, Associate Scientist
Karl E. Schleicher, Oceanographic Engineer
William J. Schmitz, Jr., Associate Scientist
Elizabeth H. Schroeder, Research Associate
Allard T. Spencer, Design Engineer
Marvel C. Stalcup, Physical Oceanographer
Henry M. Stommel, Physical Oceanographer, *nonresident* Professor of Oceanography, Dept. of Meteorology, M.I.T.
John A. Vermersch, Jr., Research Associate
Gordon H. Volkmann, Research Associate
William S. Von Arx, Senior Scientist
Arthur D. Voorhis, Associate Scientist
Bruce A. Warren, Associate Scientist
*John A. Whitehead, Jr., Associate Scientist
Geoffrey G. Whitney, Jr., Research Associate
Alfred H. Woodcock, Oceanographer *nonresident*

Marine Policy & Ocean Management

Susan B. Peterson, Research Associate
Leah J. Smith, Research Associate

Postdoctoral Investigators

Kathleen Crane (Geology & Geophysics)
Charles C. Eriksen (Physical Oceanography)
Nicholas S. Fisher (Chemistry)
Muralidhara B. Gavini (Chemistry)
Paul A. Gillespie (Biology)
Peter J. Hendricks (Ocean Engineering)
Charles L. Johnson (Physical Oceanography)
John N. Ludden (Chemistry)
Nancy H. Marcus (Biology)
David M. Nelson (Biology)
W. Brechner Owens (Physical Oceanography)
John N. Skilbeck (Physical Oceanography)
Thomas L. Torgersen (Chemistry)
John B. Waterbury (Biology)

*Leave of Absence

Publications

Biology

Farooq Azam, Ralph F. Vaccaro, Paul A. Gillespie, Eli I. Moussalli and Robert E. Hodson. Controlled Ecosystem Pollution Experiment: Effect of Mercury on Enclosed Water Columns. II. Marine Bacterioplankton. *Mar. Sci. Commun.*, 3(4):313-329. 1977. No. 3990

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Mordechai Chevion, John J. Stegeman, J. Peisach and W. E. Blumberg. Electron Paramagnetic Resonance Studies on Hepatic Microsomal Cytochrome P-450 from a Marine Teleost Fish. *Life Sci.*, 20:895-900. 1977. No. 3881

P. L. Deese, R. F. Vaccaro, B. H. Ketchum, P. C. Bowker and M. R. Dennett. Ionic Distribution in a Spray Irrigation System. *Food, Fertilizer and Agricultural Residues. Proc. 1977 Cornell Agricultural Waste Manag. Conf.*, Raymond C. Loehr, ed., Ann Arbor Sci. Pub., Inc.:39-66. 1977. No. 3977

C. F. D'Elia, J. H. Ryther and T. M. Losordo. Productivity and Nitrogen Balance in Large Scale Phytoplankton Cultures. *Wat. Res.*, 11(12):1031-1040. 1977. No. 3882

Christopher F. D'Elia, Paul A. Steudler and Nathaniel Corwin. Determination of Total Nitrogen in Aqueous Samples Using Persulfate Digestion. *Limnol. Oceanogr.*, 22(4):760-764. 1977. No. 3791

Victor A. Gallardo. Large Benthic Microbial Communities in Sulphide Biota Under Peru-Chile Subsurface Countercurrent. *Nature, Lond.*, 268(5618):331-332. 1977. No. 3664

Joy A. Geiselman. Marine Colonial Hydroid Inclusion Discovered within Planktonic *Oscillatoria* Colonies. *Bull. Mar. Sci.*, 27(4):821-824. 1977. No. 3759

Quentin H. Gibson and Francis G. Carey. Effect of Hydrostatic Pressure on Spectra of Heme Compounds. *J. Biol. Chem.*, 252(12):4098-4101. 1977. No. 3903

V. R. Gibson and G. D. Grice. Response of Macro-Zooplankton Populations to Copper: Controlled Ecosystem Pollution Experiment. *Bull. Mar. Sci.*, 27(1):85-91. 1977. No. 3681

Victoria R. Gibson and George D. Grice. The Developmental Stages of *Labidocera aestiva* Wheeler, 1900 (Copepoda, Calanoida). *Crustaceana*, 32(1):7-20. 1977. No. 3364

