Woods Hole Oceanographic Institution

Woods Hole, Massachusetts

1975

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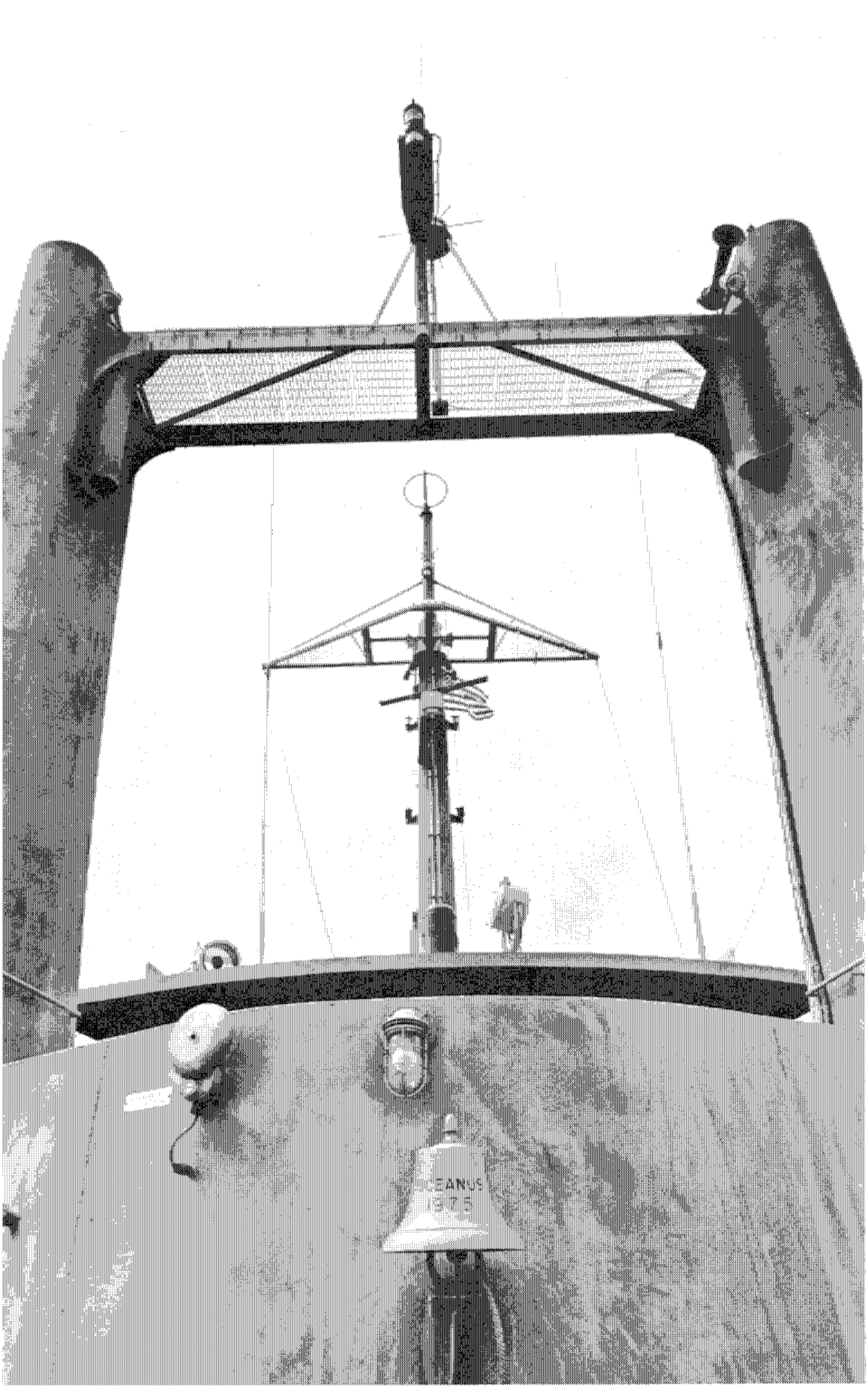

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Woods Hole Oceanographic Institution,
Woods Hole, Massachusetts 02543

MARY SEARS
P.O. Box 152,
Woods Hole, Massachusetts 02543

FREDERICK SEITZ
Rockefeller University,
66th Street and York Avenue,
New York, New York 10021

JAMES R. SHEPLEY
Time Inc., Room 34-38, Time-Life Bldg.,
Rockefeller Center, New York, New York 10020

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Massachusetts Institute of Technology
Cambridge, Massachusetts 02139

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Department of Physics, University of Illinois,
Urbana, Illinois 61801

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N.O.A.A. - U.S. Department of Commerce,
3300 Whitehaven Street, N. W., Suite 354
Washington, D.C. 20235

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Waimanalo, Hawaii 96795

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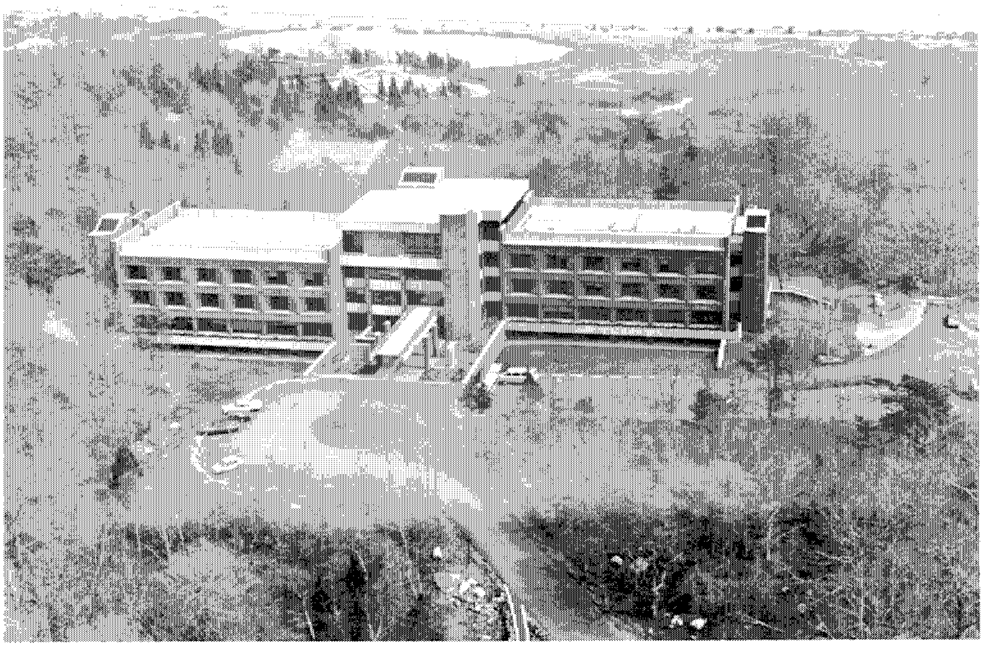


FRANK MEDEIROS

Aerial view shows Clark Laboratory with Environmental Systems Laboratory in background.

DIRECTOR'S REPORT

Broadening the Base

In this year's report I want to discuss a topic that has received much attention in recent years — broadening the base of our activities at the Institution. During the coming decades we will see unprecedented growth in man's use of the world oceans, particularly in the coastal zone, as more countries recognize its economic potential and start to exploit its resources. This increased use will result in greater and greater impact on the oceans in the way of pollution, depletion of resources and congestion. We can also expect an increase in international disputes concerning ownership of marine resources and ocean utilization with evermore complex negotiations to relieve or resolve such disputes.

It appears to me that in the next decade some of the most challenging problems for the Institution will arise out of man's need to make ever greater use of the oceans. To meet these challenges it is evident that we must expand the Institution's primary mission of increasing our basic knowledge of the oceans by becoming more concerned with man's relationship to the marine environment and with the wise use of the oceans. In addition to strengthening our basic research program and continuing our commitment to graduate education, we should enhance activities in applied research, ocean engineering and marine policy in order to increase the connections between our research and tomorrow's needs.

Traditionally about 30% of the Institution's international operations have been within 200 miles of foreign shores. If our country and others adopt a 200-mile economic zone, our need to build friendships in foreign countries will increase greatly; otherwise, our ships will be excluded from areas of vital interest to our scientists. Most of these countries are vitally concerned with the applied problems of making effective use of their fisheries and offshore mineral resources. By establishing a group at Woods Hole with broad understanding of marine ecology and applied marine technology, we can be responsive to these needs and opportunities without diluting our continuing commitment to basic research. In fact, the feedback of applied work can enrich the basic research program. I was pleased to note that the elected Staff Committee in its annual report for 1975 calls for a strengthening of the Institution's capabilities in applied oceanography and engineering.

Applied research is not a new activity for us. We have been involved in applied research throughout our history. In fact our first three contributions to published scientific literature by Harold M. Sverdrup and Floyd M. Soule describe the expedition of the submarine *Nautilus* north of Spitsbergen under the Command of Sir Hubert Wilkins. Dr. Sverdrup and Sir Hubert had hoped to take the *Nautilus* under the Arctic ice, but only succeeded in exploring the Polar Sea along the edge of the ice pack. Much of the effort described in these three articles (Papers in Physical Oceanography and Meteorology, Vol. II, 1933) was spent in developing and modifying gravimeters, magnetometers, continuous plankton recorders, Nansen bottles and chemical equipment for determining density, salinity, oxygen, phosphates, nitrites, and acidity. All of these in addition to a spectrograph, echo sounder and winches were ingeniously installed on board a U.S. Navy O-type submarine.

In World War II it was largely due to Columbus O'Donnell Iselin's efforts that the U.S. Navy became aware that oceanographic knowledge was vital to its operations. He demonstrated how underwater sound transmission could be used to hunt submarines or help submarines avoid detection by surface vessels. We did the research and then taught naval officers how to use temperature gradients to avoid detection and to operate their submarines with greater security. Virtually all of our work during the war years was applied in nature.

Thirty years ago, long before it became fashionable, several of our scientists became interested in the circulation of estuaries and the related distribution of pollutants which affected planktonic organisms. It soon became apparent that some of the engineering calculations of the dilution and dispersal of pollutants were erroneous and their application had led to higher than anticipated concentrations within the estuary. New concepts were developed that produced much more realistic estimates. This pioneering work led to a great expansion of estuarine studies and the related problems of pollution. Later approaches which depend heavily upon the development of computer capability have resulted in continuously more sophisticated calculations, but our early work in this field laid the groundwork in both recognizing and evaluating pollution problems in these critically important areas of our coastal zone.

A related example of our applied work is a study of Lake Maracaibo. The entrance needed to be deeper to admit larger tankers. Making it deeper could alter the salinity at the bottom of the Lake and possibly contaminate drinking water from wells. Furthermore, if the salinity exceeded 6 ppt, teredo (ship worms) could enter the Lake and destroy the coating on the pipes connecting production platforms. The deeper waters in the Lake were protected from sea water intrusion by the shallower depths at the entrance. Our studies of salinity, temperature and oxygen at all depths in the Lake, in the entrance channels and in the Gulf of Maracaibo made it possible to estimate how much the salinity would be increased by the greater intrusion of sea water through a deeper channel. The result was an early example of an environmental impact statement.

These are but a few examples of our applied research in the past. Today there are formidable problems in marine technology that must be solved in the years ahead. These include, just to mention a small number that are already obvious, nuclear waste disposal, sewage disposal, offshore power stations, deep seabed drilling for oil, stimulation of marine bioproduction on a large scale, industrial development of the coastal regions and offshore tanker terminals. If we are going to participate in the solution of even a few of these problems the Institution must attract engineers who have good scientific insight, scientists who are interested in applied research and economists, lawyers, political scientists and sociologists who are devoted to the development of wise marine policy. All of these must interact and work together to achieve optimum solutions of such problems.

Already we are involved. An investigation of whether or not geologic formations beneath the deep sea can be used for the disposal of radioactive wastes from nuclear power plants was initiated in 1973 under Dr. Charles Hollister with support from the

Energy Research and Development Agency. Scientists from other oceanographic laboratories in the United States, United Kingdom and Japan participated in an international workshop held recently in Woods Hole. It appears that deep formations located in stable ocean basins may provide a stable location for solidified and encapsulated wastes which could be isolated from the natural ecosystem for hundreds of thousands of years. In related work of the National Academies of Science and Engineering, Dr. Robert A. Frosch is chairing a committee which is examining all aspects of the problem of radioactive waste products. Clearly our expertise is needed and we must participate in such important policy decisions.

In 1971 we established the Marine Policy and Ocean Management Program which is now attracting a distinguished group of young scholars each year. We need to combine this with a small senior group of scientists with engineering training or operating experience in ocean industries such as fishing, shipping, offshore oil production or mining, and social scientists such as professional economists and lawyers. The economic, institutional and legal aspects of offshore ventures will present challenges to innovation which are as difficult as the scientific aspects.

The kinds of studies which such a group might undertake include the generation, analysis and comparison of alternatives which can be the basis for the development of ocean policy and management relating to food, transportation, energy and pollution.

Food. There will be a continuing demand for more food from the sea. The global fish catch seems to have leveled off at about 70 million tons per year. Would controlled fishing raise this ceiling? To what extent should fish cultivation replace hunting through husbandry (ranching) or farming (aquaculture)? What scientific and technological knowledge will be needed to support sound development of such activities? What factors would be critical for new ocean food systems to become economically feasible? What government regulations now discourage or encourage such systems? What are the interactions and conflicts with other uses such as transportation, recreation, energy production? What legal problems arise in these new situations?

Transportation. Ocean transport will remain high in spite of competition from air and land systems. What are the causative factors in collisions and groundings, particularly those posing hazards of pollution or other major dangers? What behavioral, technological, training and regulatory changes would help prevent them? What are the economic and social costs or benefits of such changes? What are the roles of governments, shipowners, unions, insurers in bringing about such changes?

Energy. The world's need for energy will triple in 25 years. What are the future technological possibilities of various means of energy production: petroleum production, nuclear, solar, wind, tidal, temperature and salinity differential? What are the potentials for genetic development of marine plants which use solar energy through the photosynthetic process and which in turn can be converted into fuels such as methane by biodegradation? What economic and social variables are involved? What matters of law and regulation are posed?

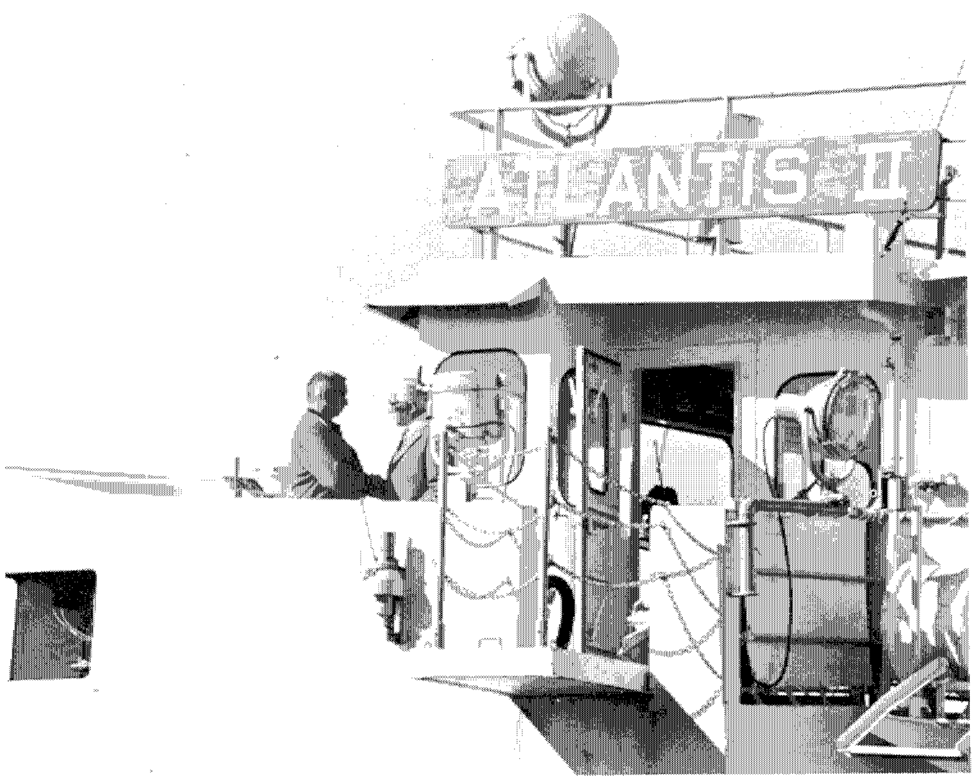
Pollution. The oceans are the global sinks. This results in great international concern. What are the dangers and opportunities in the oceans for continued disposal of various materials? What technologies would be required? How could this be monitored or controlled?

Dr. Robert A. Frosch joined us in late August as Associate Director for Applied Oceanography to head up an expanded program in these areas. He is exceptionally well qualified to provide the leadership we need. We hope to add a few professional staff members in the coming year. I believe outstanding young scholars will be attracted by the challenge of associating and working on exciting frontier problems within an intellectually stimulating group.

We expect that they will participate in the education program in ocean engineering and related subjects. Thus, we can educate more professionals in applied ocean technology. This will be an important aspect of the program.

I feel that with the cooperation of everyone involved, and by working closely with industry and government, we will be able to develop a stimulating program which will assist greatly in facing the challenges of the 1980s in ocean resources and management. Technology assessments in marine affairs must be conducted and made available to decision-makers and a concerned public. Undertaking such studies will lead the Institution into new fields. It will have the great advantage of permitting the Institution to interact more effectively in a wide range of national and international problems. Through broadening our base of activities, the potential for making important scientific, technical, economic and social contributions to the wise use of the oceans is, indeed, very large.

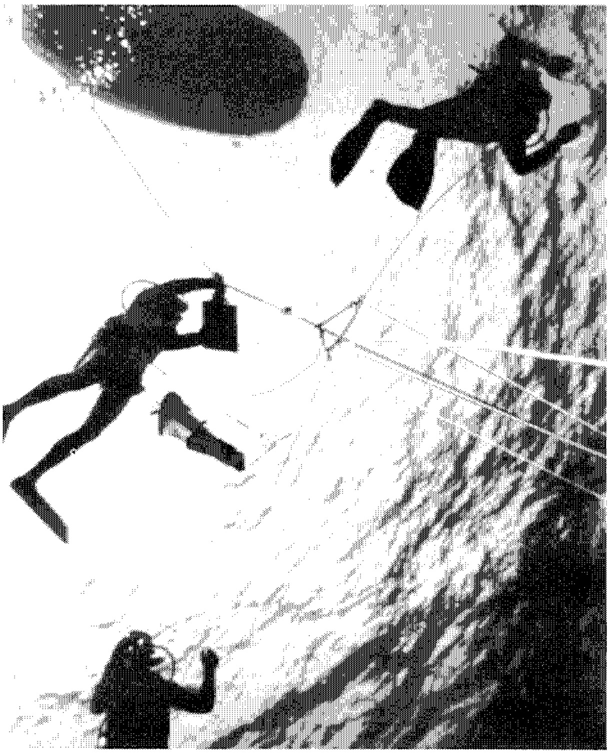
PAUL M. FYE



VICKY BRISCOE

Dr. Fye bids Capt. Pike farewell just before *Atlantis II* sails in late October for extended cruise to the Indian Ocean. Capt. Pike was temporary master through the end of 1975.

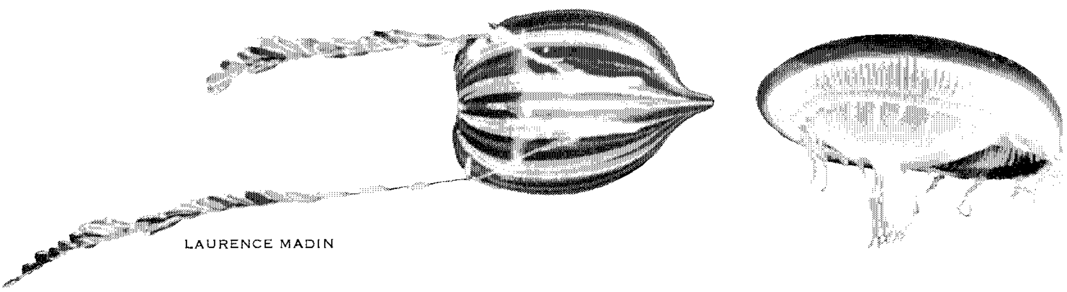
CHRIS SWANN



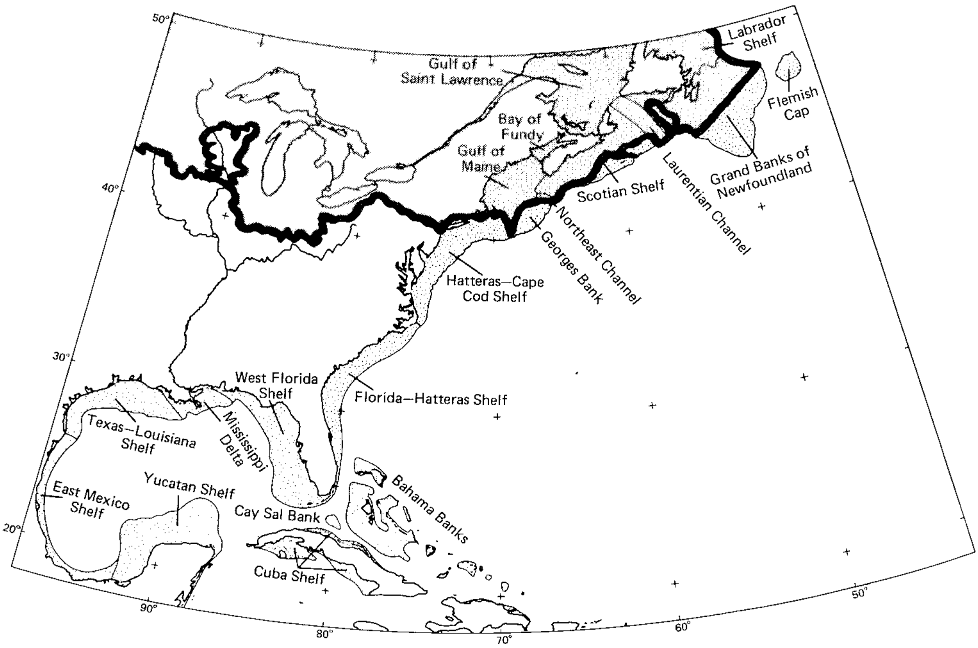
RESEARCH HIGHLIGHTS

A few of the important problems being investigated at the Institution are described in this section. This is clearly not a representation of the full scope of the research activities in the Institution but a clear idea of the diversity is represented by the list of publications in Appendix III. The examples selected for presentation this year all require the application of several disciplines to appreciate and understand the problem.

The material presented in this section has been submitted by Peter G. Brewer, Andrew F. Bunker, Werner G. Deuser, Kenneth O. Emery, Roger D. Flood, R. John Gibson, J. Frederick Grassle, G. Richard Harbison, Charles D. Hollister, Laurence P. Madin, Paul Mangelsdorf, Gilbert T. Rowe, Frederick L. Sayles, Carl O. Wirsen, Jr., and Oliver C. Zafiriou. The drafts submitted have been compiled and edited by Bostwick Ketchum.



LAURENCE MADIN



Areas covered by glacial ice (shaded) and those above present-day sea level (stippled) during the Wisconsin glacial period.