Joel C. Goldman. Biomass Production in Mass Cultures of Marine Phytoplankton at Varying Temperatures. *J. exp. mar. Biol. Ecol.*, 27:161-169. 1977. No. 3816

Joel C. Goldman. Steady State Growth of Phytoplankton in Continuous Culture: Comparison of Internal and External Nutrient Equations. *J. Phycol.*, 13(3):251-258. 1977. No. 3858

Joel C. Goldman. Temperature Effects on Phytoplankton Growth in Continuous Culture. *Limnol. Oceanogr.*, 22(5):932-936. 1977. No. 3813

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George D. Grice and Victoria R. Gibson. Resting Eggs in *Pontella meadi* (Copepoda: Calanoida). *J. Fish. Res. Bd., Canada*, 34(3):410-412. 1977. No. 3714

G. D. Grice, M. R. Reeve, P. Koeller and D. W. Menzel. The Use of Large Volume, Transparent, Enclosed Sea-Surface Water Columns in the Study of Stress on Plankton Ecosystems. *Helgoländer wiss. Meeresunters*, 30:118-133. 1977. No. 3909

Robert R. L. Guillard and Peter Kilham. The Ecology of Marine Planktonic Diatoms. In: *The Biology of Diatoms.* Dietrich Werner, ed., Bot. Monogr., Univ. Calif., 13:372-483. 1977. No. 3652

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H. W. Jannasch and C. O. Wirsen. Retrieval of Concentrated and Undecompressed Microbial Populations from the Deep Sea. *Appl. Environ. Microbiol.*, 33(3):642-646. 1977. No. 3844

David L. Johnson and Philip L. Richardson. On the Wind-Induced Sinking of *Sargassum*. *J. exp. mar. Biol. Ecol.*, 28(3):255-267. 1977. No. 3820

Richard L. Haedrich. A Sea Lamprey from the Deep Ocean. *Copeia,* 1977(4):767-768. 1977. No. 3845

G. R. Harbison, D. C. Biggs and L. P. Madin. The Associations of Amphipoda Hyperiidea with Gelatinous Zooplankton. II. Associations with Cnidaria, Ctenophora and Radiolaria. *Deep-Sea Res.*, 24(5):465-488. 1977. No. 3713

Edward M. Hulburt. Coexistence, Equilibrium, and Nutrient Sharing Among Phytoplankton Species of the Gulf of Maine. *Amer. Nat.*, 111(981):967-980. 1977. No. 3591

Warren A. Kaplan, John M. Teal and Ivan Valiela. Denitrification in Salt Marsh Sediments: Evidence for Seasonal Temperature Selection Among Populations of Denitrifiers. *Microbial Ecol.*, 3(3):193-204. 1977. No. 3730

B. H. Ketchum and R. F. Vaccaro. The Removal of Nutrients and Trace Metals by Spray Irrigation and in a Sand Filter Bed. In: *Land as a Waste Management Alternative. Proc. 1976 Cornell Agricultural Waste Management Conf.*, Raymond C. Loehr, ed., Ann Arbor Sci. Pub. Inc.:413-434. 1977. No. 3802

T. J. Lawson. Community Interactions and Zoogeography of the Indian Ocean Candaciidae (Copepoda: Calanoida). *Mar. Biol.*, 43(1):71-92. 1977. No. 3686

Thomas J. Lawson and George D. Grice. Zooplankton Sampling Variability: Controlled Ecosystem Pollution Experiment. *Bull. Mar. Sci.*, 27(1):80-84. 1977. No. 3674

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L. P. Madin and G. R. Harbison. The Associations of Amphipoda Hyperiidea with Gelatinous Zooplankton. I. Associations with Salpidae. *Deep-Sea Res.*, 24(5):449-463. 1977. No. 3682

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W. O. McLarney, J. S. Levine and M. M. Sherman. Midge (Chironomid) Larvae as Growth-Promoting Supplement in Fish and Lobster Diets. *BAMIDGEH,* 29(1):17-24. 1977. No. 3484

Tracy McLellan. Feeding Strategies of the Macrourids. *Deep-Sea Res.*, 24(11):1019-1036. 1977. No. 3906