Glacial and Pluvial Climates

The climatic changes of the past two million years, best known as a succession of alternating "ice ages" and warm periods, had a profound influence on the world's land areas, continental shelves, and even the deep oceans. During times of glacial advance, water was withdrawn from the oceans and fixed on land as ice. At the same time the major climate belts shifted so that formerly humid zones became dry or vice versa. Were the ice ages wet or dry periods in today's desert belt? This question, argued by geologists, climatologists, and archaeologists, can be answered by oceanographers looking at marine sediments. The answer is not only of historical interest but might also aid in anticipating the effects of modern or future temperature trends on the shifting or expansion of deserts, such as the Sahel drought disaster of recent years, changing sea levels, or still other phenomena important to man.

The effects of glaciation on land can be recognized in moraines, such as Cape Cod and the Islands of Nantucket and Martha's Vineyard, other ice-laid deposits, and distributions of fossil remains of animals and plants in areas distinctly different from the present distributions of the same species. Less drastic climatic changes within historical times have had important effects on human settlements and civilizations. Glacial periods must, indeed, have profoundly influenced the more primitive tribes of those times.

As oceanographers we naturally focus our attention upon the ocean, from the sediments of the continental shelves to the geological record of the deep sea. By studying them, we often find clues to climatic changes more deeply affecting the land and can help resolve some still unanswered questions.

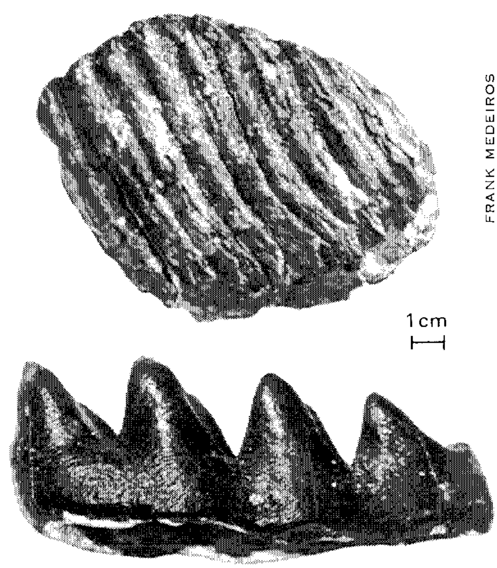
Sea Level Changes

As a result of the formation of glacial ice, sea level dropped by about 130 meters during the latest glacial advance, the Wisconsin or Würm, exposing about 27 million square kilometers of continental shelf, temporarily adding about 18% to the area of the continents and subtracting 8% from the oceans. About 55 million square kilometers of land, including some of the exposed shelf, was covered by glaciers. Confirmation of the extent of maximum lowering of sea level is provided by the correspondence in average depth of the shelf-break throughout the world except off Antarctica and Greenland, where the crust still is depressed by the ice burden on the land. Similarly, seismic-reflection profiles across shelves show unconformities or erosional levels separated by thin deposits that mark each of the glacially lowered and intervening higher sea levels of the past two million years.

Another ocean-floor clue to past lower sea levels is the presence on the continental shelves of the world of the empty shells of molluscs that live only intertidally or in shallow, brackish water. Off eastern North America the most significant are shells of *Crassostrea virginica*, the well-known edible oyster. Their shells were identified off Woods Hole in biological surveys of the nineteenth century, but they then were attributed to leftovers from picnics aboard yachts. During more comprehensive surveys of shelf sediments off the Atlantic coast during the last decade, these shells were found at hundreds of stations and all had a dark-gray, subfossil appearance. A plot of depth versus radiocarbon age for the carbonate of the empty shells depicted changes of sea level from near the present level about 35,000 years ago to about -130 meters depth 14,000 years ago, followed by a rise to about -5 meters 5,000 years ago and a slower rise thereafter. Partial confirmation was provided by radiocarbon dates of about 15 samples of fresh-water peat and one sample of deep salt-marsh peat found on the shelf. Hundreds of dates on salt-marsh peat from existing coastal marshes establish the recent history of sea-level rise during the past 5,000 years. Accurate records of sea level made by the world's tide gauges for the past century or so show a general rise of sea level, but one that is markedly affected by local disturbances, such as rebound of the continental crust after the glaciers melted or sinking caused by the weight of deltas or withdrawal of oil or water.

When sea level was low, the animals of the land also expanded their ranges to the surface of the shelf to take advantage of the grazing in new meadows and forests. Similarly, early man, especially archaic man, who arrived in North America about 12,000 years ago, must also have moved to the shelves to hunt the large and small animal prey, fish, and molluscs. Bones of larger mammals (mammoths, mastodons, sloths, cattle, elk) have been dredged from the shelf, but those of smaller mammals probably have long since disintegrated along with the bones of man. However, artifacts made and used by early man must still remain to be found eventually by aquatic archaeologists.

The remnants of the glaciers still occupy more than one quarter of their maximum area. Should the remaining ice melt, sea level would rise another 50 meters. Perhaps 75% of the world's population



FRANK MEDEIROS

Mammoth (top) and mastodon teeth from the Atlantic continental shelf.

live on what will then be submerged continental shelf. Most large modern cities would be submerged, except for the tallest buildings, and form treasure troves for future aquatic archaeologists.

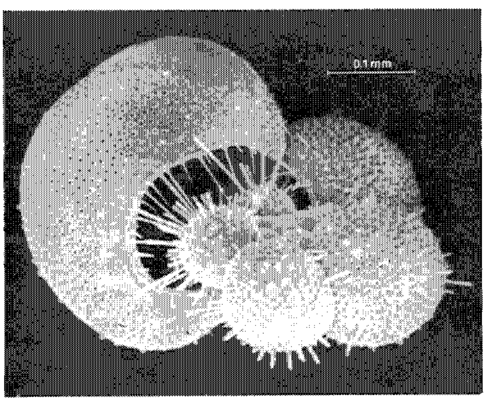
Ice-Age Climate Near the Red Sea

Oceanographic research of the past decade has revealed that, on a geological time scale of hundreds of millions of years, the ocean basins are temporary features which evolve from birth through growth and shrinking to eventual obliteration. Basins are born by the separation of continents and subsequent moving apart of the fragments. The long and narrow Red Sea is a "young" basin, tens of millions of years in age, and may eventually grow wider as Africa and Arabia continue to move apart. During its earliest existence the narrow basin was not always connected with the ocean, but underwent periodic flooding and drying so that thick salt deposits formed on its floor. Even today the Red Sea has only a tenuous connection to the Gulf of Aden by way of the narrow and shallow Strait of Bab el Mandeb. Because of this narrow connection, which limits the exchange of water with the open ocean, and the fact that the Red Sea spans the desert belt latitudes of northern Africa and Arabia, the water in the Red Sea is very sensitive to climatic changes. During periods of low precipitation and high evaporation, such as we are witnessing today, salinity rises to values higher than those of the open ocean; during periods of humid climate salinity may drop below open-ocean levels.

Archaeologic and geologic evidence, especially lake deposits, testify to successions of rainy (pluvial) periods and dry periods in the deserts and tropics of Africa when the northern temperate latitudes experienced the Pleistocene succession of glacial and interglacial periods. However, whether the more humid climate in regions that are deserts today occurred when the northern climate was cold or warm has long been disputed. The sediments of the Red Sea and Gulf of Aden hold part of the answer.

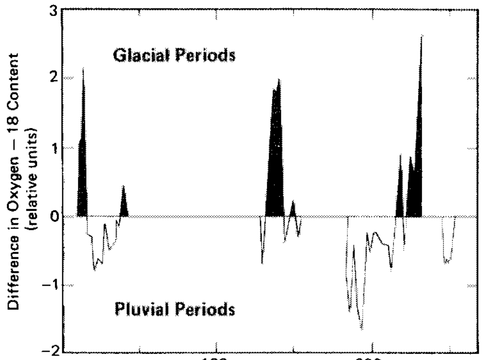
The Gulf of Aden is part of the open ocean and as such has experienced the changes in salinity caused by the formation or melting of huge volumes of ice during the Pleistocene. Since the water for the ice had to be supplied by the oceans, ice formation lowered sea level and raised the salinity of the remaining sea water whereas melt water influx during warming periods raised sea level and lowered the salinity. Salinity in the Gulf of Aden, as in the open ocean, was thus primarily affected by the climate in the higher latitudes. Salinity in the Red Sea, on the other hand, was mostly influenced by the humidity or dryness of the climate in the desert latitudes. A record of past fluctuations in the salinity of the two seas is contained in their sediments and can be deciphered by geochemists. The relationship between glacial and pluvial periods can thus be determined.

Water is made up of different isotopic species of the molecule H_2O of which the two most abundant contain oxygen of atomic weights sixteen or eighteen (symbolized as H_2O^{16}; H_2O^{18}). There is roughly one H_2O^{18} for every 500 H_2O^{16} molecules but the exact ratio of the two in sea water changes in proportion to changes in salinity. The isotopic ratio O^{18}/O^{16} in the water at any time is reflected in the calcium carbonate skeletons of planktonic foraminifera living in the water, and the



MARGARET GOREAU

Foraminifer, *Globigerinella siphonifera*, from the Red Sea.



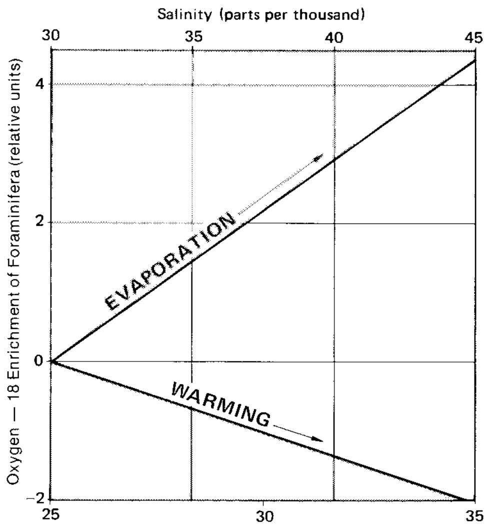
Oxygen isotope difference between foraminifera in Red Sea and Gulf of Aden sediments.

historic record is preserved in the sediment after death of the animals and deposition of the skeletons. Thus, by measuring the isotope ratio of the calcium carbonate of fossil foraminifera recovered from the sediment we can reconstruct past salinity changes in the overlying body of water. Superimposed on the effect of salinity on the isotope ratio in the fossils is an effect of temperature which, however, at the low latitudes, and especially in the isolated Red Sea, is of minor importance.

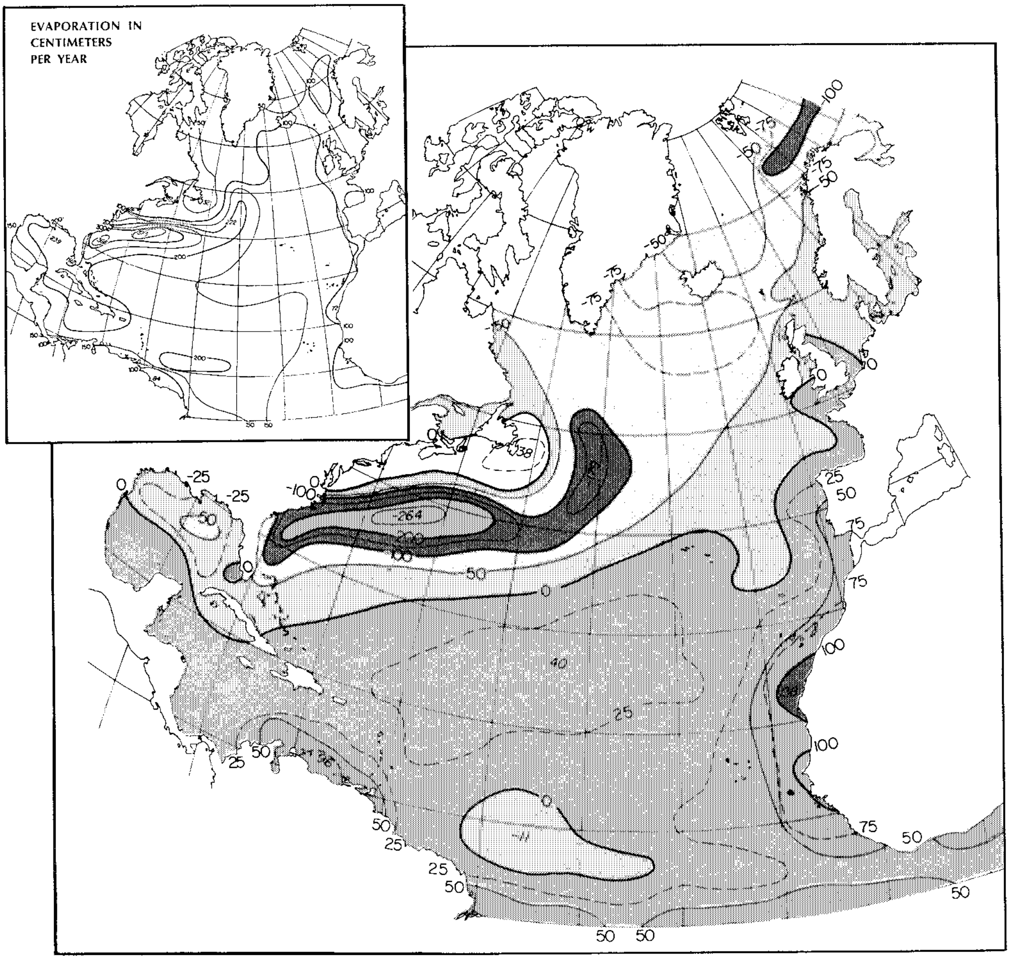
Because of the proximity of the Red Sea and Gulf of Aden the same species of foraminifera can be found in the sediments of both seas. By comparing our measurements on foraminifera of the same era from both areas we have reconstructed the climatic variations during the past 250,000 years. Towards the end of the three major glacial periods which occurred during that interval of time the oxygen-18 content of the Red Sea increased relative to that of the Gulf of Aden, indicating that the Red Sea had become highly saline. This suggests very dry conditions in the desert belt associated with glacial maxima. Conversely, between glacial maxima the oxygen isotope data suggest that the Red Sea repeatedly freshened to or below the salinity of the adjacent Gulf of Aden. This could happen only if a relatively humid climate prevailed, capable of providing a fresh-water influx by rain and river drainage which at least balanced the evaporation rate.

The exact extent of the salinity changes in the Red Sea could be calculated if we had an independent appraisal of the temperature differences between the Red Sea and the Gulf of Aden during the past quarter million years. Today the average surface water temperature of the Red Sea is 2.5°C higher than that of the Gulf of Aden, but this difference is strongly influenced by the summer monsoon in the Arabian Sea and was probably also subject to change during the climatic shifts of the Pleistocene. If there was no temperature difference between the two seas during glacial times, we can calculate that the Red Sea evaporated to attain a minimum salinity of 46‰ (compared to today's average value of 39‰). If the Red Sea was warmer than the Gulf, as it is today, the salinity reached even higher values. Similarly we can calculate that the salinity of the Red Sea during interglacial, or pluvial, times was probably below 36‰.

A global warming trend has been predicted to set in shortly and to continue into the next century with the mean world-wide temperature rising higher than at any time during the past 1000 years. If that happens, part of the remaining ice cover near the poles may melt. Sea level will rise, flooding coastal plains, but the deserts may become more habitable.



Comparative effects of evaporation and warming of sea water on the oxygen isotope content of foraminifera.



Energy exchange between sea and air; 32 year average (watts per square meter).

Surface Layer Characteristics

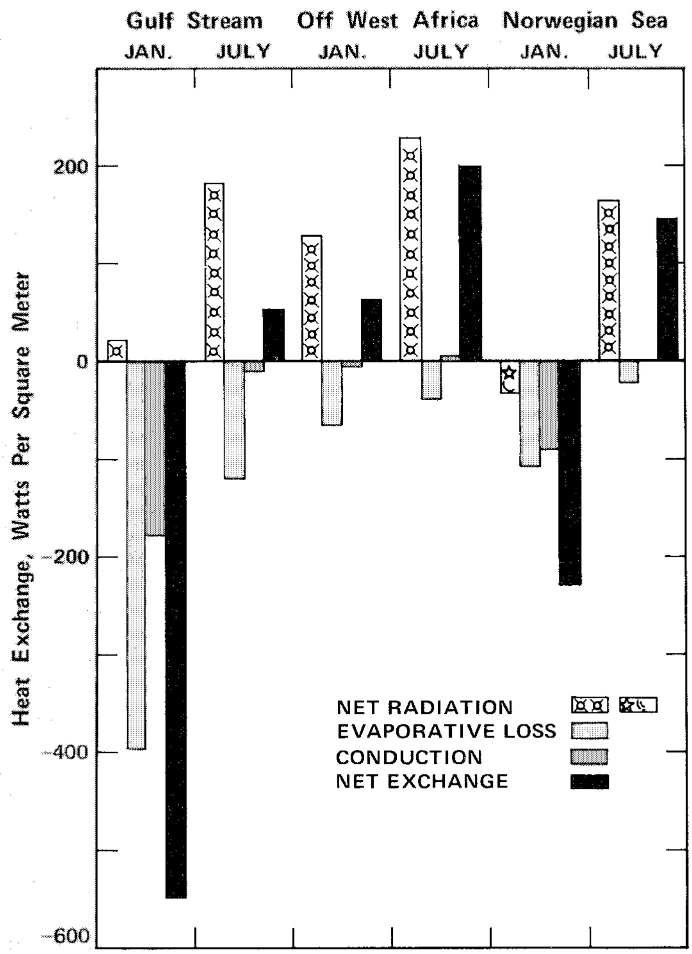
Only a small fraction of the volume of sea water on earth is illuminated by the incident energy of sunlight. About 97% of the ocean water is too dark for photosynthesis though some animals can see at lower light densities. Many important processes occur in this thin, near-surface layer. The penetrating sunlight not only heats the water directly but provides the energy for photochemical reactions in addition to the biologically mediated photosynthesis. Exchanges of heat, energy, gas and momentum take place at the very surface layer. Also, the illuminated zone is one which man can readily enter and visually observe the abundance, distribution and activities of marine organisms.

Air-Sea Exchange

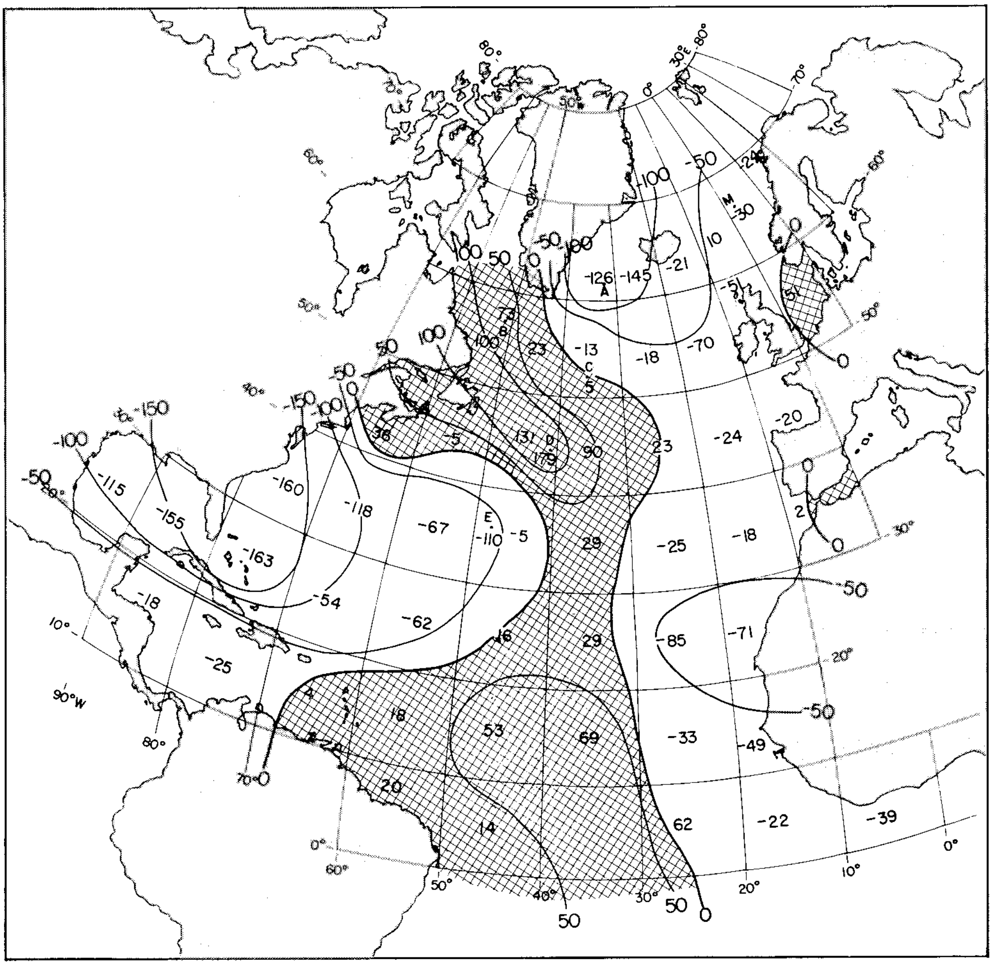
The North Atlantic energy exchanges of heat, water vapor, momentum and solar radiation have been computed from wind, temperature, pressure, and cloud observations made from ships at sea. The heat gained or lost by the North Atlantic through these exchange processes varies greatly from region to region. The Gulf Stream loses an annual average of 264 watts per square meter, primarily through evaporation of its warm water into the dry air from North America. An extreme heat gain occurs off West Africa where the wind, blowing parallel to the coast, drives surface water offshore. This water is replaced by cold nutrient-rich water upwelling from deeper levels. The cold water evaporates slowly, few clouds are formed, and the solar radiation reaches a maximum for the North Atlantic. The nutrients and sunshine are the necessary ingredients which allow the plankton and fish to grow in great abundance in these regions.

Cooling of Norwegian Sea water during the dark winter months by infrared radiation, evaporation and conduction increases the density of the water until it becomes denser than surrounding water and sinks. The cold water cascades southward through the Denmark Strait to the depths of the Atlantic. There it spreads out and stagnates for long periods mixing slowly with other water masses. Eventually, greatly modified in temperature and salinity, it reaches the surface in an upwelling region and once again interacts with the atmosphere.

The equilibrium sea temperature attained in various parts of the Atlantic through exchange processes controls the intake or loss of gases by the ocean. At high latitudes the water becomes richer in gas content since it has a lower temperature and absorbs gases from the atmosphere. At lower latitudes the tem-



Surface energy exchange in three ocean areas during January and July. Positive values indicate flow into the ocean.



Bands of abnormally strong and weak cooling of Atlantic waters occurred during January 1958. Negative values indicate greater than normal cooling, expressed in watts per square meter.

perature is higher and some dissolved gases return to the atmosphere. Absorption of atmospheric oxygen by the ocean supplies a basic necessity for the varied animal life of the oceans. Oxygen content is also a valuable research tool for oceanographers trying to trace trajectories of water masses. In conjunction with other properties the oxygen content has helped identify water masses found outside their source regions.

Large variations in evaporation, rainfall and river runoff produces large variations in the salinity of the surface water. The saltiest water is found in the trade wind region where the evaporation is high, rainfall is slight, circulation is sluggish, and the area is far from the source of any fresh river water. The freshest water of the North Atlantic is found in the Gulf of St. Lawrence. The water is a mixture of fresh St. Lawrence River water and Labrador Current water. The Labrador Current water is the relatively fresh end product of heavy rainfall over the northeastern Atlantic, melting glaciers and icebergs, and North Polar Sea water.