M. E. Nicotri. The Impact of Crustacean Herbivores on Cultured Seaweed Populations. *Aquaculture,* 12(2):127-136. 1977. No. 3937

Christopher P. Onuf, John M. Teal and Ivan Valiela. Interactions of Nutrients, Plant Growth and Herbivory in a Mangrove Ecosystem. *Ecology,* 58(3):514-526. 1977. No. 3617

Peter B. Ortner and Allan Rosencwaig. Photoacoustic Spectroscopic Analysis of Marine Phytoplankton. *Hydrobiologia,* 56(1):3-6. 1977. No. 3922

M. R. Roman. Feeding of the Copepod *Acartia tonsa* on the Diatom *Nitzschia closterium* and Brown Algae *(Fucus vesiculosus)* Detritus. *Mar. Biol.* 42(2):149-155. 1977. No. 3860

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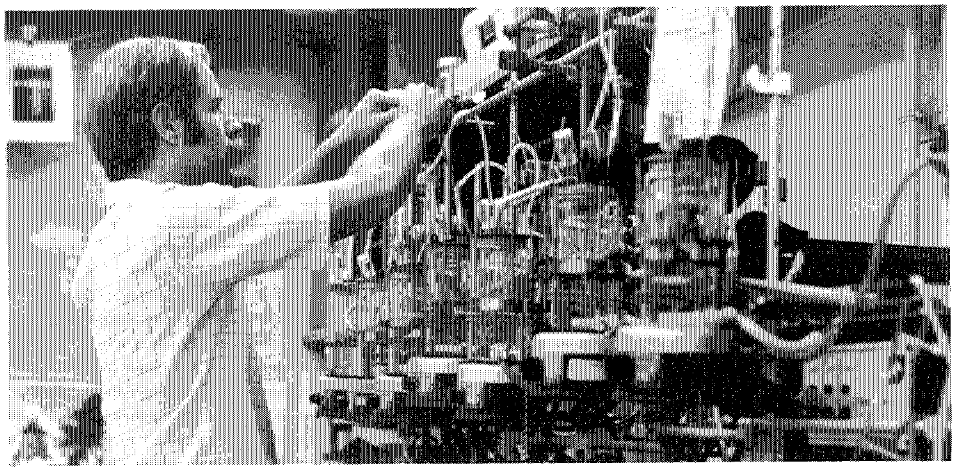
Gilbert T. Rowe and K. L. Smith, Jr. Benthic-Pelagic Coupling in the Mid-Atlantic Bight. *Ecology of Marine Benthos.* Bruce C. Coull, ed. Belle W. Baruch Library in Marine Science, Columbia, South Carolina, 6:55-65. 1977. No. 3122

John H. Ryther. Preliminary Results with a Pilot-Plant Waste Recycling-Marine Aquaculture System. In: *Wastewater Renovation and Reuse.* F. M. D'Itri, ed., Marcel Dekker, Inc.:89-132. 1977. No. 3762

Dennis J. Sabo and John J. Stegeman. Some Metabolic Effects of Petroleum Hydrocarbons in Marine Fish. In: *Physiological Responses of Marine Biota to Pollutants.* F. J. Vernberg, A. Calabrese, F. P. Thurberg and W. B. Vernberg, eds. Academic Press, Inc., New York, San Francisco, London:279-287. 1977. No. 3684

VICKY CULLEN



Steve Molyneaux adjusts bacteria culture vessels in Holger Jannasch's lab.

H. L. Sanders and J. A. Allen. Studies on the Deep Sea Protobranchia (Bivalvia); the Family Tindariidae and the Genus *Pseudotindaria*. *Bull. Mus. Comp. Zool.*, 148(2):23-59. 1977. No. 2983

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William A. Watkins, William E. Schevill and Peter B. Best. Underwater Sounds of *Cephalorhynchus heavisidii* (Mammalia: Cetacea). *J. Mammal.*, 58(3):316-320. 1977. No. 3807

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Kenneth L. Webb, Christopher F. D'Elia and William D. DuPaul. Biomass and Nutrient Flux Measurements on *Holothuria atra* Populations on Windward Reef Flats at Enewetak (Eniwetok), Marshall Islands. *Proc., Third Internat. Coral Reef Symp.*, Univ. Miami:409-415. 1977. No. 3914