Evaporation over the ocean is essential for mankind and other forms of land life, since it is the source of rainfall for the continents. Also water vapor evaporated from the oceans, and transported great distances with little loss, is the major energy source for the circulation of the atmosphere. Some of the water vapor accumulated by the trade winds rises and condenses in the southern convergence zone, releasing its latent heat, and producing the energy to feed the general circulation of the atmosphere. Other masses of water vapor are transported northward and the latent heat released in the storm systems of the middle and high latitudes, supplying them with energy.

The three components of the energy exchange go through an annual cycle as the sun changes its altitude, the wind increases and decreases, and as the air moderates from cold and dry to warm and humid. These cycles are different in nearly every region of the Atlantic. Off the coast of Venezuela the amplitude of the annual cycle is so small that the energy exchanges are nearly constant throughout the year. By contrast, over the Gulf Stream the net exchange varies from -550 to +50 watts per square meter. Heat is gained by the Stream only during June and July. The radiational flux over the Norwegian Sea is negative during 5 winter months, but there is a net heat gain during 4 summer months. During June and July Labrador Current water off Newfoundland is warmed by the condensation of water vapor directly on the cold sea surface as well as by the sun and heat conduction from the atmosphere. In the upwelling region off Spanish Sahara, West Africa, heat is gained each month of the year with most of the variation caused by the annual excursion of the sun.

Weather over the continents is highly variable and, as might be expected, the energy exchange between the atmosphere and the ocean also varies greatly from the monthly and annual means. Seasonal heat exchanges during some winters produce great cooling of the water while others produce only moderate cooling. Trends develop that continue for 1 or 2 decades. For example, cooling of the Gulf Stream increased from the early 40's until about 1960 and then decreased slowly. The cooling variations were closely related to evaporation variations which in turn were related to wind speed and sea temperature changes.

Anomalous patterns of cooling and warming over the Atlantic are being studied by plotting monthly deviations from long-term average heat exchange at the surface. A wide variety of patterns emerge but most frequently bands of alternately greater and less cooling during winter months extend across the ocean. These bands may be oriented north-south as shown in the anomaly chart presented or they may be oriented in other directions. Calculations now being made of the South Atlantic heat exchange indicate that the North Atlantic bands are continuous across the equator and into the Southern Hemisphere. It is obvious that large-scale perturbations are producing these air-sea interaction anomalies. Investigation shows that global-scale atmospheric pressure anomalies are related to these heat exchange deviations through the monthly mean wind field. Deviations in the average direction of the wind strongly influence the heat gain or loss by the ocean by bringing warmer or colder air over the water. The deviations of the mean properties of the ocean resulting from these anomalies in turn influence the atmosphere. This energy feed-back mechanism in some cases may strengthen the original atmospheric perturbation causing it to persist and continue to perturb the ocean for several months.

Photochemical Reactions

Sunlight, the largest source of energy on earth, penetrates the sea surface and is absorbed in the near-surface layers. Most of this energy is converted directly to heat, producing the oceanic and atmospheric effects discussed above. Some is transformed into the energy of chemical bonds. Marine plants may use less than 1% of the available solar energy for photosynthesis, but this small fraction produces the organic matter upon which all life in the sea depends. This biological conversion of solar to biochemical energy is paralleled by purely chemical processes. Although these conversions represent only a small fraction of the total energy, the global total is so large that highly significant effects can result. The purely photochemical transformations in sea water are little known, in marked contrast to the biological processes, and the purpose of our studies is to clarify their nature and to evaluate their importance in various marine processes.

Solar radiation has energy in excess of that holding most molecules together, and typically the interaction with molecules results in breaking bonds to yield highly reactive molecular fragments, or radicals. Although there is as yet no conclusive evidence that these radicals have significant effects in the ocean, there is reason to suspect that they do. Many substances in the upper layers of the oceans are processed very rapidly by living organisms; however, part of the organic matter in sea water seems to be very stable and refractory to biological and ordinary chemical processes. From carbon-14 dating measurements, the mean age of the accumulated organic material is a few thousand years, similar to oceanic circulation times. Little cycling of this material appears to occur in the deep sea, so that the surface layers of the ocean where high-energy processes are available may contribute significantly to its recycling.

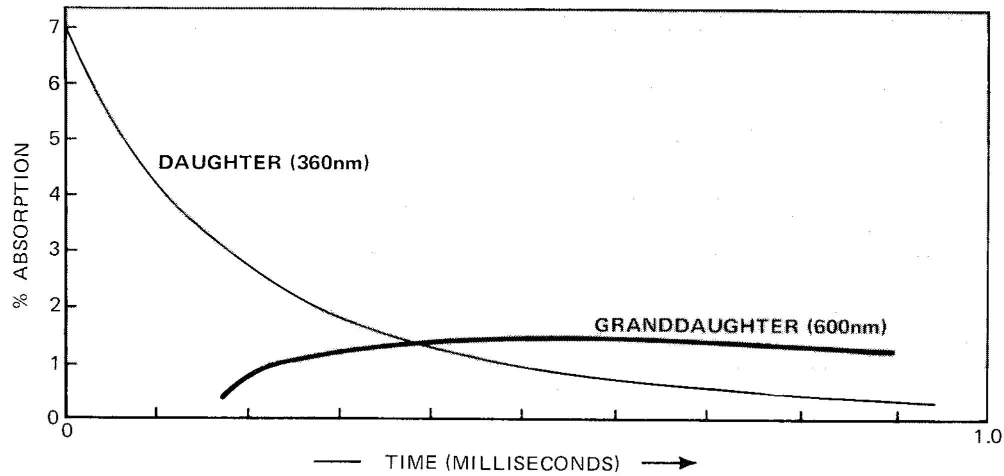
For our initial studies we selected two substances that are unstable in light and have a special significance in sea water: the nitrogen-containing compounds nitrate and nitrite. These are two of the principal forms in which the nutrient element nitrogen is available to marine organisms. Often nitrogen availability limits the total amount of growth possible in a given volume of water. In field studies we estimate the rates of destruction of nitrate and nitrite in sea water.

The measurement of these rates is straightforward, but it is important to ensure that changes in nitrate and nitrite levels are photochemical, and not the result of uptake or production by marine plants and bacteria. We have filtered sea water samples to remove the plants and bacteria, sealed them in flasks, and analyzed them before and after exposure to sunlight while immersed in the open ocean at shallow depths (about one foot). We find that nitrite is destroyed to the extent of about 12% per day on a sunny day in the tropics, but the loss of nitrate is much smaller. The gases NO and NO_2 are the nitrogen-containing products of the reactions. They both almost certainly react further rapidly, but more work is needed to determine whether or not they become biologically available again.

The speed of destruction suggests that photochemical effects on nitrogen availability in the sea may be significant in some locations. A particularly interesting area in this respect is the equatorial Pacific, where the concentrations of nitrate and nitrite are high in surface waters and sunshine is intense. We hope to extend our studies at sea to this area.

One shortcoming of field studies is that they are not suited to determining the nature or effects of the products formed in the reaction. The individual energy packets, called photons, that comprise sunlight are sufficiently energetic that they frequently split sensitive molecules into smaller reactive fragments. These fragments often enter rapidly into further reactions within a small fraction of a second after their formation. No existing methods can detect such fragments directly in the sea, and the traditional chemical oceanographic approach of sampling water and returning it to the deck of a ship for study is clearly far too slow to be useful.

We have therefore utilized laboratory studies to learn more about the products formed when nitrate or nitrite is destroyed by sunlight. These produce a common



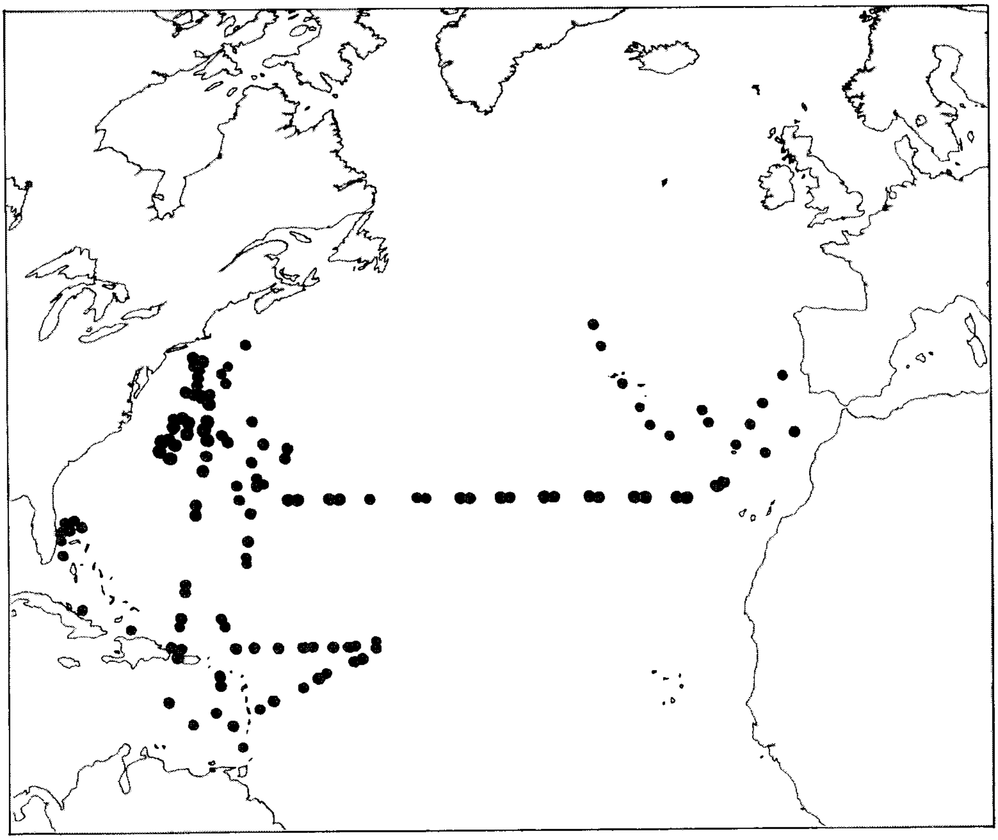
Growth and decay of radicals in sea water.

highly reactive product, a fragment of water (HOH) called hydroxyl radical, or simply OH. With Dr. Elie Hayon of the U.S. Army Natick Laboratory, we have used the flash photolysis-kinetic spectrophotometry method to study the effects of creating OH in sea water. In this method, an extremely brief and intense burst of light is used to create large quantities of the reactive species in sea water. The properties and subsequent reactions of the reactive products are then observed by measuring changes in light absorption by the sample, a very effective method since free radicals tend to be highly colored and to absorb different wave lengths of light.

The results confirmed our initial estimate that the products of the reaction would disappear very rapidly. By the time the flash itself is complete — a few millionths of a second — the parent hydroxyl radical, OH, is already entirely transformed to a daughter product that disappears, with simultaneous formation of a granddaughter product during the next one thousandth of a second. The disappearance of the daughter and concurrent growth of the granddaughter product are observed by their light absorption in the violet (360 nm) and red (600 nm) portions of the spectrum. We were able to account quantitatively for the data in terms of a heretofore unknown chemical reaction, but we still do not know the fate of the last observed product. It, too, is unstable and highly reactive chemically.

The laboratory results have some very interesting features. It was thought that the reactive products would seek out some of the other, more reactive constituents of sea water as reaction partners — perhaps organic compounds or heavy metals. Instead, we found that some of the simple inorganic constituents of sea salt, such as bromide, carbonate, and magnesium ions are involved in these initial, very fast reactions. These substances are usually considered to be rather inert chemically, especially towards the "redox" type of chemical reaction observed. This finding of reactivity by the simpler salts has an interesting implication concerning the "chemical evolution" process that generated life: it was probably very important that the primitive oceans were salty rather than fresh, as the simpler components of this sea salt profoundly influenced some of the products produced by intense solar ultraviolet radiation. Thus, it appears that salinity could well have been a strong shaping factor in the processes that gave rise to life.

This study has served to demonstrate that species too dilute and too reactive ever



Locations in the North Atlantic where specimens of gelatinous zooplankton were collected by SCUBA divers.

to be found directly in sea water nevertheless can be studied in it, and has suggested that the resulting chemistry is somewhat unusual. We are now turning our attention to the quantitative importance of this type of reaction, particularly that caused by solar ultraviolet light interacting with nitrite and nitrate at the surface of the tropical oceans.

Gelatinous Zooplankton

Two centuries ago, when naturalists began the systematic study of marine plankton, they collected organisms from the surface of the sea and observed them alive. In this way, they described many strange new creatures, and learned much about their habits. But this observational approach began to be replaced by an increasing emphasis on quantitative data. So, marine biologists turned to the use of towed nets, which provided large samples and enabled them to study organisms that lived at great depths. Plankton nets have been the standard technology ever since, and today's discipline of biological oceanography rests almost entirely on data collected with nets. While biologists gained much from the use of nets to study plankton, they were forced to concentrate on those animals that nets could collect.

Large gelatinous animals such as salps, ctenophores, medusae and siphonophores are examples of animals which cannot be collected well with nets because of their large size, their patchy distribution, and their great delicacy. Yet these animals, perhaps better than any others, exemplify adaptation to the peculiar nature of the open-ocean environment. It is an environment without motion and without boundaries. Temperature and salinity are almost always constant, and standing crops of phytoplankton are low, varying little with the seasons.

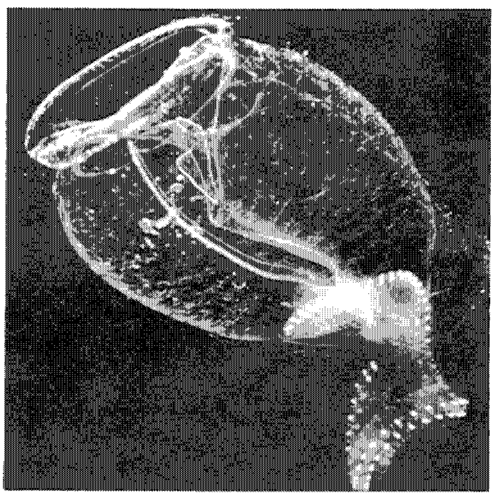
During the past few years, we have returned to the collecting and observational approaches of the past. But now we are not limited to the surface of the sea. We have penetrated it with SCUBA, and we plan to explore it even deeper with submersibles. No longer groping blindly beneath the surface from the deck of a ship, we have passed through the boundary that separates sea and sky.

The open ocean that we see is very different from that suggested by net samples. We cannot see microscopic organisms, but we can see large animals in abundance, animals that are rare in most plankton collections. The reason for this disparity is simple. Plankton nets filter relatively small volumes of water; one thousand cubic meters is typical for a plankton tow. This amount of water is contained in a sphere forty feet in diameter. As we drift through the water collecting animals, we visually sample much more water than this. The water of the open ocean is so clear that horizontal visibility usually exceeds one hundred feet, and in 30 minutes or so, we see tens of thousands of cubic meters. Our perception of the ocean environment has a corresponding emphasis on large animals sparsely distributed through a vast volume.

In addition to revealing large volumes of water to observation, our methods have two other advantages. We can observe plankton in their natural environment, studying their behavior and the nature of interactions among them. Also we can collect delicate animals in undamaged condition to use for experiments in the laboratory. This latter capability has made possible some of the first energetic and physiological research on gelatinous plankton.

Among the herbivores that we commonly see are salps (transparent, barrel-shaped relatives of the inter-tidal sea-squirts), larvaceans (tiny animals that resemble tadpoles), and pteropods (planktonic molluscs related to snails). At the next level of the food chain are the predators and parasites, animals which feed on other animals. Predators that we regularly encounter include jellyfish, siphonophores (relatives of the Portuguese Man-of-War), ctenophores ("comb jellies" that catch their prey with sticky tentacles), and fish. We also see many varieties of crustaceans, including copepods, amphipods and euphausiids. These crustaceans may be either herbivores, predators, or parasites. Most oceanographers consider crustaceans as the dominant animals in the plankton community, but we feel that many of the gelatinous animals also have important positions.

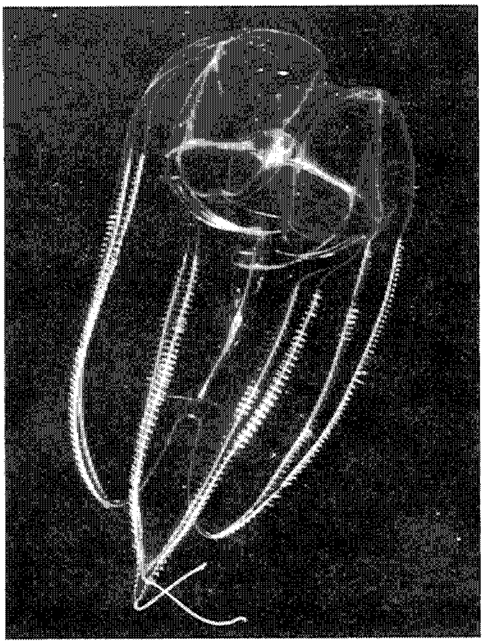
One of the most striking roles we have seen for gelatinous animals in the sea is as substrates and sustenance for other organisms. For example, the hyperiid amphipods, a major group of open-ocean crustaceans, appear to be intimately associated with gelatinous animals, usually as parasites or commensals. The course of their evolution has been closely tied to the nature of their gelatinous hosts. These amphipods are not the only examples; alciopid worms, many copepods, larval crustaceans and small fish make their homes in such hosts as salps, sipho-



LAURENCE MADIN

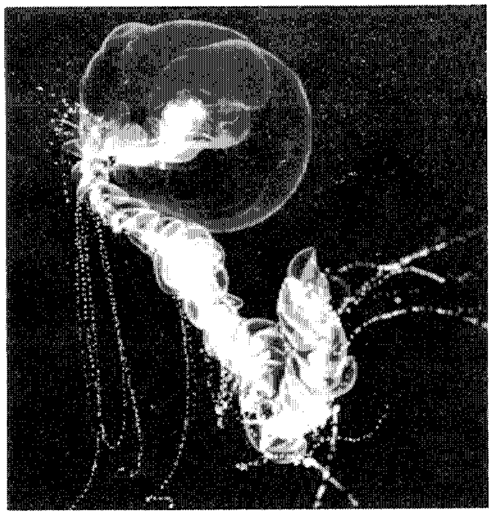
A salp, *Pegea confederata*, budding a chain of young individuals. Salps multiply dramatically in this way.

LAURENCE MADIN



The ctenophore, *Eurhamphaea vexilligera*, eludes its predators by releasing a distracting cloud of bioluminescent ink.

LAURENCE MADIN



Actually a colony of many individuals, the siphonophore, *Rosacea cymbiformis*, captures its prey with stinging tentacles.

nophores and ctenophores. The gelatinous animals serve as "islands" complete with food and shelter for a host of hangers-on and in this role are important in organizing spatial and trophic relationships within the plankton community.

Gelatinous animals make another, more indirect, contribution to spatial structure in the plankton. Many of them release quantities of mucus as part of feeding or defensive mechanisms. Shed mucus and the decomposing bodies of the animals are major sources of "marine snow", the name given to amorphous cobweb-like aggregations of organic matter in the water column. These aggregations serve as surfaces on which particulate material collects, and organisms have apparently evolved to exploit this unusual resource. We have found flatworms, amphipods, copepods and ostracods grazing on organic aggregations. This congregation upon scattered concentrations of food is another example of the ways animals find enough to eat in the open sea.

But it is really in their own right that large gelatinous animals have the greatest impact on the open-ocean ecosystem. This is illustrated by what we have learned about salps in the past few years. In order to study salps in the laboratory, they must be collected very gently; the success of experiments depends on the condition of the animals used. Salps stop filter-feeding when handled roughly, and many ctenophores and siphonophores break into fragments if jarred in the least. Collecting with hand-held jars has proved to be the only satisfactory way to obtain animals for physiological experiments. The salps caught by divers have much higher and more consistent feeding rates than do net-collected animals.

Salps filter prodigious amounts of water, removing all particles over a thousandfold range of size with high efficiency. We have found that, on the average, an individual salp filters at least two orders of magnitude (100 x) more water per minute than do the larger herbivorous copepods. Why then, have biologists and oceanographers so neglected them?

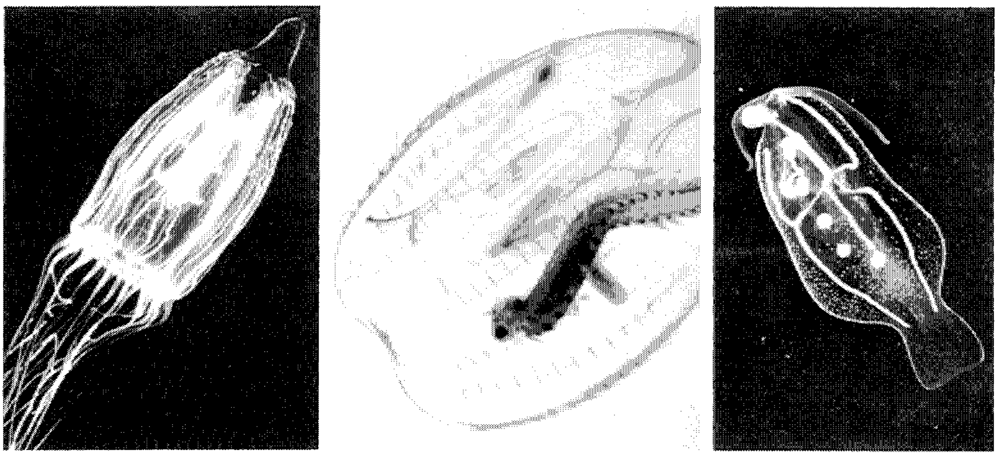
The primary reason is that with past methods of sampling with plankton nets, scientists have been unable to estimate accurately the abundance of salps. Our experiments have shown that a small number of salps can have an impact on the environment equivalent to a large number of herbivorous copepods. Since plankton tows are designed to obtain adequate samples of copepods, they filter far too little water to obtain adequate samples of salps. The salps are often absent from short plankton tows, and it is therefore concluded that they are insignificant. A certain circularity of reasoning is apparent here — one starts out assuming that copepods are the major herbivores, designs nets to collect them, and ultimately finds that these nets do indeed confirm the predictions. This circularity can be easily broken by going beneath the surface and observing. On this larger scale, salps are ubiquitous and often dominant, even though plankton nets often fail to catch a single one.

We have found that the digestive process of salps is rather inefficient, so that most of the food they collect is packaged into fecal pellets, which rapidly sink to the bottom. At the densities we commonly observe in the open ocean, this fecal production is considerable. When salps are present in very large numbers, and densities as high as 1,000 salps per cubic meter have been recorded, their impact on benthic communities must be tremendous.

Salps also grow at remarkable rates. One small species has the fastest growth rate of any metazoan animal, with a minimum generation time of two days. Our work has been done with larger species which grow and reproduce more slowly, but even these can double in length in less than 24 hours. In addition to the rapid growth of individuals, salps have astonishing reproductive fecundity. As a result salp populations can fluctuate drastically, changing as much as a thousandfold in a few weeks. Plankton collections made at monthly intervals are useless for assessing the salp standing crop in such cases. Sampling strategies need to be revised in order to study salps, or any other animal whose number and size distribution can change dramatically over the course of a few days or weeks.