I. P. Williams, V. R. Gibson and W. K. Smith. Horizontal Distribution of Pumped Zooplankton During a Controlled Ecosystem Pollution Experiment: Implications for Sampling Strategy in Large-Volume Enclosed Water Columns. *Mar. Sci. Commun.*, 3(3):239-253. 1977. No. 3964

Timothy C. Williams, Philip Berkeley and Victor Harris. Autumnal Bird Migration Over Miami Studied by Radar: a Possible Test of the Wind Drift Hypothesis. *Bird-Banding*, 48(1):1-10. 1977. No. 3740

Timothy C. Williams, Janet M. Williams, Leonard C. Ireland and John M. Teal. Autumnal Bird Migration Over the Western North Atlantic Ocean. *Am Bird*,: 31(3);251-267. 1977. No. 3812

Chemistry

M. P. Bacon. ^{210}Pb and ^{210}Po Results from F. S. "Meteor" Cruise 32 in the North Atlantic. *"Meteor" Forsch.-Ergebnisse*, A(19):24-36. 1977. No. 3809

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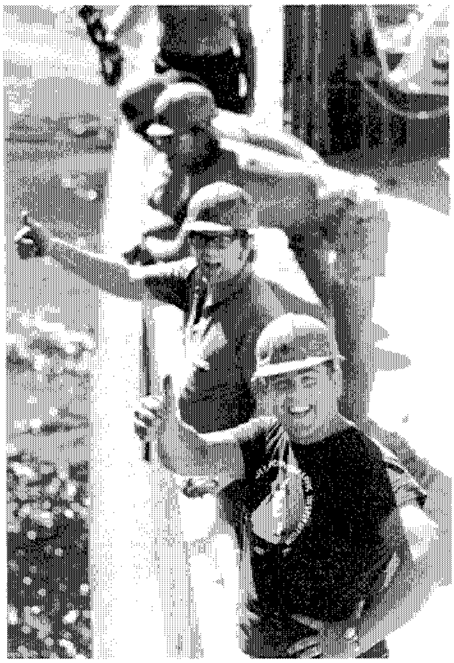

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A. C. Redfield and K. O. Emery. The Evolution of Pilgrim Lake. *The Cape Naturalist,* 6(1):4-9. 1977. No. 3859

Sources of Support for Operating Expenses

AGENCY	1975 Amount	1975 % of Total	1976 Amount	1976 % of Total	1977 Amount	1977 % of Total
National Science Foundation	$ 9,226,000	44.1	$ 9,555,000	41.9	$10,123,000	42.6
Office of Naval Research	5,061,000	24.2	5,636,000	24.7	5,897,000	24.8
Energy Res. & Dev. Admin.	1,140,000	5.5	1,427,000	6.3	1,320,000	5.5
Other Government	1,716,000	8.2	2,003,000	8.8	2,623,000	11.0
Private	3,775,000	18.0	4,172,000	18.3	3,829,000	16.1
Totals	$20,918,000	100.0	$22,793,000	100.0	$23,792,000	100.0

WOODS HOLE OCEANOGRAPHIC INSTITUTION
1930

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IN 1952, 10 members of the Woods Hole residential community asserted their interest in the Institution and its activities by forming the Associates of the Woods Hole Oceanographic Institution. The organization has been described as a human endowment fund that pays dividends in loyalty, enthusiasm, understanding and moral support. The Associates provide the scientific community with encouragement, criticism, and advice, and they have contributed substantial financial assistance to the Institution, including funds for fellowships, special equipment, and the exploration of new areas of research. In recent years, Associates' contributions have spearheaded the drive for funds to build educational facilities and laboratories on the Quissett Campus. We are very fortunate in having, at present, more than 900 Associates supporting activities and developments not funded by our research grants and contracts. Information about Associates' membership may be obtained from L. Hoyt Watson, Associates' Executive Secretary, at the address below.

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THE Institution publishes *Oceanus,* the illustrated magazine of marine science. Scientists and policymakers are commissioned to write articles for the magazine on all aspects of marine research. The quarterly publication is an Associates' membership privilege and is available to the public by subscription.

Woods Hole Oceanographic Institution
Woods Hole, MA 02543
(617) 548-1400

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