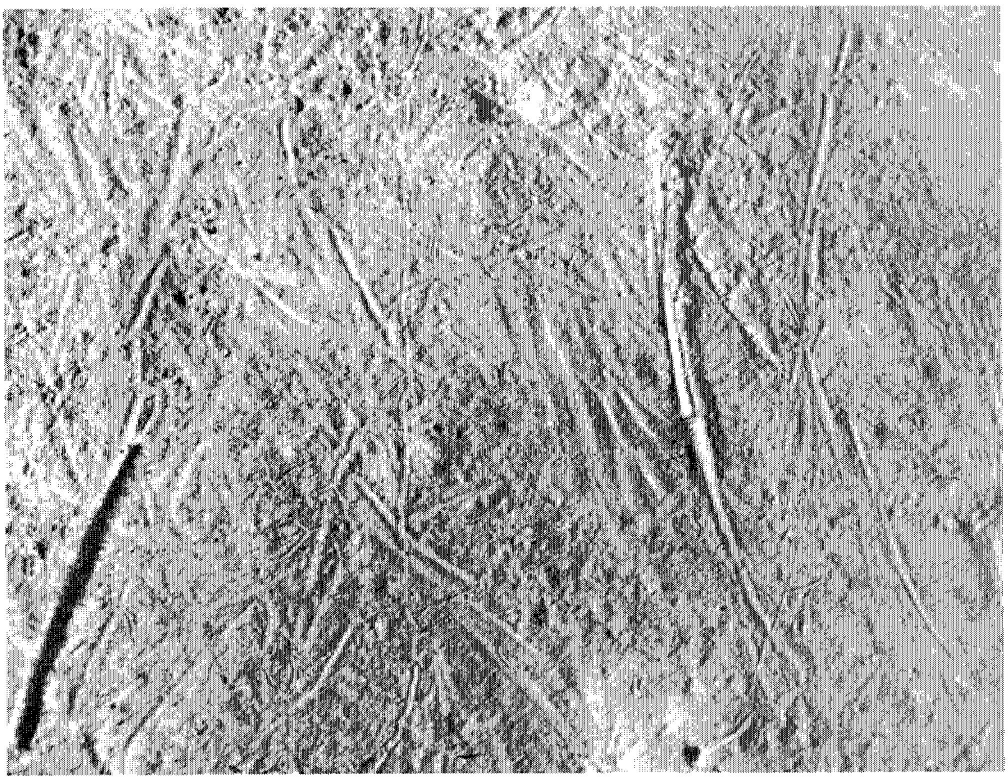
The open ocean is the largest and probably the oldest ecosystem on Earth. During the last century, biologists have used devices of ever-increasing complexity and models of greater and greater sophistication to develop a picture of what life in the pelagic realm is like. We now know that certain portions of this picture are incomplete and suggest that a useful way to learn about what is happening on the other side of the looking glass is to slip through it and look around.

LEFT & CENTER—LAURENCE MADIN



RON GILMER

Left: Medusae, such as this *Pandea conica*, are important predators in the open ocean. They, like other gelatinous zooplankton, often contain hyperiid amphipods. Center: Alciopid worms are often found living in ctenophores. This is only one example of the many symbiotic relationships we see in the plankton. Right: *Phyllirhoë*, a pelagic nudibranch, eats siphonophores.



DAVID OWEN

Tube worms burrowing into continental margin sediment off the New England Coast.

Benthic Boundary Properties

Except for regions of active volcanism, faulting and strong bottom currents, the deep sea floor is generally covered with a blanket of sediment ranging in thickness from centimeters to kilometers. This material, from both terrigenous and biogenic sources, arrives on the sea bed at rates ranging between tenths of a millimeter per thousand years (e.g., central North Pacific) to meters per thousand years (continental margins) to meters per hundreds of years on certain deltas and estuaries. Recent data from deep-sea drilling and sub-bottom profiling show that this sediment is very often preferentially deposited and does not appear as an even blanket. A large proportion has been resuspended and redeposited at new locations.

While the sediments constitute a physical boundary at the bottom of the ocean, they are still an integral and critical part of the ocean system. The interface between sediment and ocean is, in many respects, a permeable boundary. Billions of tons of material, derived from the weathering of continental rocks, are added to the oceans annually by the rivers. However, the relative concentrations of major salts in sea water remain constant. In large part, this may be controlled by exchanges with bottom sediments. Organisms, chemicals, energy in the form of heat and chemical potential energy move across this interface. The fluxes, both into and out of the sediments, exert a strong and often critical influence upon the composition of the overlying waters.

Recent investigations have also shown that the benthic organisms are far more abundant and diverse than had previously been thought. The communities are fragile and the organisms there mature slowly and live a long time compared to their relatives in more shallow water. Organisms stir up the sediments and tunnel through them, adding to the complexities and fascination of the benthic boundary layer.

Sediment Resuspension and Transport

Resuspension of material from the sea floor into the overlying water is dependent on the activity of benthic organisms, current induced shear stress, bottom slope angle, particle size of the sediment, the degree of size sorting of the sediment and the amount of organic material it contains. A great deal of interest has been focused recently on processes active within the benthic boundary layer, the region wherein most of the physical, chemical and biological gradients are steepest and most closely affected by the bottom. This area is generally assumed to be a zone extending from 100 meters above the bottom to about 1 meter below the bottom. It is within this region, the one most strongly affected by the presence of the bottom, that a special set of laws and processes are believed to occur.

In a recent meeting in November, 1974, sponsored by NATO and held in the Alpine retreat Les Arcs, France, the benthic boundary layer was defined as the zone in the water column near the sea bed where there are strong biotic, chemical and physical gradients controlled by the sea bed and the zone in the sea bed where mixing processes are controlled by exchange or activity occurring at the boundary. Later, in the spring of 1975, the Office of Naval Research conducted a seminar focusing on the physical oceanographic and dynamic aspects of the fluid flow in the benthic boundary layer. The results of these two formal seminars were the same: we know virtually nothing about benthic boundary layer processes in the deep ocean and have yet to explain many of the phenomena that we see in deep-sea sediments. A knowledge of these processes is critical and, up until recently, they have been virtually ignored.

The physical process within the benthic boundary layer that is easiest to describe and to conceptualize is the physical stirring of the bottom by the benthic organisms that reside within the sediment, on the sediment or impinge on the bottom from the overlying water. Bottom photography was one of the first and remains one of the easiest ways to obtain qualitative and quasi-quantitative information on the effects of deep-sea animals. The animals that are large enough to be seen are the principal stirrers and mixers, plowers and trackers of the deep sea bed. Most of the larger and visible tracks and trails, grooves, furrows and plowmarks are made by animals restricted to a few taxonomic groups. The most important mixers are the well-known Echinodermata which include the sea cucumber or holothurian, the starfish or asteroid, the sea star or ophiuroid, and the sea urchin or echinoid. These animals are found virtually everywhere in the deep sea and in all ocean basins except for some restricted enclosed basins like the Cariaco Trench. They rove along the bottom in search of food and in doing so impart physical energy to the sea floor, moving the sediment into suspension, just as a line of cattle slowly walking across a wind-swept prairie leaves little miniature plumes of dust every time a foot hits the ground. However, in the absence of the cattle (or the bottom organisms) the velocity of the wind (or of the water current) is not enough to put the dust or sediment into suspension.

Another group of important organisms that stir the bottom is the fish that feed on animals and debris in and on the sea floor. They are probably responsible for many of the pockmarks and depressions that are scooped out. They have been observed in many submersible bottom photographs to stir actively the bottom in search for food.

The crustaceans, for example crabs, also have been observed stirring the bottom by their motion.

Burrowing organisms that live within the sediment push material out of their burrows in the form of tiny volcanos. These excavating animals thus introduce sediment into the flow of the benthic boundary layer without the need for high bottom shear stress for resuspension.

Deep ocean currents are another agent responsible for the entrainment of sediment into the benthic boundary layer. Our recent data suggest that most, if not all, deep-sea sediments have been affected by some form of lateral transport, even in the most tranquil mid-plate regions of the central North Pacific. It has been long recognized that the rate of sedimentation on the tops of low abyssal swales is about half that found in the valleys. Thus, there is some preferential deposition of material in the valleys that can only be attributed to lateral motions. Lateral advection by bottom circulation appears to be the single most important method of continuing the transfer of material once put into suspension by organisms or physically entrained in the bottom water. Current erosion of sediment occurs only when the shear stress at the bottom exceeds about 1 dyne per square centimeter. In order for this to occur, the mean velocity above the logarithmic layer, measured at 100 centimeters above the sea bed, must exceed about 18 centimeters per second. Once the fine material is in suspension these currents can transport the sediment long distances before it settles out and is redeposited. Bottom water velocities of this magnitude are often measured where current meters have been placed within the benthic boundary layer, thus it is not surprising that sediments appear to have been transported laterally after their initial arrival on the sea floor.

It has been less than ten years since the marine geologists have come to the realization that the motion of water plays a significant role in the redistribution of sediment and may, in fact, be the most important agent of lateral transport. The central theme of our sediment dynamics program at Woods Hole is to understand and predict rates of lateral transport and the directions of this transport in the abyssal parts of the world oceans.

Fluxes Between Sediments and Water

The chemistry of the muds and the oozes on the sea floor, or more specifically of the interstitial pore waters of these sediments, has been the subject of a series of investigations using the "harpoon" interstitial water sampler developed at Woods Hole. This *in situ* instrument penetrates the top two meters of the sediment column and draws filtered pore water samples from six different levels. The chemical concentration gradients revealed by vertical profiles of the pore water composition enable us to infer diffusive fluxes, just as temperature gradients measured with thermal probes are used to infer heat flow. These determinations of chemical diffusive fluxes at the sea floor are expected to help us balance the ocean's chemical budget and to help explain what mechanisms control the salt content of the ocean.

COURTESY OF SMITHSONIAN INSTITUTION

Sea urchins plowing through the soft abyssal sediments.

Every year the world's rivers carry into the oceans some 20 billion tons of weathered continental rocks, about one fifth as dissolved salts. At the rates of delivery from modern rivers it would require only 10-20 million years to double the concentration of calcium, magnesium and potassium in the oceans. However, we know that the concentrations of major elements in the oceans have changed little or not at all over at least the past 300 million years. The constant composition of the oceans over such a prolonged time period requires that the salts be removed at about the same rates at which they are supplied. The processes that remove these salts in constant proportions are poorly understood.

For the past several years we have been engaged in research related to the mapping and understanding of the distribution and composition of particulate matter in sea water. Since virtually all of the variability in sea salt chemistry is due to the introduction and the dissolution or oxidative regeneration of particles, and since most authigenic material in marine sediments is derived from sinking skeletal debris and expired organisms, this is central to marine geochemical studies. The strategy has been to collect samples of sea water, filter them through a 0.5 μm pore size filter and carry out chemical analyses of the retained particles, either by instrumental neutron activation analysis or by atomic absorption spectroscopy. In addition to these studies, we have made measurements of the naturally occurring radioisotopes, lead-210 and polonium-210, in the particulate form. The data reveal a complex picture. Near the surface the chemical composition reflects planktonic growth, with pronounced enrichments of several elements including calcium, strontium and barium. Near the bottom, we find consistent evidence of sediment resuspension, with elevated levels of calcium, aluminum and magnesium up to 1000 m or more above the bottom. The chemical assemblage in mid-water appears to have an exotic composition with unusual concentrations of some heavy metals such as chromium, copper and mercury. The most elaborate precautions and stringent tests of cleanliness are necessary to avoid sample contamination from ships' debris, paint chips or smoke stack particles. The conclusion we must reach is either that the particulate assemblage represents industrial debris in the depths of the ocean, which effectively masks the natural signal, or that the material is delivered naturally from some unknown and highly unusual source.

Simple chemical analysis of the particles does not give information on the mass flux and settling velocities. We have attempted to obtain this information from examining the oceanic disequilibrium between radium-226 and lead-210 (half life = 22 years). The observation that from 10-50% of the lead-210 is lost from the system leads to speculation that removal of the lead by sinking particles is a probable mechanism, and that the radioactive clock can time this removal. This simple theory does not appear to hold, for careful analysis of the data shows that removal by adsorption at the sediment-water interface is a more likely mechanism.

Much of the material of sediments is not in equilibrium with sea water. The clay minerals of most sediments have been formed by weathering of the land under fairly acid conditions and in very dilute solutions. Consequently, they are not, at least initially, in equilibrium with sea water. The minerals of metamorphic and igneous rocks, formed at high temperatures and pressures, are also not in equilibrium with sea water. Similarly, much of the biogenic detritus that settles through the oceans to the sea bottom is unstable. The bottom waters of most of the ocean are undersaturated with respect to both calcite and aragonite, two polymorphs of calcium carbonate, the calcareous skeletal material of marine organisms. Other organisms produce skeletons of amorphous silica, but the ocean is undersaturated with respect to this material. The organic matter produced by organisms is also unstable in oxidizing environments such as the ocean and most sediments.

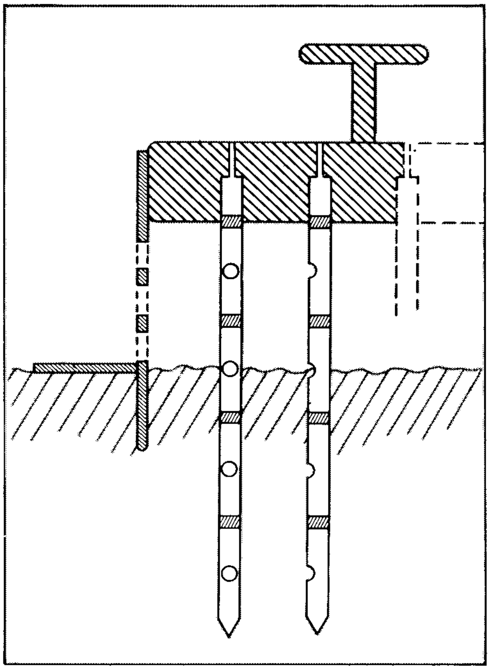
The presence of materials in the sediments which are not in equilibrium leads to reactions which drive the system toward equilibrium and produce diffusive fluxes across the bottom of the ocean. For example, amorphous silica and calcium carbonate tend to dissolve, being undersaturated in ocean bottom waters. We observe steep concentration gradients of such compounds in the pore waters. Since the concentration increases with depth, the fluxes return these components to the ocean water. Such a return is essential as processes in the upper ocean form skeletal material faster than the dissolved skeletal components are supplied by the rivers and balance can be achieved only by a backflow from the sea floor.

The sediments act as a sink, rather than a source, for potassium, magnesium and sulfate, balancing, in part at least, the addition of these elements by the rivers. We know little specifically of the uptake mechanisms for magnesium and potassium but are investigating them. The sulfate ion is lost to the sediments as a consequence of its reduction to sulfide ion and precipitation as iron sulfide. This process is mediated by anaerobic bacteria in the oxidation of organic matter after free oxygen and nitrate are exhausted.

The rates at which dissolved components are resupplied to or removed from the oceans through the sea floor exert a strong influence on concentrations in the ocean. These rates depend upon the fluxes across the sediment-water interface, and ultimately upon the nature and rates of reactions that produce the gradients we observe in the interstitial solutions of the sediments.

The breakdown of organic matter in the sediments regenerates nutrients, resupplying part of the phosphorus and nitrogen originally buried. We have developed an approach to measure flux rates *in situ* using bell-jar-like enclosures placed over small areas of the bottom. The accumulation of inorganic nutrients in such a chamber and the disappearance of oxygen from it are measures of the metabolism of the total bottom community. The rates at which oxygen is converted to carbon dioxide can be used as an indication of the dependence of the bottom biota on the sedimentation of organic matter from the water column, whereas the production of ammonia and nitrate by the bottom community are measures of the recycling of inorganic nutrients which can be used again by the phytoplankton.

Our findings indicate that in shallow waters of the continental shelf this interdependence, or the benthic-pelagic coupling, is extremely high. Similar experiments have also been carried out in the deep sea using a free vehicle respirometer developed at this Institution and using bell jar respirometers implanted at deep ocean stations with *Alvin*. The results indicate that in the deep sea off the coast of Massachusetts the rates of metabolism are at least an order of magnitude less than in shallow water at similar temperatures. This suggests that offshore the interdependence between surface water production and deep bottom metabolism is much less than on the continental shelf. These investigations of the flux of biologically important materials across the sediment-water interface have been carried out off New York in regions contaminated by sewage sludge, off Baja California, and off Spanish Sahara in productive zones of upwelling which support major fisheries. This comparison indicates that bottom metabolism is high in regions subject to high rates of organic matter input, whether the organic load is natural or man-made. Return of nutrients, however, into the water column is less in areas subject to low oxygen concentrations in the water or reducing sediments, as sometimes characterize a site of sewage sludge dumping. Off the coast of Peru, reducing sediments are a natural condition brought about by high



Positioned rack used to evaluate decomposition of organic materials above, at and below the sediment-water interface.

productivity. Here nutrients are not returned to the water column at high rates, but the sediments are characterized by the formation of phosphorite deposits, a mineral of importance in commercial fertilizer. The mechanism of the formation of phosphorite is related to low oxygen concentrations, high organic matter and the retention of nutrients. We are continuing our sampling of phosphorite off the coasts of Peru and southwest Africa.

Considerable effort has gone into enumerating bacteria present in surface sediment and overlying water but few conclusions can be drawn as to what the *in situ* metabolic activity of these microorganisms actually is on the sea floor. Studies on decompressed samples incubated at ambient pressure have shown that viable microorganisms are present in the benthic boundary layer in high numbers, but their actual *in situ* activities may be greatly reduced due to suppressed metabolic activity imposed by the natural environmental conditions of high hydrostatic pressure and low temperature.

The preservation of food material recovered from the sunken submersible *Alvin* after a 10-month exposure to deep-sea conditions led to more quantitative studies of the bacterial degradation of organic matter in the deep sea. Rates of microbial activity at depths of 5,000 meters or more are reduced to one-tenth or one one-hundredth the rate found in laboratory controls at one atmosphere pressure.

The problem of sample decompression was overcome using *Alvin* by inoculating and incubating samples *in situ*. Experiments were conducted at a depth of 1830 meters in the North Atlantic and of 1960 meters in the Tongue of the Ocean in the Caribbean. Quantitative experiments, conducted *in situ*, revealed very slow rates of microbial transformations of radio-labeled organic substrates contained in bottles and incubated for over a year, as compared to laboratory controls.

Semi-quantitative measurements also have been made of the degradation of solid organic matter held in containers open to the environment and incubated on the deep sea floor. Plastic sediment racks were constructed, housing sectioned tubes, each section being exposed to the outside environment through a small hole. The openings were 3.5 cm. above the sediment, at the sediment-water interface and 3.5 and 7.0 cm. within the sediment. The sections were filled with sterilized solid substrates such as agar and starch. *Alvin* transported and positioned the sediment racks on the sea floor. The racks were retrieved after 12-15 months' exposure, examined and the contents of the tubes were chemically analyzed to determine how much substrate remained. A similar rack for comparison was incubated for 5 weeks at 2 meters in the Eel Pond, Woods Hole. Large populations of bacteria developed on the surface of several of the exposed sections. Anoxic conditions developed in several exposures below or at the sediment surface.

At the station in the North Atlantic the rate of decomposition of both agar and starch was nearly the same in the segments exposed at, above or below the sediment-water interface. After a year of exposure more than half of the substrate remained in all but one test section. At the more southern station, in the Tongue of the Ocean, decomposition at and above the interface was greater than the rates within the sediment. Decomposition of agar was generally slower at the southern station, but decomposition of starch was generally more rapid. The rates of decomposition of both agar and starch were considerably more rapid in the Eel Pond, ranging from four to over twenty times faster than at either deep station.

These *in situ* experiments thus confirm earlier estimates of the slow rates of microbial degradation of organic material in sediments of the deep sea, as well as indicating the importance of the macrofauna to the degradation of solid organic matter that may reach the benthos. While decompression of samples may have an effect on microbial populations and subsequent measurements, the reduced activities measured *in situ* are real, and not an artifact produced by laboratory manipulation.

Populations of the Bottom

It has been commonly believed that the density of benthic life in the depths of the world ocean is extremely low and that the few species there are distributed uniformly over vast stretches of the deep ocean floor. Most of the earlier collections were made with trawls or dredges that move on rather than in the bottom. As a result, traditional concepts concerning the nature of this fauna were almost entirely based on the larger epifaunal organisms, the animals captured by these techniques. The relatively few quantitative samples taken previous to our studies seldom contained as many as ten specimens and, frequently, they were entirely devoid of living organisms.

Meaningful interpretations can be drawn from the data only when statistically significant numbers of benthic animals are available for study. We have used an oversized anchor dredge which takes a much larger sediment sample and the organisms are retrieved by washing samples through a fine-meshed screen (0.42 mm). Most of the animals recovered are small and would pass through the cruder collecting devices and coarser-meshed screens used in earlier studies. There is an abundance of these small animals, and our concepts about deep-sea benthos have changed greatly since our work began over a decade ago.

In order to relate our studies to previous investigations as well as to provide basic information on the largely neglected smaller epifaunal animals, we use an epibenthic sled which has proved to be most successful in capturing large numbers of

Location Depth Duration	**N. Atlantic 1830 m 12 mos.**	**Caribbean 1960 m 15 mos.**	**Eel Pond 2 m 1.25 mos.**
AGAR			
+ 3.5 cm.	4.33	3.20	18.4
Interface	3.50	4.07	50.4
- 3.5 cm.	4.0	1.47	23.2
- 7.0 cm.	3.83	1.53	30.4
STARCH			
+ 3.5 cm.	2.25	5.73	36.0
Interface	2.17	5.33	47.2
- 3.5 cm	2.25	3.53	31.2
- 7.0 cm.	2.42	2.20	33.6

Degradation of organic materials (given as percentage loss per month) at four points of exposure above and below the sediment interface.

animals from the sediment-water interface. Also we have incorporated a timing device that closes a door at the mouth of the sled to eliminate winnowing of the sample as it is brought through the long water column to the surface. Winnowing has taken place in most deep-sea samples, leaving only a minute complement of the total fauna such as some heavy-shelled molluscs and echinoderms or an anemone on a rock. The lighter density fauna, the vast majority of the sample, is selectively lost.

Previous to the use of the anchor dredge and epibenthic sled, by far the largest number of deep-sea benthic animals taken in a single sample from the deep ocean floor was by the *Galathea* Expedition. This sample yielded 132 species and about 2100 specimens. The three richest abyssal samples out of a total of 138 bottom trawlings and dredgings taken on the *Challenger* Expedition contained 53 to 87 species and about 150 to 200 specimens. The total sum of all invertebrates and fishes taken at depths greater than 915 meters on the *Challenger* Expedition by all sampling techniques was approximately 6670 specimens, or less than a mean value of 50 specimens per sample.

Quantitative investigations on a transect from Gay Head to Bermuda demonstrated that each geographic region supported a characteristic number of animals – ranging from as many as 23,000 per square meter on the shallower continental slope to as few as 25 to 100 per square meter on the Sargasso Sea abyss. The numerically dominant animal group is the Polychaeta, marine infaunal worms, forming 40-80% of the samples and always represented by many species. The Crustacea, represented by numerous species of tanaids, isopods, and amphipods comprise from 5-50% of a sample. In addition to a greater abundance than previously expected, there is also a marked variety of species and a surprisingly high diversity present at depths ranging from 200 to 5000 meters.

We have also collected similar samples from soft-bottom marine and estuarine habitats in both high and low latitudes and in regions dominated by continental or maritime climates. The deep-sea benthic fauna possess a diversity similar to that of tropical shallow seas and the richer shallow boreal localities dominated by a maritime climate. This finding, that the deep sea is characterized by a high diversity of species, has led to acceptance of the concept that highly diverse faunas are the product of evolution in parts of the globe where sudden catastrophic climate change is uncommon.

Growth and gonad development are very slow in deep-sea specimens, just as microbial decomposition is slow there. In collaboration with Dr. Karl Turekian and colleagues at Yale, we have learned that an 8.4 mm deep-sea protobranch, *Tindaria callistiformis*, was at least 100 years old at the time of capture. Analyses of 228-Ra isotope in smaller individuals of the same species demonstrate that gonad development begins when the bivalve achieves a length of 4 mm and an age of about 50-60 years. These findings of slow rates of biodegradation, metabolism and growth and the longevity of deep-sea organisms support the idea that life processes for many, if not most, deep benthic organisms are occurring in slow motion compared with their shallow water or terrestrial counterparts.

The best way to learn about rates of life processes in a wide variety of deep-sea life is to conduct *in situ* experiments on the sea floor. With surface ships it is virtually impossible to follow a single organism or group of organisms through periods of time approximating an entire life cycle. With *Alvin* it has been possible to set up a permanent bottom station on the sea floor where experiments can be placed and returned to at regular intervals over a period of years.

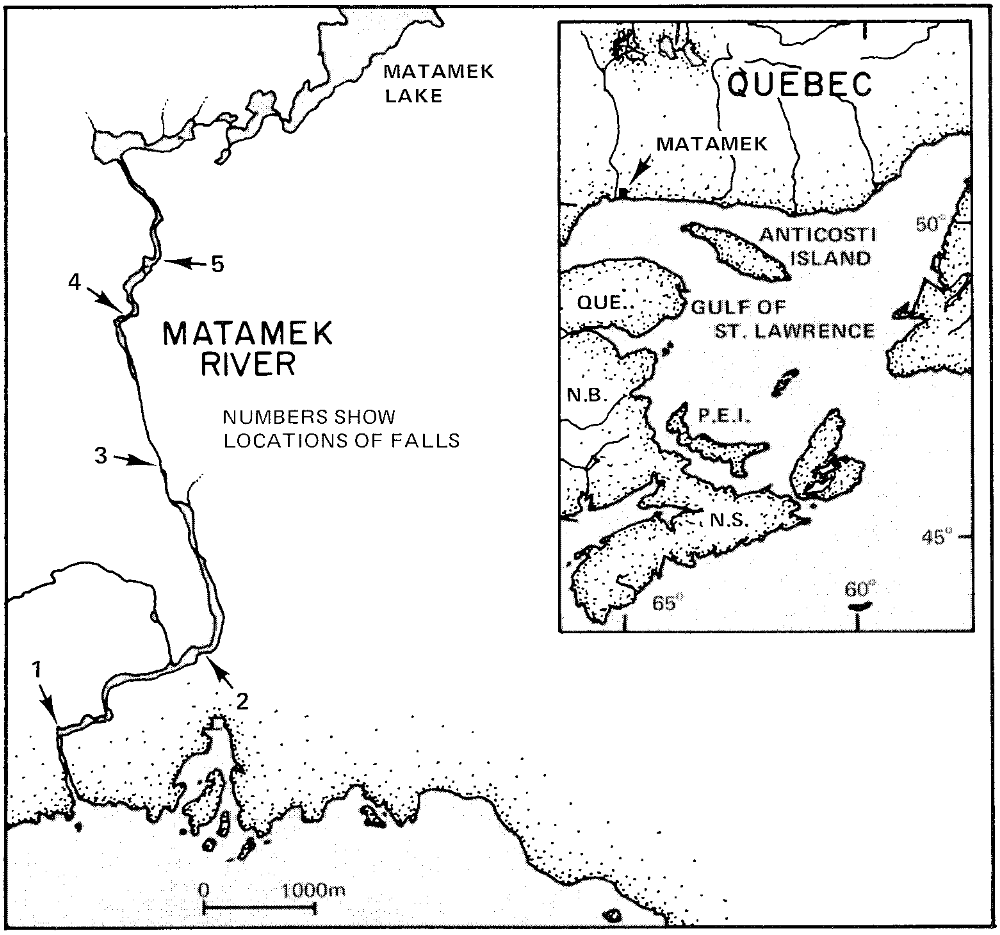
Our most recent experiments using *Alvin* have helped us learn more about how so many species can coexist in such a homogeneous environment. We would like to know how long it takes deep-sea animals to reach adulthood and how long they live. How quickly do populations recover following disturbance? Are populations rapidly expanding and competing for space?

A box of sediment containing no animals was placed at a depth of 1830 m on the sea floor more than 2 years ago and retrieved last fall. The sediments in the boxes were from the immediate area and were made azoic by freezing at -30°C for one month before being returned to the sea floor. Organisms that settled and grew in the boxes during the 25-month interval were almost exclusively small juveniles. This is in sharp contrast to the control samples from the immediately surrounding sea floor where most of the individuals were adults. The population density was an order of magnitude lower and qualitatively depauperate relative to the highly diverse community outside the boxes. These data support our prediction, based on the small brood size and high proportion of adults in deep-sea benthic populations, of low rates of recruitment and growth compared to the opposite pattern that seems to typify the boreal shallow-water benthos.

Five species in the box recovered from the 1830 m bottom station after 25 months were relatively common with abundances of 14 or more per 0.25 m^2. Two of the abundant species are not normally common to the area: the juvenile stages of a parasitic gnathiid isopod and the prime marine opportunist, the polychaete, *Capitella capitata*, and the latter was the only abundant species represented by adult individuals. Wherever intensive shallow-water benthic studies have been conducted, *Capitella capitata* (or one of the several species referred to as *C. capitata*) has been recognized as an indicator of disturbed conditions. In shallow water, *Capitella* rapidly invades biologically undersaturated habitats and, since it becomes sexually mature in 4-6 weeks, it quickly saturates the environment. In the deep sea, this species is rare, having been found only once before at depths greater than 300 m. It may respond to the unique occurrence of barren sediments in the boxes.

We cannot tell whether recruitment to the boxes is continuous or begins only after a threshold of suitability for larval settlement is reached. For comparison, we retrieved a sediment box last fall that had been exposed on the bottom at the same location for only two months. We found 30 postlarvae and two small adult snails, a total of 32 individuals belonging to 12 species. This compares with 141 individuals and 32 species in the two-year sediment box. Two relatively abundant species in the sediment box exposed for 2 months were not present in the sediment box exposed for 2 years. Thus, settlement of certain species can apparently be rapid in azoic sediment, although extended time, more than 2 years, may be required to reach population densities characteristic of the area.

The low rates of recruitment and growth indicate that deep-sea organisms recover very slowly following disturbance. The general impression of life in slow motion supports other observations of low rates of microbial activity, respiration of communities and of larger organisms. Deep-sea communities will recover very slowly if some species are killed or removed by disturbance. Accurate predictions of rates of recovery will require species by species information on life histories. Measurements of rates of response of populations to disturbance are of practical value in predicting the effect of such activities as dumping of wastes at sea or deep-sea mining. We are just beginning to understand how these very low rates of biological activity and great variety of life have evolved. With increased interest in the resources of this vast area, experimentation on the sea floor will be an increasingly important part of our work.



The Matamek River and its location on the Gulf of St. Lawrence.

The Matamek Research Station

Matamek is located on the North Shore of the Gulf of St. Lawrence, about 400 miles east of Quebec City. It is situated at the mouth of a salmon river, which drains a watershed of about 270 square miles of unexploited boreal forest. The Station was acquired by the Institution in 1966, through the generosity of Mr. J. Seward Johnson.

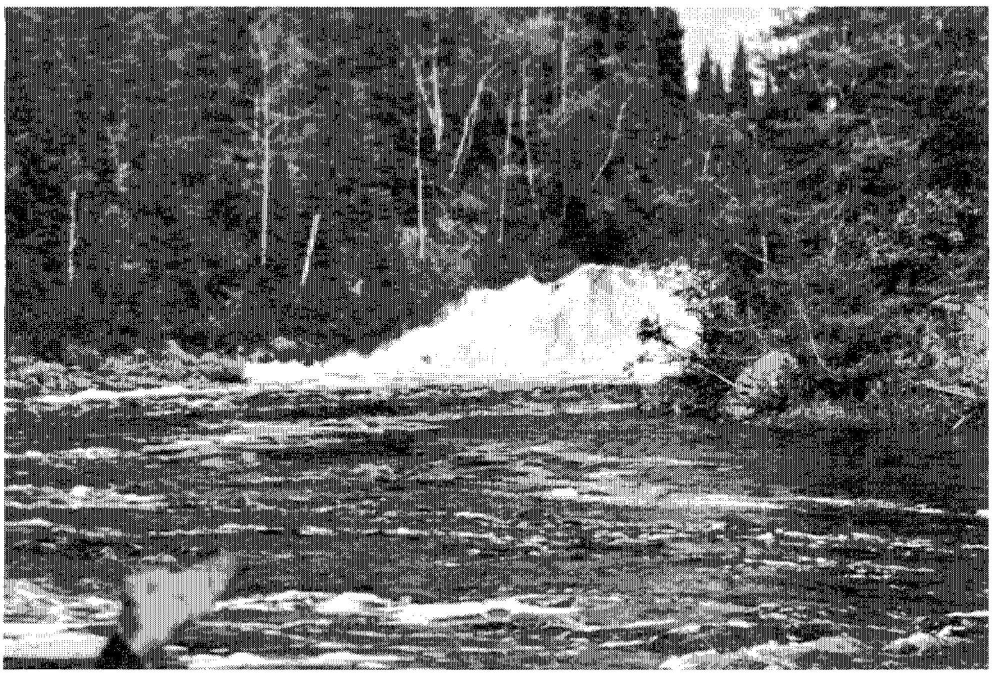
The studies at Matamek are unusual in that we can work in a pristine area virtually untouched by man. Adjacent areas are being changed rapidly by logging, mining, hydroelectric dams and recreational pursuits, so that the work at Matamek is providing valuable baseline studies. No similar research at present is conducted on the North Shore of the Gulf of St. Lawrence. The watershed is protected by being a fish and game reserve. However, a road has recently been opened along the coast, so negotiations are in progress to further protect the watershed as an ecological reserve under a new Quebec law. This would preserve this unique basin solely for scientific research.

The area is on the Pre-Cambrian Shield, which is characterized by igneous and metamorphic rocks, and the rivers in this area can generally be said to be in the youthful stage of development, with many rapids and waterfalls. The vegetation is typical of the boreal forest and appears lush, but is slow growing. There are five waterfalls on the lower reaches of the river that drains Matamek Lake (see map on page 39). Salmon can negotiate the first three, but the fourth, 3.6 miles from the sea, has an almost vertical drop of 20 feet, and is a barrier to further migration. The geology of the area, plus the recent glacial history, has provided an interesting distribution of fish fauna. In the lower river, each falls is a barrier to further upstream penetration of some species of fish. For example, alewives and sea trout stop at the first falls, the four-spine stickleback at the second falls (a relict species between these two falls), the longnose sucker at the third falls, salmon at the fourth falls and eels at the fifth falls. In Matamek Lake smelt and two varieties of arctic char are found. These are also relict species which immigrated before glacial rebound provided the falls as barriers.

Some lakes have isolated populations of only trout, and one has only smelt and sticklebacks. Matamek Lake is on the Champlain Plain, and immediately north of this is the Labrador Plateau, above the Labrador escarpment, which begins at about 500 feet above sea level. The limit of fish distribution in the basin is up to between 550-750 feet, except in the upper Matamek River, where the gradient is not so sharp, and here trout have penetrated to the top of the northeast part of the watershed. Hills in the northern part of the watershed rise to 2,150 feet. There are many lakes and streams above the escarpment which have no fish. This unique basin with its unusual fish distribution provides a rare opportunity to study interactions of various fish species and interrelationships with their prey.

The Salmonid Populations

A fish ladder has been built by the Quebec government at the first falls from the sea and was completed in 1975. This provides an easier migration route for adult



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The fourth falls, barrier to upstream migration of salmon.

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The fish counting ladder at the first falls.

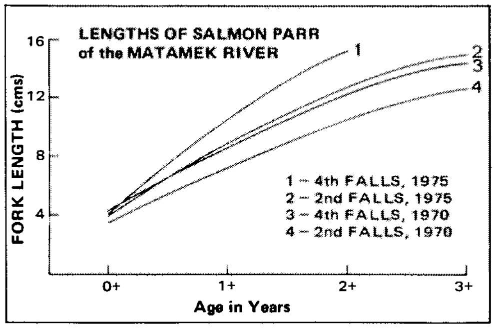
salmon, which they tend to take in preference to leaping the falls. They are trapped in a compartment of the ladder where they are counted and sampled. A retainer pool is incorporated in the design so that live fish can be kept for experiments and introduction upstream beyond the normal limit of migration. In 1975 all the fish released were tagged, and a further sample taken in a trap set upstream to assess the proportion using the fish ladder (about half).

The male salmon tend to return a year earlier than the females. There are, therefore, in the Matamek mainly two sizes of adult salmon, fish that have been to sea for one year, called grilse, which are about 3 lbs. in weight, and fish that have been at sea for two years and are about 9 lbs. in weight. The few larger fish are usually repeat spawners. An estimate of the population was first possible in 1975 after completion of the fish ladder. This gave a total of about 160 adult salmon. There may have been a decrease in the salmon run over the last few years. Some evidence for this is that in 1975, 76% of the run was composed of grilse, the small-sized salmon, whereas in 1967, when the run was first sampled, grilse made up 55% of the run. Also the early July run of predominantly 2-sea-year salmon, found in previous years, did not materialize. The larger salmon are caught in greater proportion than grilse by commercial fisheries at sea, so that heavy exploitation leaves a greater proportion of smaller fish. Salmon runs in rivers further south have shown a similar trend. As the grilse are mainly males (94% in the Matamek) and the salmon mainly females (65% in the Matamek), the consequences will be serious for similar small rivers unless exploitation is considerably diminished.

The number of parr (the juvenile stage of salmon found in the River) and smolt (the young salmon which migrate to sea, at three years old in the Matamek) have decreased in recent years. The decrease in number of the juveniles is probably due to a fewer number of spawners. Because of the decrease in number of parr more food and space is available, so that growth has increased. At the upstream limit of salmon distribution, below the fourth falls from the sea, two-year-old parr have a fork length (tip of nose to fork of tail) of 15.0 cm., and the one-year-old 10.6 cm. Up to 1970, the two-year-old here were 12 cm. in length and the one-year-old parr 8.6 cm. in length. Salmon parr further downstream also have shown this increase in growth since 1970. At the fourth falls the growth of salmon parr is greater than further downstream, but the general growth rate of salmon parr since 1970 has been increasing, and below the second falls salmon parr are now larger than they were below the fourth falls in 1970. Our salmon studies are continuing, so that the optimum salmon production of these northern rivers and relative production from different types of habitat can be estimated.

Interactions and Behavior

Interactions have been found between salmon parr and brook trout, the two dominant fish species in the lower river. These two species are similar in feeding habits and in habitat requirements, so that competition would be expected. Each species, when alone, is most abundant near rapids and falls all summer. Where the two species co-exist, both are numerous near the falls in early summer where the preferred food is most abundant, but after mid-July food becomes sparse, and the two species separate into different habitats. The salmon parr remain near the falls and rapids, but trout move off into slower and deeper waters downstream. Also the diet of each species became different. The mechanism of this segregation has been studied in stream tanks. Both species show aggressive behavior, but parr are more territorial and more aggressive than trout. Salmon parr displace smaller trout, but not larger trout, by aggression. Trout are faster growing than parr, and are larger at the same age, and parr were not seen to displace trout larger than themselves. Salmon parr are apparently more efficient than trout in fast water, and displace the latter by competition when food is scarce. Parr are less buoyant than trout, and in fast water apply the leading edges of their large pectoral fins to the substrate, to act like suckers, whereas trout continually swim against the current, and must therefore require relatively more energy than parr to hold station in fast water.



Growth of juvenile salmon at the second and fourth falls.

The relative biomass, or general weight; of each species in the Matamek River is about the same. However, the trout grow faster and are generally larger than the salmon parr which, though smaller, are more numerous. This may come about by the strong territoriality of the parr, which has the effect of sharing the habitat among more individuals. The trout tend to be more roaming in nature, especially in slow water. It is more valuable for a fish to be large early, as it is then less vulnerable to predation, more efficient in using energy, and it matures and reproduces at an earlier age. However, salmon can do their principal growing at sea, so it is more useful for this species to split up the biomass into more units, yet at a size where sufficient survival is guaranteed for successful return and reproduction.

Experimental studies on fish behavior were made in stream tanks, built at the second falls, 1.5 miles from the sea. Interactions and habitat preferences were tested with brook trout and salmon parr.

Both species are aggressive and react to each other as though they were the same species. However, salmon parr are more territorial and initiate more attacks. Trout are generally more tolerant of the proximity of other fish and have a greater tendency to school with a dominant trout in the lead. In habitat preference experiments, no preference could be demonstrated for type of substrate, but in shallow water of about 30 cm. depth, both had a strong attraction to shade. However, if the two species are tested together, trout occupy the shaded section and are not displaced by the smaller salmon parr. This is in contrast to the situation near rapids, where salmon parr can displace trout by competition. The preference for shade disappears in both species when the water is about 50 cm. deep, and they are then distributed through the tank. This is in contrast to the situation in the river where salmon parr are found in shallow water away from shade in areas of rapids where the water surface is rough, but not where the surface is smooth. This is probably an adaptation against predatory birds, such as kingfishers, which can easily see parr in shallow water with a smooth surface, but not where the surface is turbulent.

Water velocity preferences of trout and salmon are very similar and both are found in fast and slow water at various times. However, in the stream tanks salmon parr hold stations in medium flow, of 17 to 24 cm./sec. significantly more often (42% of fish seen) than trout (7%), which are more often seen in slow flow (73%), of less than 17 cm./sec. In slow water velocities (5 cm./sec. or less) salmon parr are less aggressive and hide more amongst rubble or under shade. This reduced aggression may be associated with a reduced availability of food. Much of the food of both trout and salmon parr is from insect larvae drifting in the current, so the supply

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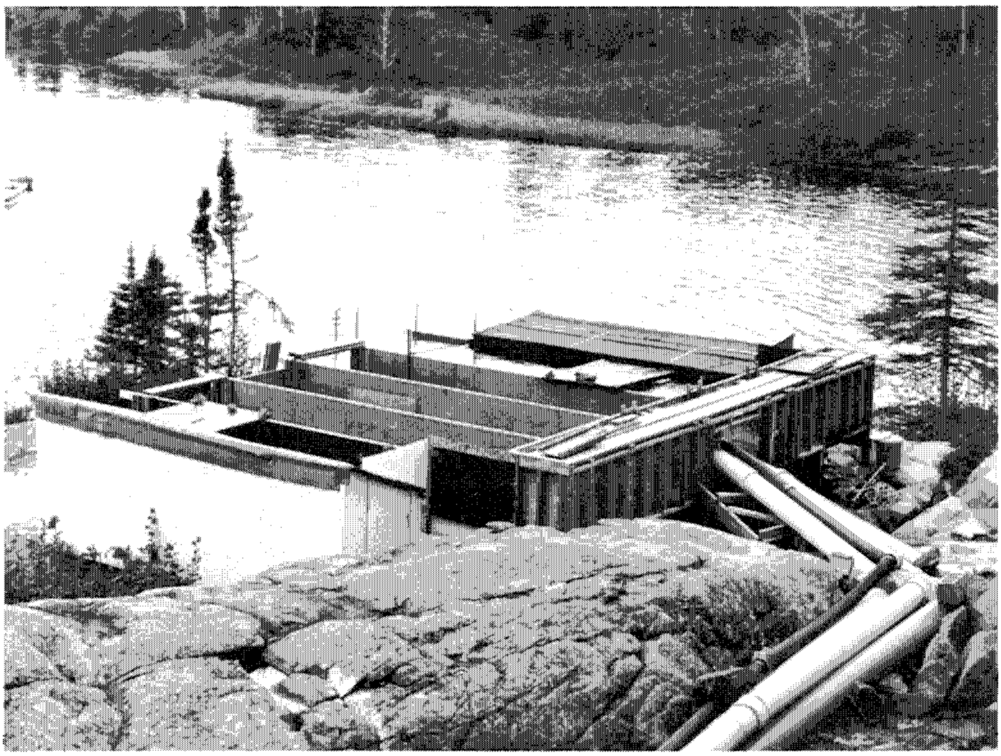


The experimental stream tanks at the second falls.

would be considerably reduced in slow water. Water velocity preferences also change with feeding regimes and temperature. Starved fish of both species spend less time in fast water than fed fish, and cooling the water to 9°C or lower decreases activity and aggression and increases the occurrence of both species in slow flow. At 9°C salmon parr, and to a lesser extent trout, hide in rubble. In the river salmon parr could not be seen or caught below temperatures of 9°C, and probably at these temperatures they are normally dormant, most likely hiding under rocks and rubble.

Food and Relative Biomass

The preferred food of salmon parr and trout is aquatic insects, and in the Matamek River their availability varies considerably, both through the season and down the length of the river. The volume of drifting insects in the water last year was about eight times greater in June than in August, and was twice as abundant upstream at the fifth falls near Matamek Lake, than 2.5 miles downstream, at the second falls. The greatest difference was with the filter feeding insects, such as black fly larvae, which were four times more abundant at the upstream station. The differences down river were produced by decreases of the plankton on which the insects feed. Fish abundance also decreases down river. Four miles from the sea, below the fifth falls, the biomass of brook trout was more than eight times greater than that for trout and salmon parr combined below the second falls, 2.5 miles further downstream. Trout are fatter and more numerous upstream and generally mature earlier there. In Matamek Lake and its tributaries, however, the growth rate and production of trout are low. In Matamek Lake the biomass was found to be less than 2% and in four tributary streams it ranged from 6.8% to about 30% of that found in the river below the fifth falls. Studies are continuing of the production of the river, the relative importance of contributions of food from the lake, production within the river itself and additions to the system from the vegetation along the banks.

THE BIOMASS OF SALMONIDS
(trout and salmon parr)
FROM SEVERAL WATERS IN THE MATAMEK RIVER BASIN.

Location	Biomass of Salmonids kilograms per hectare*
Matamek Lake (brook trout and several other species present, but no eels)	3.1
MacRae Lake (only brook trout)	4.3
Bill Lake (brook trout with eels present)	0.34
Tributary streams of Matamek Lake (brook trout)	12.1 to 53.3
Matamek River below the fifth falls (brook trout)	178
Matamek River below the second falls (brook trout and salmon parr)	21

*Multiply by 0.89 to give pounds per acre.

Populations and Properties of Other Lakes

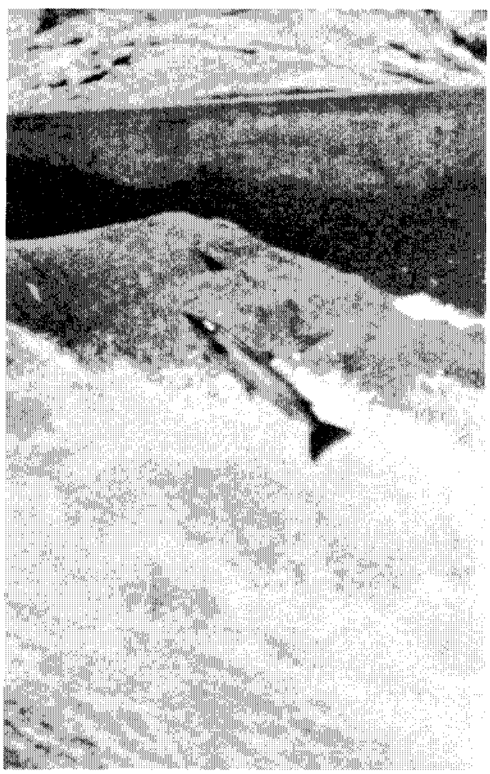
Some species of zooplankton, such as the larval stage of phantom midges (*Chaoborus*) are exceedingly abundant in lakes that have no fish. Other zooplankton show considerable differences in occurrence in various lakes due to predation and competition. Salmon have been introduced into some of these waters and have shown surprisingly good growth. The size of the introduced fish was 22 to 32 cm. long at two years old, and about 40 cm. long weighing 0.8 kg. (1¾ lb.) at three years old. Surprisingly, the salmon did not leave the lakes as smolt, probably responding to the abundant food and to the lake environment. It is planned to introduce adult salmon to spawn naturally in a tributary of one of these fishless lakes. The production and distribution of salmon can then be compared with waters having trout, and perhaps the density found at which smolt will leave the lake.

Studies on water chemistry and primary production in the lakes have shown that nutrients and primary production are exceedingly low. The water is somewhat brown from humic acids, but some of the higher lakes are more transparent. These latter (such as L. Randin) have lower nutrient concentrations but have a greater primary production (3.0 g $C/m^2/yr$) than the browner lakes (such as L. à la Croix; 2.2 g $C/m^2/yr$), because of the deeper light penetrating zone.

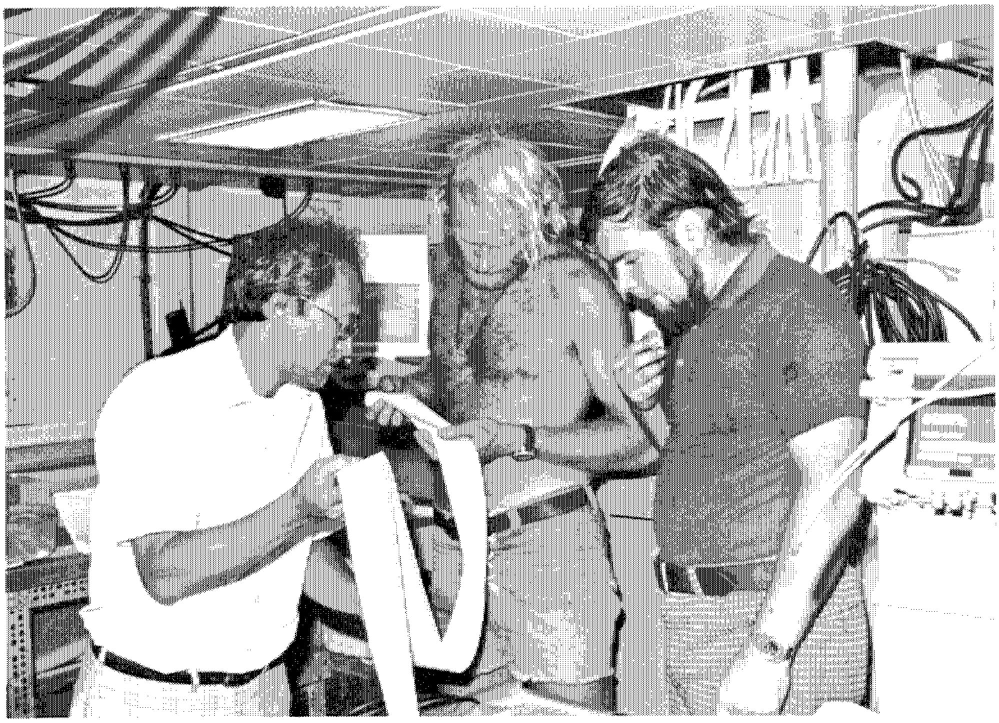
Phosphorus is the major limiting nutrient controlling the production of phytoplankton in the lakes. The proportions of particulate and soluble phosphorus and the turnover rate are being calculated using a kinetic approach to develop a phosphorus budget for representative lakes. It will then be possible to construct a model relating phosphorus loading, chlorophyll, phytoplankton biomass and primary production. This model should be predictive and will enable the assessment to be made of any environmental disturbance in the watershed, such as logging or fertilization.

The geological history of the lakes is being studied by taking cores of the sediments. One finding here is that lead in the surface sediments, representing recent events, is much more abundant than in deeper layers.

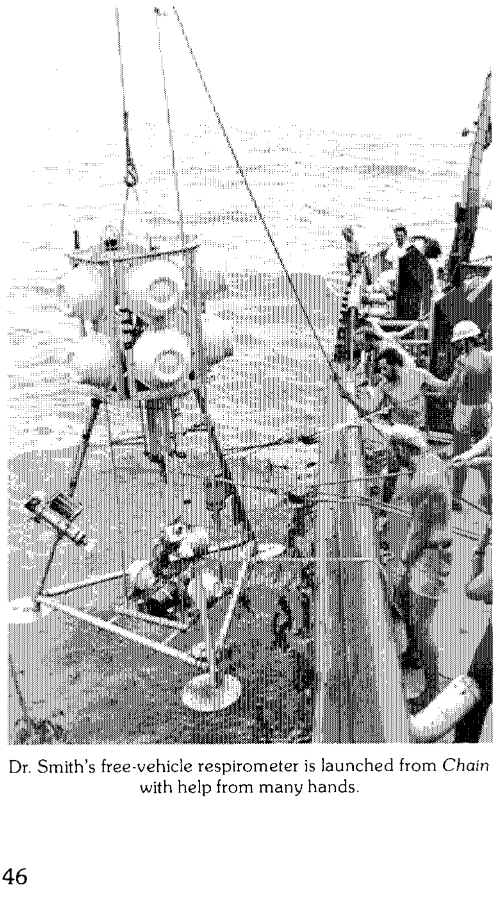
Very little is known of the limnology of eastern shield lakes. Matamek thus has the potential of providing important new information about this rapidly "developing" region. This research is providing information on the community ecology of North Shore salmonid waters, particularly with reference to energy sources and amounts. Matamek has developed into a thriving research station, and is continuing to provide a base for researchers in this area in cooperative programs with Canadian universities, the Quebec government and the Institution.


JOHN GIBSON

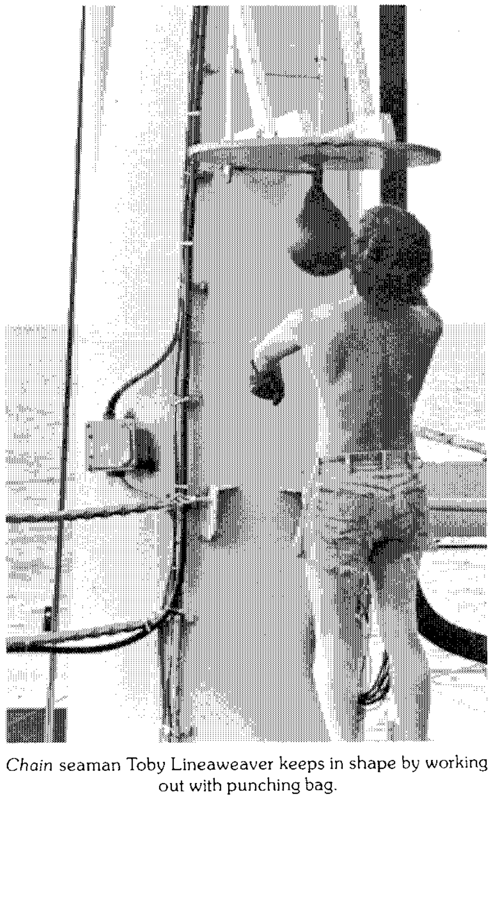
A salmon leaping at the first falls.



Dr. Mario Pamatmat of Auburn University, at left, Assistant Scientist Ken Smith, and Research Assistant Andy Eliason examine data from free-vehicle respirometer.



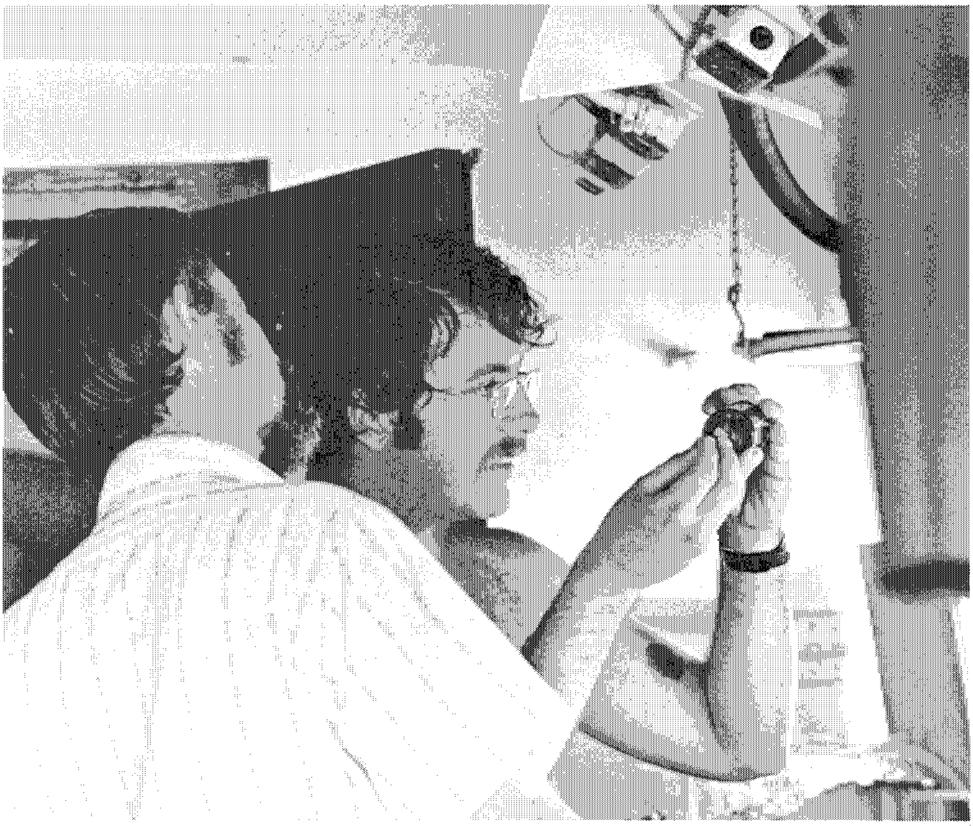
Dr. Smith's free-vehicle respirometer is launched from *Chain* with help from many hands.



Chain seaman Toby Lineaweaver keeps in shape by working out with punching bag.

PHOTOS BY VICKY BRISCOE

VICKY BRISCOE



Student Doug Biggs examines scuba-collected specimen as Senior Scientist John Teal, one of his advisors, looks over his shoulder aboard *Chain* in June.

Report of the Dean of Graduate Studies

Several important milestones were reached during the year in our educational programs. The first Ph.D's in Ocean Engineering and in Biological Oceanography were awarded. The year also saw the establishment of the Educational Assembly, a faculty-like organization designed to formalize the staff's role in setting educational policies.

The Educational Assembly for the first time provides a comprehensive framework within the Institution for the governance of educational activities. Prior to its establishment many of us had been keenly aware of the absence of a formal arrangement by which the staff collectively could decide upon the nature of our educational programs. This deficiency had also been emphasized by the 1974 visiting committees. Without an arrangement by which the staff responsible for the conduct of the programs can debate educational issues, arrive at a consensus and enforce the conclusions on themselves, many important questions must remain either unresolved or decided without exposure to general criticism. For example, the question as to what extent our graduate students should be expected to have knowledge about fields of oceanography outside their home departments requires common discussion and agreement.

The Educational Assembly was established by a charter approved by the Trustees. Some of the most important features of the charter are these:

— The Educational Assembly has both the authority and responsibility to regulate the Institution's educational programs. It does this as a legislative body chaired by the Dean.

— Membership is made up of the Resident Scientific Staff plus those others who have a responsibility in the conduct of educational programs. Voting membership is also provided for eight elected students. Total membership is about one hundred twenty-five.

— Because of the relatively large size of the Assembly most of the detailed and preparatory work is done by an elected Educational Council which operates as the Assembly's executive committee.

Since its formation in April 1975 the Educational Assembly has had two meetings, the first of which was largely organizational. The Educational Council met over a dozen times during the year, operating similarly to an internal visiting committee, in order to identify those educational problems most deserving the attention of the full Assembly. Issues which were addressed during the year include: staff policies on appointments and promotions as they are related to the educational programs; organizational matters, particularly the educational responsibilities of the departments; a possible Master's degree program or a special training program for foreign oceanographic personnel; future modifications to our engineering and biological programs.

The first motion on the agenda of the fall meeting of the Assembly is worth comment because it dealt with a question which has been a central one in the development of the graduate program at the Institution since 1968: namely, the role of education relative to research in the evaluation of a staff member's qualifications for promotion. This question was prominent in the minds of the Educational Council during the summer when they investigated departmental educational practices. Their findings contradicted some widely held assumptions. They found that "most scientific staff members do in fact participate in the graduate program, at least to the extent of providing research advice or serving on student advisory committees. (Only one person of the twenty-four promoted to Associate Scientist in the past four years has not participated.)" In addition, they found that the question of educational participation now explicitly enters the deliberations at times of reappointment and promotion and that there were several recent cases when the departmental chairmen felt that educational contributions "had a significantly positive effect on the outcome" of the promotion.

Although the Educational Council was gratified to find that promotional practices had recently become more supportive of the educational programs, they felt that the Institution's policies should be modified to reflect the actual practice. The first motion of the Assembly consequently recommended changing the Appointment Policies to read, "The Institution expects that members of the Resident Scientific Staff will participate in the educational programs." The previous language had used the word "encourages" instead of "expects." The motion proved controversial enough to provide a heavy attendance and a good debate for launching the Assembly. As it turned out the motion was heavily defeated, not because the Assembly objected to the practice of rewarding staff for educational efforts, but because the word "expects" had too strong a suggestion of coercion. While it is doubtful if future agendas can always attract such wide interest, the operation of the Assembly this first year suggests that it could well add an important new dimension to the life of the Institution.

In addition to the Graduate Program in oceanography, our other educational programs continued with vitality. The Marine Policy and Ocean Management Program conducted an interdisciplinary group study of the possible effects of offshore petroleum development on commercial fishermen off the East Coast. Two workshops were held in Woods Hole with fishermen and oilmen. Members of the study team visited the Gulf of Mexico, the North Sea and interviewed many government officials in the Federal agencies and in the affected states. A report from the study is expected to be issued in the spring of 1976.

The summer program on Geophysical Fluid Dynamics continued for the seventeenth consecutive summer. The topic concerned fluid motion in the earth's mantle and core.

The Postdoctoral Scholars Program, through which we bring promising young scientists to the Institution for independent study, was at a record level of ten scholars due to the addition of four special awards in aquaculture. These were made possible by a grant from the Jesse Smith Noyes Foundation.

We continue to receive large numbers of highly qualified applicants for our programs. For the Joint Graduate Program with M.I.T., we received 204 applicants (the same number as in 1974). From these we offered admission to thirty-two (16% of those applying) of which twenty-seven accepted (84%).

This year there were eighteen summer student fellows who worked with staff members on research projects. These were chosen competitively from 171 applications from students attending colleges and universities all over the country.

In one sense it is unfortunate (and certainly the selection process is painful) that we are forced to select so few from so many qualified applicants. On the other hand, we are not a classroom institution. The unique strength and quality of our program depends on our ability to have young people work in close association with scientists who can share with them the special experience of scientific research.

ROBERT W. MORSE

Massachusetts Institute of Technology/Woods Hole Oceanographic Institution

Joint Program in Oceanography/Ocean Engineering

DEGREE RECIPIENTS — 1975

Degree of Ocean Engineer

JAMES L. DURHAM
B.S., United States Naval Academy
Special Field: Ocean Engineering
Dissertation: *Analysis of a High Resolution Deep Ocean Acoustic Navigation System*

JOHN R. KREIDER
B.S., Lehigh University
Special Field: Ocean Engineering
Dissertation: *The Influence of Mean Stress and Notches on the Corrosion Fatigue Behaviour of a High Strength Aluminum Alloy*

PAUL F. SULLIVAN
B.S., United States Naval Academy
Special Field: Ocean Engineering
Dissertation: *Creep Buckling of Shells of Revolution Loaded Under Uniform External Pressure*

SUSAN SCHULTZ TAPSCOTT
B.S., Swarthmore College
Special Field: Ocean Engineering
Dissertation: *The Tangential Drag of an Axially Oscillating Cylinder*

Doctor of Philosophy

HARRY L. BRYDEN, JR.
B.A., Dartmouth College
Special Field: Physical Oceanography
Dissertation: *Momentum, Mass,Heat and Vorticity Balances from Oceanic Measurements of Current and Temperature*

KATHRYN A. BURNS
B.S., Michigan State University
Special Field: Biological Oceanography
Dissertation: *Distribution of Hydrocarbons in a Salt Water Marsh Ecosystem After an Oil Spill and Physiological Changes in Marsh Animals from the Polluted Environment*

RICHARD A. BURROUGHS
B.A., Princeton University
Special Field: Marine Geology
Dissertation: *The Structural and Sedimentological Evolution of the Somali Basin: Paleo-oceanographic Interpretations*

BRADFORD BUTMAN,
B.A., Cornell University
Special Field: Physical Oceanography
Dissertation: *On the Dynamics of Shallow Water Currents in Massachusetts Bay and on the New England Continental Shelf*

ROSS M. HENDRY
B.S., University of Waterloo
Special Field: Physical Oceanography
Dissertation: *The Generation, Energetics and Propagation of Internal Tides in the Western North Atlantic Ocean*

KUH KIM
B.S., Seoul National University
M.S., Seoul National University
Special Field: Physical Oceanography
Dissertation: *Instability and Energetics in a Baroclinic Ocean*

KEVIN D. LEAMAN
B.S., University of Michigan
Special Field: Physical Oceanography
Dissertation: *The Vertical Propagation of Inertial Waves in the Ocean*

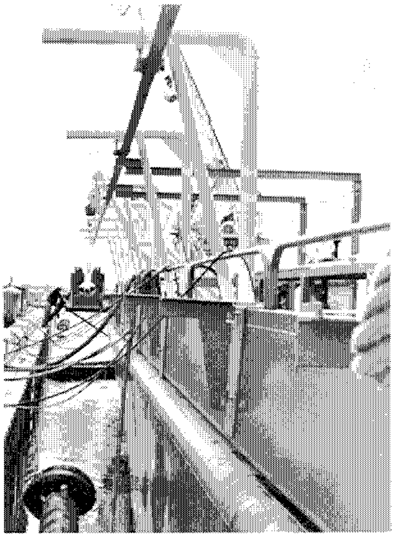
JEAN NICHOLS-DRISCOLL
B.A., Pomona College
Special Field: Biological Oceanography
Dissertation: *Transient Structure in Benthic Communities: The Effects of Oxygen Stress, Burial and High Rates of Sedimentation*

DANIEL H. STUERMER
B.A., University of California, Santa Barbara
Special Field: Chemical Oceanography
Dissertation: *The Characterization of Humic Substances in Seawater*

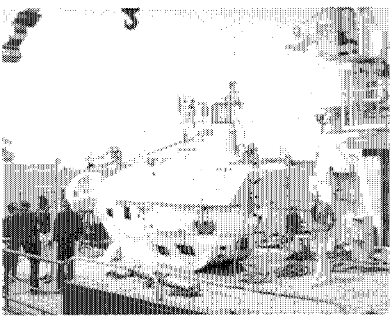
WILLIAM G. SUNDA
B.S., Lehigh University
Special Field: Chemical Oceanography
Dissertation: *The Relationship between Cupric Ion Activity and the Toxicity of Copper to Phytoplankton*

J. KIM VANDIVER
B.S., Harvey Mudd College
M.S., Massachusetts Institute of Technology
Special Field: Ocean Engineering
Dissertation: *Structural Evaluation of Fixed Offshore Platforms*

ROBERT A. YOUNG
B.S., Brooklyn College
Special Field: Marine Geology
Dissertation: *Flow and Sediment Properties Influencing Erosion of Fine-Grained Marine Sediments: Sea Floor and Laboratory Experiments*



FRANK MEDEIROS



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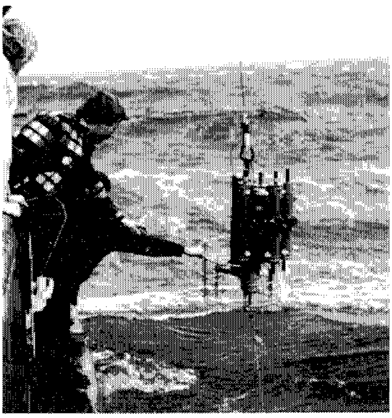


ROBERT MUNNS

FRANK MEDEIROS

Ashore and Afloat

Two distinguished speakers gave J. Seward Johnson Marine Policy Lectures this year. In March Dr. Dixy Lee Ray, former Chairman of the Atomic Energy Commission and then the first Assistant Secretary of State for Oceans and International Environmental and Scientific Affairs, discussed the current status of Law of the Sea negotiations, fishery and aquaculture work, possible energy sources from the sea, and the need for high-level scientific advice to the U.S. Government. In May Senator Ernest F. Hollings (D-S.C.), originator of the Coastal Zone Management Act of 1972 and Chairman of the Senate Commerce Committee's National Ocean Policy Study, spoke on "Federal vs. State Relationships in Coastal Zone Management and Offshore Oil Development".

Emperor Hirohito of Japan, who is a marine biologist specializing in hydroids, visited the Institution on October 4th. After a brief welcoming ceremony in the Redfield Auditorium, which included an introduction to ten of our Senior Scientists, the Emperor spent a half hour in Dr. Howard Sanders' laboratory examining and discussing Cephalocarida and Mystacocarida, both crustaceans of particular interest to him. He then paid a similar visit to the Marine Biological Laboratory.

On February 14th the Institution was host to 110 scientists and crew of the Russian Research Vessel *Akademik Kurchatov.* Conducted tours of the laboratories and dock facilities were made during the day, followed by dinner and folk singing in the evening. The 407-foot *Kurchatov,* too large to come to Woods Hole, was tied up at the Massachusetts Maritime Academy pier to take on oceanographic equipment and embark three Institution scientists for the next leg of her cruise.

Six scientists from the People's Republic of China were in Woods Hole October 6-7 to visit Institution, Marine Biological Laboratory and National Marine Fisheries Service scientists and facilities. The trip was part of a month-long tour of U.S. laboratories, universities and observatories sponsored by the National Academy of Sciences Committee on Scholarly Communication with the People's Republic of China.

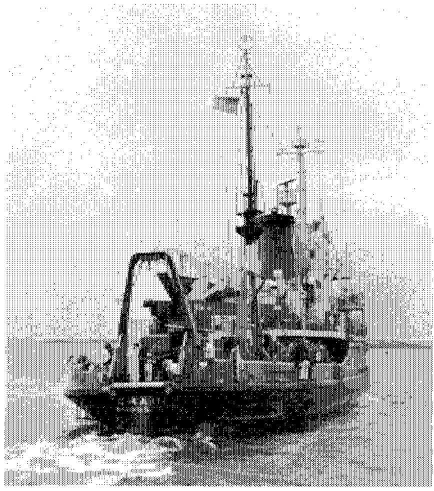
Following a recommendation of the Library Study Committee, a Research Librarian was added to the staff to serve as a liaison between the Institution and the M.B.L. Library to coordinate the Institution's library resources and to provide assistance to students and staff of the Institution. The M.B.L. Library which serves both M.B.L. and W.H.O.I. under a cooperative arrangement and other members of the scientific community is one of the best in the world in marine sciences. The holdings include 156,000 volumes, 250,000 reprints, and approximately 2,800 journals are received periodically. The Institution also maintains a technical report collection in the Document Library, a map and atlas collection in the Data Library, a specialized Marine Policy collection in Crowell House, and libraries on each of the research vessels. Computer-based information retrieval services are now offered through the office of the Research Librarian in the Clark Laboratory.

In the coming year, the Research Librarian plans to redefine the relationship between the library units; improve the services provided to the students and staff; upgrade the Marine Policy collection; coordinate the exchange arrangements with other institutions for our *Collected Reprints,* technical reports, and *Oceanus;* and assume the responsibility for the publication of *Collected Reprints.* At the present time the Institution sends 527 copies of *Collected Reprints* to research and educational institutions throughout the world and an additional 211 copies to institutions within the United States. Requests from institutions in the developing nations are increasing yearly and usually result in an exchange of publications.

A new organization, the East Coast Marine Science Librarians, was initiated by the Research Librarian. In October, a meeting of the librarians from 27 institutions and government agencies of the United States, Canada and Bermuda was sponsored by the Institution and M.B.L. Librarians. Common problems were identified and cooperative projects started. Another meeting is planned for 1976, this time to include librarians from Gulf Coast institutions.

The beginning of 1975 saw the Institution's three major vessels back at sea, following the economy layups of late 1974. During the year, the *Atlantis II, Chain* and *Knorr* logged almost 104,000 nautical miles while providing 924 days at sea for 803 scientists in our scientific programs (see Appendix IV). The *Atlantis II* operated mostly in the North Atlantic and Caribbean until she left in October on cruises leading to the South Atlantic. The end of the year found *Atlantis II* off Capetown on a prolonged voyage to the Indian Ocean and Australian waters, to return in mid-1977 via the Suez Canal and the Mediterranean. *Chain* was occupied in a five-month cruise to the Mediterranean and Black Seas and spent the second half of the year on shorter cruises in the western

FRANK MEDEIROS

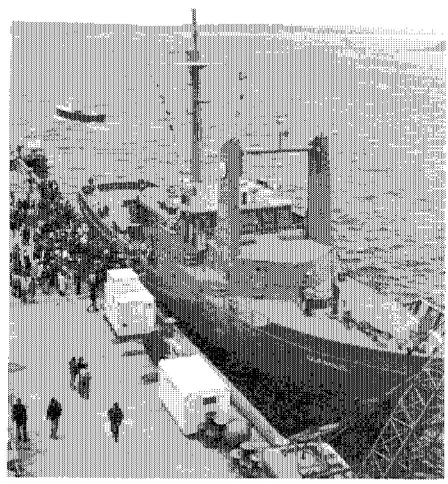


After a final buoy cruise in December of 1975, *R/V Chain* retired from the fleet, having sailed some 600,000 miles for oceanography.

North Atlantic. During the first half of 1975, *Knorr* worked in a large area of the western North Atlantic centered around Bermuda, followed by an extended voyage to the Azores, Iceland and Scotland. *Knorr* completed the year on shorter cruises to the western Atlantic and Sargasso Seas. As always, these voyages provided research opportunities for members of each of our scientific departments.

The research vessel *Chain* completed its 129th cruise on December 22, 1975, and was taken out of service on that day. The *Chain,* a Navy ARS salvage vessel, was delivered to Woods Hole on November 24, 1958, and completed a 6-day scientific cruise that year. Although our scientists had opportunities during 1958 and the previous year to work on the U.S. Coast Guard Ship *Yamacraw,* the *Chain* was the first large vessel available for our scientific investigations at sea. The spaciousness of the laboratories and of the quarters for scientists and crew were in marked contrast to the cramped conditions on *Atlantis* and *Crawford* and a host of other smaller vessels previously available for our oceanographic investigations. The *Chain* was made available

VICKY BRISCOE



In November of 1975, the new 177-foot *R/V Oceanus* was delivered to Woods Hole for final outfitting before embarking in 1976 on an oceanographic career.

through the efforts of the Office of Naval Research, and as stated in the 1958 Annual Report, it was needed because:

> *"It was found to be increasingly difficult to operate with reasonable efficiency on our small ships, particularly in studying the relationship between shallow temperature structures and sound transmission and in submarine geophysics. . . . Another limitation has been the small working space available on our ships for the increasingly complex apparatus of modern oceanography."*

The *Chain* represented a substantial advance in the capability of the Institution to conduct research at sea.

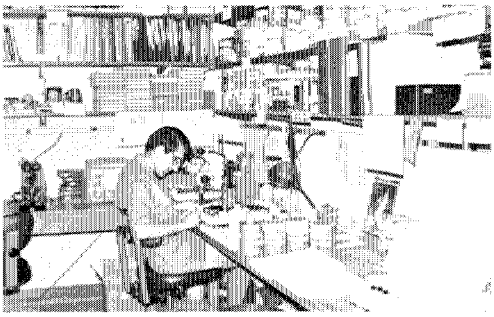
During nearly 18 years of service at Woods Hole, *Chain* logged 600,000 nautical miles and carried scientists to every ocean of the world, including a circumnavigation of the globe in 1970-71. A particularly sea-kindly and able vessel, *Chain* has been the favorite ship of many of our scientists who hope that useful years as an oceanographic vessel may still lie ahead.

The deactivation of *Chain* was offset by the delivery of the Institution's new ship, the *R/V Oceanus.* Built at Peterson Builders Shipyard in Sturgeon Bay, Wisconsin, under a grant from the National Science Foundation, *Oceanus* was christened on May 31, 1975, along with her sister ship, *R/V Wecoma,* built under the same grant for Oregon State University. Sponsor of the *Oceanus* is Louise Resley Stever, who presented the ship with a rare antique half model for the ship's library. The delivery voyage from Wisconsin to Woods Hole through the Great Lakes and St. Lawrence Seaway included chemical and biological observations, and thus is considered her first scientific cruise. The *Oceanus* arrived at Woods Hole on November 21st for full outfitting preparatory to commencing regular operations in April, 1976.

The Institution continued to operate the University-National Oceanographic Laboratory System (UNOLS) office on behalf of the major academic oceanographic laboratories in the United States. Many new and interesting scientists have been brought aboard our ships through UNOLS. They vary from individual students and investigators to complete scientific parties taking over entire cruises. Some of the larger groups included personnel from the National Oceanic and Atmospheric Administration (NOAA), the Navy's Advanced Research Projects Administration (ARPA), the U.S. Geological Survey, the University of Washington, and the State University of New York.

Foreign research vessels which tied up at the Institution pier during the year included the Russian *Poisk* and *Belogorsk,* the Polish *Wieczno* and the West German *Anton Dohrn.* All of these vessels were participating in cooperative research with the U.S. Marine Fisheries Service on behalf of the International Commission for the Northwest Atlantic Fisheries (ICNAF).

Research Assistant Linda Cole is at the microscope.

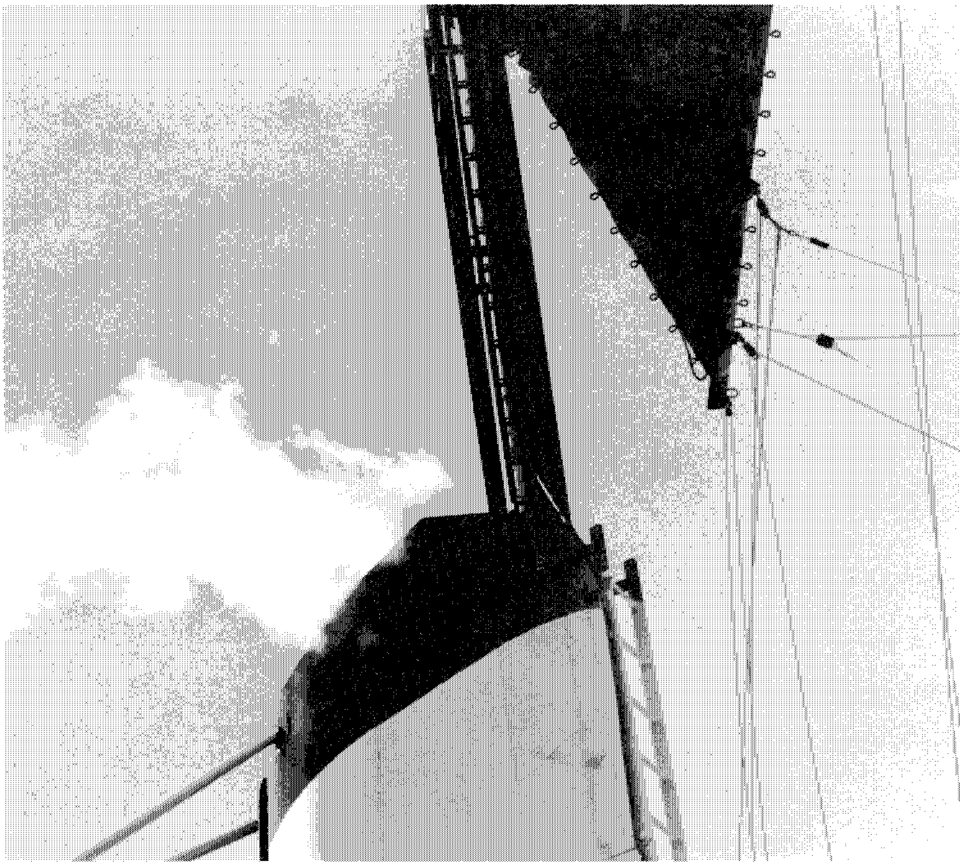


Associate Scientist Rudolf Scheltema sorts samples in his biology laboratory.

Associate Scientist Gil Rowe and student Nick Staresinic assemble otter trawl aboard *Chain*.

PHOTOS BY VICKY BRISCOE

Upper deck of *Atlantis II* is packed with deldrums for storage of large-volume water samples on chemistry cruise.



SUSAN FLETCHER

Alfred L. Loomis
4 November, 1887 — 11 August, 1975

Alfred Loomis was associated with the Institution throughout most of its existence. He had been a Member of the Corporation since 1932 and served as a Trustee from 1932 to 1935. He was elected an Honorary Member in June of 1974.

Dr. Loomis, most widely known as a physicist, graduated from Yale and later received his law degree from Harvard. Following World War I, he entered and was very successful in the investment banking business. During World War II, Dr. Loomis headed the research division of the United States Office of Scientific Research and Development and was a pioneer in developing radar and loran.

Following his business career, Dr. Loomis devoted himself entirely to scientific pursuits. He founded the Loomis Institute for Scientific Research and was director for thirteen years. He was a founder and trustee of the Rand Corporation, a Member of the Corporation of M.I.T. from 1931-1962, and a Life Member Emeritus and Trustee of the Carnegie Institution.

Dr. Loomis was a Member of the National Academy of Sciences, the American Association for the Advancement of Science, American Chemical Society, American Philosophical Society, Audio Engineering Society, Institute of Radio Engineers, American Astronomical Society and Royal Astronomical Society.

Detlev Wulf Bronk

13 August, 1897 — 17 November, 1975

Detlev Bronk had been a Member of the Woods Hole Oceanographic Institution Corporation since 1948. He served as a Trustee from 1963 until 1969. From 1965 to 1967 he served as member of the Trustees' Education Committee. In June of 1974, Dr. Bronk was designated an Honorary Member of the Corporation.

Dr. Bronk received his undergraduate education at Swarthmore and his Master's and Ph.D. at the University of Michigan, and was the recipient of over 100 honorary degrees. Dr. Bronk also served on the faculty of various universities, was past president of The Johns Hopkins University and Rockefeller Institute, the name of which he later changed to Rockefeller University. In 1968 he was appointed Chairman of the New York State Science and Technology Foundation. Other past positions were Coordinator of Research, Air Surgeons Office, Army Air Force; Director of the Johnson Research Foundation, University of Pennsylvania; Chairman of the National Research Council; President of the National Academy of Sciences; Chairman of the Board of the National Science Foundation; a member of the President's Science Advisory Board; and Chairman of the Panel on International Science.

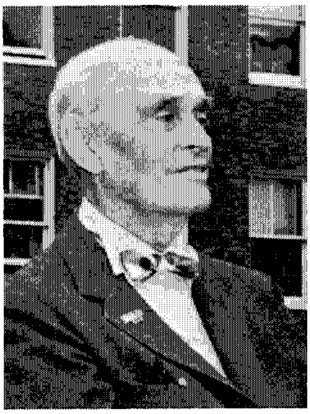
In addition to serving as a Corporation Member of the Institution and the Marine Biological Laboratory, he served as a Trustee of the Atoms for Peace Awards, Inc., Rensselaer Polytechnic Institute, Tulane University, University of Pennsylvania, Bucknell University, The Johns Hopkins University, the Population Council, the Protein Foundation, Rockefeller Brothers Fund, and Sloan-Kettering Institute. He was meticulous in his attendance to the affairs of the Institution and despite the intense competition for his time and effort, he was ever conscious of the Institution and its programs.

Sumner Tucker Pike

30 August, 1891 — 21 February, 1976

Sumner Pike, a Member of the Corporation since 1958 and an Associate since 1959, was a pioneer and early advocate of marine science. He was a graduate of Bowdoin College and following a distinguished career in business and government was awarded honorary Doctor of Laws degrees by both Bowdoin and Bates Colleges. His business career included senior management positions with Stone and Webster, Eastern Texas Electric Company, Equipment Sales Company, G. Amsinck and Company, Continental Insurance Company and Case Pomeroy and Company. In the early forties, he was Business Advisor to the U.S. Secretary of Commerce, a member of the temporary National Economy Committee, a Commissioner on the Securities and Exchange Commission, a Director of the Fuel Price Division, OPA. His more recent government positions also included five years as Chairman of the U.S. Atomic Energy Commission and Chairman of the Maine Public Utilities Commission. In 1959 he was a member of the Maine Legislature and chaired the Governor's Committee on Passamaquoddy Tidal Power.

During World War I, Dr. Pike served in the U.S. Coastal Artillery Command. In addition to serving as an overseer at Bowdoin, he also was a member of the American Association of Petroleum Geologists and the American Geographical Society. He was an early member of the National Academy of Sciences Committee on Oceanography, which for many years held its summer meeting at his fishing camp near Lubec, Maine. Dr. Pike was one of many Corporation Members who responded early in the 1970's and contributed generously to the Development Program.



Paul Lyman Hammond
16 December, 1882 - 5 May, 1976

Captain Paul Hammond, O.B.E. USNR (Ret.), our most senior Honorary Trustee and Corporation Member, began his very active interest in the Woods Hole Oceanographic Institution as an Associate in 1954, becoming a Life Associate in 1960.

Elected to the Corporation in 1958, he became an Honorary Trustee in 1966 and an Honorary Member in 1974. He served as Vice Chairman of the Trustees' Development Committee from its inception. Until recently when travel became difficult, he was a faithful attendee at Institution meetings and functions and continued his intense interest in Institution affairs until his death. Frequent correspondence and telephone calls to the Director and other members of the Directorate kept him continuously abreast of Institution activities ashore and afloat. Over the years he was instrumental in bringing several active members into the Corporation, and he contributed generously to the Institution in wisdom, advice and personal efforts.

Captain Hammond was born in Egypt, Massachusetts, and educated at Thayer Academy and at Harvard University. He was senior partner of Hammond, Kennedy & Co., Inc., private industrial bankers. He served in both World Wars as a Lieutenant Commander in 1917-1918 and as a Captain USNR 1940-1946. He received the Bronze Star with a citation for the development of anti-submarine weapons and rockets and also was decorated with the Order of the British Empire. He was a member of the Overseers Committee, Astronomy Department, Harvard University; a Director of the Whaling Museum Society in Cold Spring Harbor, Long Island; and on the Advisory Committee and the past treasurer of the U.S. Committee for the United Nations.

A very well-known yachtsman, he was the former owner of *Rara Avis* and in 1924 he won the King's Cup of the New York Yacht Club in *Iroquois II*, his yacht at that time. In the early twenties, he started the Herreshoff "S" class, owning *Spinster*, Number One in the large and successful fleet at the Seawanhaka-Corinthian Yacht Club. It is perhaps as the owner and skipper of the schooner *Nina* that Paul Hammond became best known to yachtsmen. In this remarkable yacht, built for him and Elihu Root, Jr., for the Transatlantic Race to Spain, he won the cup given by the Queen of Spain in 1928 after a close race of 23 days and 23 hours.

The Institution will miss this man of many interests and experiences who zealously devoted much of his time to the affairs and future of the Institution.

SUSAN FLETCHER

Tom Lyon adjusts antenna on crosstrees of *Atlantis II*.

VICKY BRISCOE

Atlantis II is moored to the Woods Hole pier as *Knorr* departs for October cruise.

Department of Physical Oceanography (continued)

C. GODFREY DAY, *Research Associate*
JEROME P. DEAN, *Research Associate*
GIFFORD C. EWING, *Senior Scientist, Emeritus*
NICHOLAS P. FOFONOFF, *Senior Scientist*
Gordon McKay Professor of the Practice of Physical Oceanography, Harvard University
FREDERICK C. FUGLISTER, *Senior Scientist, Emeritus*
ROBERT H. HEINMILLER, *Buoy Engineer*
NELSON G. HOGG, *Assistant Scientist*
TERRENCE M. JOYCE, *Assistant 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*
JAMES R. McCULLOUGH, *Instrument Engineer*
WILLIAM G. METCALF, *Associate Scientist*
ROBERT C. MILLARD, JR., *Research Associate*
ARTHUR R. MILLER, *Associate Scientist*
DONALD A. MOLLER, *Research Associate*
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*
PETER M. SAUNDERS, *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*
ROBERT J. STANLEY, *Research Associate*
HENRY M. STOMMEL, *Physical Oceanographer, non-resident*
Professor of Oceanography, Department of Meteorology, Massachusetts Institute of Technology
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, non-resident*
VALENTINE WORTHINGTON, Department Chairman, *Senior Scientist*

Postdoctoral Investigators in 1975

RICHARD P. BLAKEMORE (Chemistry)
YVES J.F. DESAUBIES (Physical Oceanography)
HENRY J.B. DICK (Geology and Geophysics)
NICHOLAS S. FISHER (Chemistry)
EDWIN F. FORD (Physical Oceanography)
HOWARD J. FREELAND (Physical Oceanography)
PAUL A. GILLESPIE (Biology)
LOREN R. HAURY (Biology)
CYNTHIA L. LEE (Chemistry)
CHRISTOPHER P. ONUF (Biology)
W. BRECHNER OWENS (Physical Oceanography)
JAMES D. SULLIVAN, JR. (Biology)

Departmental Assistants*

Department of Biology

Azarian, Debra M.
Bowker, Paul C.
Bowman, Pamela E.
Boyd, Steven H.
Cole, Linda M.
Davidson, John A.
Dennett, Mark R.
Ellis, Elaine M.
Garner-Price, Susan P.
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Kneale, Douglas C.
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Moore, Karen E.
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Peterson, Jane M.
Quinby, Helen L.
Rogers, Mary Dorothy
Sherman, Albert C.
Stanley, Helen I.
Volkmann, Suzanne B.
Williams, Isabelle P.

Department of Chemistry

Ball, Lary A.
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Tripp, Bruce W.
True, Mary B.

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Department of Geology and Geophysics

Allen, Ben G.
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Canning, Christine J.
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Dynan, Suzanne E.
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Riley, Anne S.
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Van Dyk, Barbara S.
Vermersch, Kathy J.
von der Heydt, Keith
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Whiteley, Lynn
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Wooding, Christine M.

Department of Ocean Engineering

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Barnes, Nancy M.
Bartlett, Arthur C.
Bento, Joseph, Jr.
Broderson, George deP.
Chute, Edward H.
Clay, Peter R.
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Connell, William L.
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Crook, Thomas
Curtis, Philip R.
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Doherty, Kenneth W.
Evans, Emily
Fairhurst, Kenneth D.
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Freund, William F., Jr.
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Gunderson, Allen C.
Gustavsson, James R.
Hampton, Carolyn S.
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Hollis, Ralph M.
Kennedy, Percy L., Jr.
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McCarthy, Jack W.
McElroy, Marguerite K.
McLeod, John W.
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Morton, Alfred W.
Muzzey, Charlotte A.
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Page, William F.
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Pires, Clara, Y.
Polloni, Christopher F.
Porteous, John
Reynolds, William A., Jr.
Rosenblad, Stanley G.
Sass, Warren J.
‡Shepard, George W.
Shultz, William S.
Simkins, Samuel T.
Stern, Margaret P.
Terry, William E.
Thayer, Robert J.
Vaillancourt, Dennis G.
Wing, Carleton R.
Woods, Donald E.

Department of Physical Oceanography

Armstrong, Harold C.
Bailey, Phyllis T.
Barbour, R. Lorraine
Bauchmann, Nancy J.
Breivogel, Barbara B.
Chaffee, Margaret A.
Chausse, Dolores H.
‡Daly, Kathleen
Dunlap, John H.
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Frazel, Robert E.
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Horn, William H.
Kelley, Michael D.
Knapp, George P., III
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Ostrom, William M.
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Reese, Mabel M.
Simoneau, R. David
Spencer, Ann
Stoecker, Leigh A.
Tarbell, Susan A.
Tupper, George H.
Valdes, James R.
Whitlatch, Ann W.
Whittemore, Harry B.
Williams, Audrey L.
Zemanovic, Marguerite E.

‡On Leave of Absence

FRANK MEDEIROS

Dr. Fye watches as the Emperor of Japan signs for Institution guest book during his early October visit to Woods Hole.

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HENRI O. BERTEAUX . . . . . Institution Staff Engineer
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WILLIAM O. RAINNIE, JR. . . . . . Supervisor of Planning & Construction
ELOISE M. SODERLAND . . . . . Executive Assistant/Physical Oceanography
THOMAS R. STETSON . . . . . Co-ordinator, Ocean Industries Program
L. HOYT WATSON . . . . . Executive Assistant/Associates Program
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CAROLYN P. WINN . . . . . Research Librarian
BERNARD L. ZENTZ . . . . . Personnel Manager

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Battee, Janice R.
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Berthel, Dorothy J.
Black, Earle N.
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Botelho, Linda J.
Bourne, Wallace T.
Bowman, Richard W.
Brauneis, Frederick A.
Breivogel, Richard J.
Brown, Norma H.
Burt, Sandra J.

†Deceased, 27 July, 1975.
*Full Time Employees.

†Cambell, Eleanor N.
Carlson, Gustaf A.
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Chalmers, Agnes C.
Charette, Ernest G.
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Martin, Olive
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Pineault, Florence T.
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Souza, Donald P.
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Sutcliffe, Thomas
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Tavares, William R., Jr.
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Vallesio, Barbara M.
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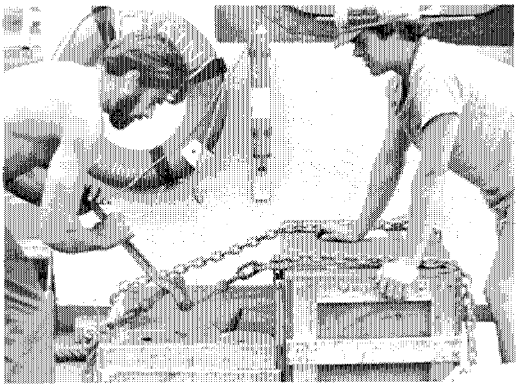
Wege, Jane P.
White, Haskel E.
Wildes, Nancy K.
Willert, Clarice S.
Williams, Ronald J.
Wing, Asa S.
Woods, Ronald E.
Woodward, Fred C., Jr.
Woodward, Martin C.
Woodward, Ruth F.
Young, Carleton F.
Zwinakis, Jeffrey A.

VICKY BRISCOE

Provost Art Maxwell visits *Lulu* amid last-minute preparations for spring cruise.

†Deceased, 22 October, 1975



Bosun Bill Moye, left, and seaman Toby Lineaweaver secure gear before a *Chain* cruise.

Dick Flegenheimer, left, master of *Lulu*, and Don Metzger, *Knorr* chief mate, chat at dockside.

PHOTOS BY VICKY BRISCOE

Marine Staff

DAVID F. CASILES	Master, R/V ATLANTIS II
RICHARD H. DIMMOCK	Port Engineer
RICHARD S. EDWARDS	Marine Superintendent
RICHARD C. FLEGENHEIMER	Master, R/V LULU
EMERSON H. HILLER	Master, R/V KNORR
JONATHAN LEIBY	Naval Architect
BARRETT H. McLAUGHLIN	Chief Engineer, R/V KNORR
PAUL R. MERCADO	Chief Engineer, R/V CHAIN
MICHAEL PALMIERI, JR.	Master, R/V CHAIN
JOHN F. PIKE	Port Captain
RAYMOND H. RIOUX	Chief Engineer, R/V ATLANTIS II
TREFTON A. SOUCY	Chief Engineer, R/V LULU

Marine Personnel

Babbitt, Herbert
Bailey, James A.
Baker, William R.
Bazner, Kenneth E.
Bizzozero, John P.
Bluestein, Keith
Bowen, Harold
Bradford, Thomas
Brady, George
Brennan, Edmund
Brennan, Edward J.
Brodrick, Edward R.
Bumer, John Q.
‡Butler, Dale
Clinton, Harry F.
Colburn, Arthur D., Jr.
Cotter, Jerome M.
Dawicki, Michael
Dunlap, George
Dunn, Arthur J.
Eident, William
‡Farnsworth, Donald C.
Flaherty, Peter M.
Fortes, Eugene B.
Frawley, J. Michael
Gassert, John M.
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Gould, Matthew
Hartke, David L.
Hayden, David
Howland, Paul C.
Huckabee, Walter
Hutchinson, John
Jefferson, Albert C.
Johnston, Alexander T.
La Casse, David
Leahy, James E.
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LeSueur, Jeffrey
Lineaweaver, Toby T.
Linscott, Kenneth
Lobo, John T.
Lobo, Wayne
Madison, William J., Jr.
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McAuliffe, J. Brian
Metzger, Donald J., Jr.
Moniz, Michael
Moye, William E.
Mulberry, William
Munns, Robert G.
Murphy, George E.
‡Murphy, William E.
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Ocampo, Conrad H.
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Sepanara, James M.
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Stack, William M.
Stanton, Harry
Sweet, John K., Jr.
Vestarhis, Michael
Vogel, Carl E.
Warecki, Joseph
Worthington, Lawrence

‡On Leave of Absence.

Fellows, Students, and Visitors

Doherty Professor

SIR EDWARD C. BULLARD
University of California, La Jolla

Rossby Fellow

ANGUS D. McEWAN (1974-75)
Commonwealth Scientific and Industrial Research Organization, Victoria, Australia

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Awardees 1975-76

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California Institute of Technology

DAVID M. NELSON
University of Alaska

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Jesse Smith Noyes Postdoctoral Fellows in Aquaculture

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Menai Bridge, United Kingdom

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University of Washington

Marine Policy and Ocean Management

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University of Rhode Island

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Northwestern School of Law at Lewis and Clark College

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Columbia University School of Law

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The Johns Hopkins University

RUSSELL L. WINNER
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Woods Hole Doctoral Program

1975-76 Academic Year

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PHILIP M. GSCHWEND
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PETER B. ORTNER
Yale University

M.I.T./W.H.O.I. Joint Graduate Program

1975-76 Academic Year

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MICHAEL P. BACON
Michigan State University

DOUGLAS C. BIGGS
Franklin & Marshall College

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University of British Columbia, Canada

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Brown University

JAMES R. BROOKS
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University of California, Los Angeles

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Harvey Mudd College

ALAIN COLIN DE VERDIERE
Ecole de Physique Chimie de Paris, France

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Massachusetts Institute of Technology

MICHAEL S. CONNOR
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University of California, San Diego

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CHARLES ERIKSEN
Harvard University

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University of New Orleans

CHARLES N. FLAGG
Massachusetts Institute of Technology

ROGER D. FLOOD
Massachusetts Institute of Technology

LEE-LEUNG FU
National Taiwan University

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Massachusetts Institute of Technology

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Carleton College

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University of Bristol, England

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DALE B. HAIDVOGEL
Massachusetts Institute of Technology

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Amherst College

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Brown University

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Wesleyan University

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University of Wisconsin

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Gettysburg College

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Massachusetts Institute of Technology

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University of California, Berkeley

PAUL W. MAY
Southern Missionary College

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Massachusetts Institute of Technology

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Northeastern University

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Florida State University, Tallahassee

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Rensselaer Polytechnic Institute

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Smith College

JAMES G. RICHMAN
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Rice University

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Massachusetts Institute of Technology

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Princeton University

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The Cooper Union

JOHN M. TOOLE
University of Maine

KEVIN M. ULMER
Williams College

GEORGE T. F. WONG
California State College

JOHN D. ZITTEL
Pennsylvania State University

Summer Student Fellows

DOUGLAS S. BROWN
Worcester Polytechnic Institute

SUKNAN SYLVIA CHANG
Yale University

G. KENT COLBATH
Oregon State University

PATRICIA J. COLBERG
North Dakota State University

Summer Student Fellows (Continued)

PATRICIA S. DEESE
Massachusetts Institute of Technology

SUZANNE DYKSTRA
University of California, Berkeley

GEORGE V. LAUDER
Harvard University

RICHARD LIMEBURNER
University of Massachusetts

NANCY S. MARKS
Williams College

PETER J. MICHAEL
Colgate University

THOMAS J. PALLONE
Massachusetts Institute of Technology

CLARE E. REIMERS
University of Virginia

MARK L. RIVERS
Harvard University

DEBBIE C. SCHACHTER
Massachusetts Institute of Technology

CHRISTOPHER R. SCOTESE
University of Chicago

ELLEN SIMPSON
Simmons College
University of Massachusetts

ANDREW B. WALKER
Washington and Jefferson College

Geophysical Fluid Dynamics Summer Seminar

Staff Members and Lecturers:

TANYA M. ATWATER
Massachusetts Institute of Technology

EDWARD R. BENTON
University of Colorado

FRIEDRICH H. BUSSE
University of California, Los Angeles

STEPHEN H. DAVIS
The Johns Hopkins University

DANIEL E. FITZJARRALD
NOAA, Boulder Colorado

HERBERT E. HUPPERT
Cambridge University, England

ANDREW P. INGERSOLL
California Institute of Technology

JOSEPH B. KELLER
Courant Institute of Mathematical Sciences

DAVID E. LOPER
Florida State University

WILLEM V. R. MALKUS
Massachusetts Institute of Technology

DAN P. McKENZIE
Cambridge University, England

PETER MOLNAR
Massachusetts Institute of Technology

ALAN C. NEWELL
Clarkson College of Technology, New York University

JOSEPH PEDLOSKY
University of Chicago

WILLIAM R. PELTIER
University of Toronto, Canada

MICHAEL PROCTOR
Cambridge University, England

PETER B. RHINES
Woods Hole Oceanographic Institution

KAY ANN ROBBINS
Massachusetts Institute of Technology

S. KEITH RUNCORN
University of Newcastle on Tyne, England

JOHN G. SCLATER
Massachusetts Institute of Technology

RONALD B. SMITH
University of Colorado

EDWARD A. SPIEGEL
Columbia University

MELVIN E. STERN
University of Rhode Island

STEVEN T. SUESS
NOAA, Boulder, Colorado

DONALD TURCOTTE
Cornell University

GEORGE VERONIS
Yale University

JOHN A. WHITEHEAD, JR.
Woods Hole Oceanographic Institution

Fellows:

PHILLIP COLELLA
University of California, Berkeley

WILLIAM A. FACINELLI
Yale University

KIRK S. HANSEN
University of Chicago

HOWARD C. HOUBEN
Cornell University

STEPHEN JONES
Cambridge University, England

MARK KOENIGSBERG
Massachusetts Institute of Technology

H. JAY MELOSH
California Institute of Technology

BARRY E. PARSONS
Massachusetts Institute of Technology

MASANORI SAITO
University of Tokyo

JOHN N. SKILBECK
Cambridge University, England

ALLEN M. WAXMAN
University of Michigan

Visiting Scholars

ALAN BERMAN
Department of the Navy

PIERRE E. BISCAYE
Lamont-Doherty Geological Observatory

ROBERT G. COLEMAN
U.S. Geological Survey

CHRISTOPHER GARRETT
Dalhousie University, Canada

EDWIN A. LINK
Harbor Branch Foundation, Inc.

HEINZ A. LOWENSTAM
California Institute of Technology

CHARLES R. O'MELIA
University of North Carolina

MICHAEL R. REEVE
University of Miami

GORDON A. RILEY
Dalhousie University, Canada

EDWARD O. WILSON
Harvard University

Visiting Investigators

STEPHEN C. DEXTER
Woods Hole Oceanographic Institution

ROGER HEKINIAN
Centre Oceanologique de Bretagne, Brest, France

IAN S. F. JONES
RAN Research Laboratory,
Edgecliff, New South Wales, Australia

LAURENT O. LABEYRIE
University of Paris, France

EDWARD L. MURPHY
SACLANT ASW Research Centre,
New York, New York

BRYCE PRINDLE
Babson Institute

MICHAEL A. SCHOENBERG
Tel-Aviv University, Israel

RENE P. SCHWARZENBACH
Institute of Organic Chemistry, Zurich, Switzerland

HERBERT H. UHLIG
Massachusetts Institute of Technology

JOHN B. WATERBURY
University of California, Berkeley

TIMOTHY C. WILLIAMS
State University of New York, Buffalo

Guest Investigators

RICHARD H. BROMUND
College of Wooster, Ohio

FRANCESCO BRUZZONE
Department of the Navy, Australia

KATHRYN BURNS
M.I.T./W.H.O.I.

RICHARD L. CHASE
University of British Columbia, Canada

RONALD B. COMEAU
University of New Hampshire

H. LEE DANTZLER, JR.
U.S. Naval Academy

DAVID A. DEESE
Tufts University

ROBERT S. DIETZ
National Oceanic & Atmospheric
Administration, Miami

DONALD L. DORSON
University of Rhode Island

JOHN P. DUGAN
Ocean Science Division, Naval Research Laboratory,
Washington, D.C.

ALBERT J. ERICKSON
University of Georgia

JOSE I. ESTEVEZ
Instituto Espanol De Oceanografia, Spain

MICHELE M. FIEUX
Museum d'Histoire Naturelle, Paris, France

GLENN R. FLIERL
Harvard University

LUCH FOMIN
Institute of Oceanology, Moscow, USSR

OLCOTT GATES
State University of New York at Fredonia

A. JANE GIBSON
Cornell University

QUENTIN H. GIBSON
Cornell University

YURI GRACHEV
Institute of Oceanology, Moscow, USSR

ROBERT GRIFFITH
Brooklyn College

DANIEL GUEVEL
Service Hydrographique et Oceanographique
de la Marine Paris, France

STEVEN J. HELLINGER
Massachusetts Institute of Technology

HERBERT E. HUPPERT
Cambridge University, England

PAUL A. KETCHUM
Oakland University, Rochester, Michigan

STUART L. KUPFERMAN
College of Marine Studies, University of Delaware

ELROY O. LaCASCE, JR.
Bowdoin College, Brunswick, ME.

T. G. METCALF
University of New Hampshire

ROBERT E. MOONEY
University of New Hampshire

KIYOSHI NAKAMURA
National Institute of Radiological Sciences, Japan

PETER NIILER
School of Oceanography, Oregon State University

THOMAS J. NOVITSKY
National Institute of Health, General Medical Sciences
Bethesda, Maryland

ANGELA J. ORREN
University of Cape Town, South Africa

MICHAEL J. ORREN
National Research Institute for Oceanology, South Africa

ISABELLA PREMOLI-SILVA
University of Milan, Italy

CARL A. PRICE
Rutgers University

GARY D. PRUDER
University of Delaware

JAMES G. QUINN
University of Rhode Island

T. C. S. RAO
National Institute of Oceanography, Goa, India

MAURICE REIFMAN
Essex County College

KONSTANTIN SABININ
Acoustical Institute, Moscow, USSR

GEORGE G. SHOR, JR.
Scripps Institution of Oceanography

KERWIN C. STOTZ
University of New Hampshire

HANS R. THIERSTEIN
Columbia University

SHIZUO TSUNOGAI
Hokkaido University, Japan

JANET M. WILLIAMS
State University of New York at Buffalo

WALTER ZENK
Institut für Meereskunde, Kiel, Germany

Guest Students

ABDULLAH ABU AL-SAUD
King Abdul Aziz University, Saudi Arabia

WILLIAM L. ACKERMAN
Massachusetts Institute of Technology

JAMES D. ALBERT
Ithaca College, N.Y.

ALISON S. AMENT
University of Pennsylvania

Guest Students (Continued)

GARY F. ANDERSON
Southampton College, N.Y.

ROBERT R. BALLARD
University of Pacific, California

JOHN J. BALLETTO, JR.
Bates College, Lewiston, Maine

BRUCE BYERS
Hampshire College, Amherst, MA

KATHARINE E. CALDWELL
Smith College, Northampton, MA

DEBORAH A. DION
University of Massachusetts, Amherst

LAWRENCE DRUCKER
University of Massachusetts

JAY C. ELLIS
U.S. Coast Guard Academy

JAMES O. FARLOW, JR.
Yale University

DOUGLAS E. FLUDDY
U.S. Coast Guard Academy

MARDI M. FORMAN
University of Massachusetts

THOMAS E. HAASE
U.S. Coast Guard Academy

MARGO G. HAYGOOD
Harvard College

THOMAS J. HIPP
University of North Carolina

JEFFREY K. KEENE
St. George's School, Newport, R.I.

PATTI ANNE KELLY
Lehman College

EDWARD A. LANE
U.S. Coast Guard Academy

DIANA LASSALLE
The Lenox School, New York, N.Y.

LAWRENCE A. LAWVER
Scripps Institution of Oceanography

SANG MYUNG LEE
Florida State University

VALERIE A. LEE
Bates College, Lewiston, Maine

VALERY E. LEE
Massachusetts Institute of Technology

THOMAS G. LEGARE
University of Massachusetts

MICHAL LIBNI
Hebrew University of Jerusalem

SANDRA E. LOCKE
University of Massachusetts

GLEN K. MAHONEY
University of Massachusetts

NANCY L. McDAVITT
Plymouth State College

R. SCOTT McKENZIE
Massachusetts Institute of Technology

DANIEL J. MORAST
University of Michigan

DOMINICK V. NINIVAGGI, II
Southampton College

T. M. PARCHURE
Poona University, India
(Special Student — U.N. Fellowship)

JEFFREY S. PARKIN
Southamptom College

JAN A. PECHENIK
Massachusetts Institute of Technology

JOSEPH F. PEPE
U.S. Coast Guard Academy

GEORGE H. PERRY
Southampton College

SUSAN M. QUINN
University of Massachusetts, Amherst

CRAIG A. RESNICK
Yale University

MICHAEL ROMAN
University of New Hampshire

MARY E. SANTOS
University of Massachusetts, Amherst

SERGIO R. SIGNORINI
Graduate School of Oceanography,
University of Rhode Island
(Special Student — U.N.E.S.C.O.)

PAMELA L. SMITH
University of California, Santa Cruz

JAMES W. STARK
U.S. Coast Guard Academy

PETER F. STRALEY
Middlebury College, Middlebury, Vermont

CLARE C. SWANGER
Wellesley College

PETER A. UNDERHILL
College of Marine Studies, University of Delaware

TERRY A. VIANCOUR
University of California, La Jolla

PHOTOS BY VICKY BRISCOE

Scuba divers prepare to leave *Chain* in Sargasso Sea for collection trip.

Postdoctoral scholar Bob Griffith displays *Chaulodius* (viperfish) taken in midwater trawl from *Chain*.

No. 3202 FREDERICK L. SAYLES, T.L. KU and PAUL C. BOWKER. The Chemistry of Ferromanganoan Sediment of the Bauer Deep. *Bull. Geol. Soc. Amer.*, 86(10): 1423-1431. 1975.

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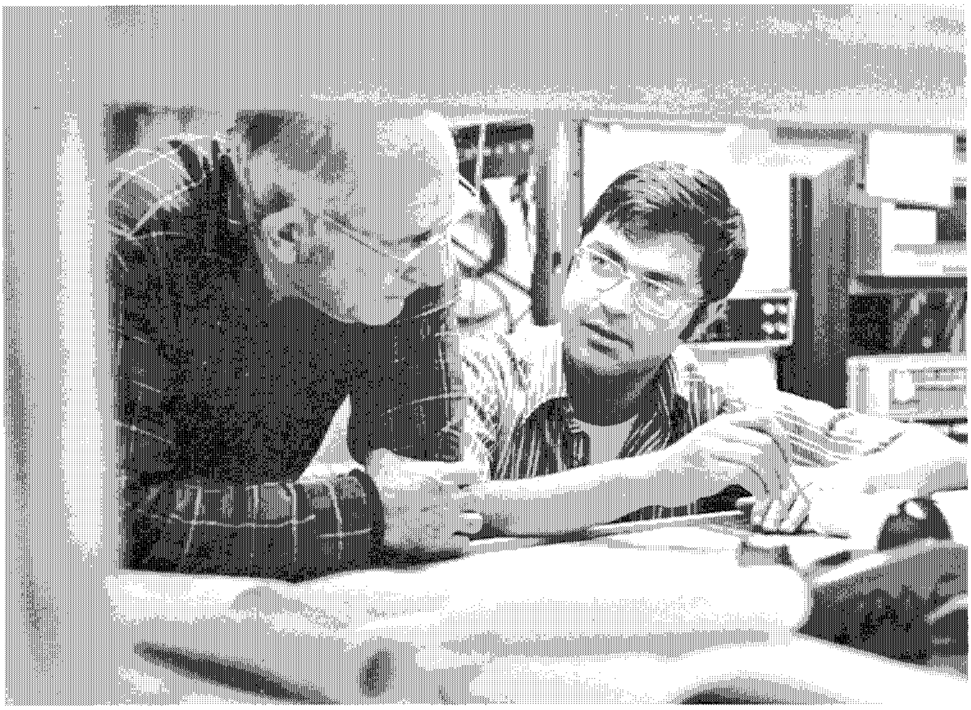

KEITH VON DER HEYDT

Bigelow Oceanographer K. O. Emery, left, and Dr. Arthur Baggeroer of MIT discuss data aboard *Atlantis II*.

VICKY BRISCOE

Senior Scientist Howard Sanders and Dr. Ruth Turner of Harvard were co-chief scientists for *Alvin/Lulu* cruise in August.

Voyage Statistics for 1975

Appendix IV

R/V ATLANTIS II

Total Nautical Miles for 1975 — 41,401

Voyage No.	*Depart*	*Arrive*	*Ports*		*Area of Operations*	*Chief Scientist*
86-Ia	4 Jan	11 Jan	Woods Hole	Cape Cod Canal	Gulf of Maine	Spencer
Ib	11 Jan	24 Jan	Cape Cod Canal	San Juan	Caribbean Sea	Burke
II	28 Jan	13 Feb	San Juan	Fort de France	and Atlantic Ocean	Bowen
	13 Feb	20 Feb	Fort de France	Puerto Sucre		
	20 Feb	22 Feb	Puerto Sucre	La Guaira		
	22 Feb	23 Feb	La Guaira	Willemstad		
	23 Feb	1 Mar	Willemstad	San Juan		
III	4 Mar	21 Mar	San Juan	Woods Hole	Bermuda & Hudson Canyon	Haedrich
87	26 Mar	9 Apr	Woods Hole	Woods Hole	Continental Shelf	Walsh
88	10 Apr	10 Apr	Woods Hole	New Bedford	To fuel dock	
	10 Apr	10 Apr	New Bedford	Woods Hole	and return	
89-I	13 Apr	14 Apr	Woods Hole	Woods Hole	Continental Shelf	Grow
	14 Apr	28 Apr	Woods Hole	Woods Hole		Grow
II	30 Apr	15 May	Woods Hole	Norfolk		Oldale
III	18 May	30 May	Norfolk	Woods Hole	Outer Shelf & Slope	Grow
IV	1 Jun	12 Jun	Woods Hole	Woods Hole	Baltimore Canyon	Knebel
90	12 Jun	13 Jun	Woods Hole	Staten Island	To shipyard	
	20 Jun	21 Jun	Staten Island	Woods Hole	and return	
91-I	7 Jul	7 Jul	Woods Hole	New Bedford		
	7 Jul	8 Jul	New Bedford	Woods Hole		Prada
	10 Jul	22 Jul	Woods Hole	Woods Hole	Southwest of	Prada
II	25 Jul	20 Aug	Woods Hole	Woods Hole	Georges Bank	Prada
92-I	23 Aug	24 Aug	Woods Hole	Earle		Purdy
	24 Aug	12 Sep	Earle	St. George's	Central Atlantic Ocean	
II	15 Sep	13 Oct	St. George's	Woods Hole	Mid Atlantic Ridge	Purdy
93-I	28 Oct	28 Oct	Woods Hole	New Bedford		Schouten
	28 Oct	15 Nov	New Bedford	Recife	Mid Atlantic Ridge	
II	18 Nov	18 Dec	Recife	Cape Town	and Brazilian Waters	Thompson
III	22 Dec		Cape Town			Farrington

R/V CHAIN

Total Nautical Miles for 1975 — 31,550

Voyage No.	*Depart*	*Arrive*	*Ports*		*Area of Operations*	*Chief Scientist*
118-I	21 Jan	2 Feb	Woods Hole	Gibraltar	Atlantic Ocean	Seaver
II	4 Feb	18 Feb	Gibraltar	Alexandria	Mediterranean Sea	Bryden
119-I	22 Feb	18 Mar	Alexandria	Alexandria	Nile Delta	Ross
II	22 Mar	11 Apr	Alexandria	Alexandria	Nile Delta	Summerhayes
120	15 Apr	18 Apr	Alexandria	Istanbul	Transit	Jannasch
	19 Apr	29 Apr	Istanbul	Istanbul	SW & Central Basin of Black Sea	Jannasch
121	3 May	18 May	Istanbul	Cadiz	Mediterranean Sea	Burke
122	23 May	23 May	Cadiz	Rota	Fuel Stop	Carpenter
	23 May	7 Jun	Rota	St. George's	North Atlantic	Carpenter
123	10 Jun	24 Jun	St. George's	Woods Hole	Gay Head-Bermuda Transit	Smith
124	1 Jul	16 Jul	Woods Hole	Woods Hole	Hudson Canyon	Haedrich
125	31 Jul	18 Aug	Woods Hole	Woods Hole	Sargasso Sea	Wiebe
126	22 Aug	3 Sep	Woods Hole	Woods Hole	Continental Shelf/ Sargasso Sea	Scheltema
127-I	8 Sep	1 Oct	Woods Hole	St. George's	Bermuda Waters	Spindel
II	4 Oct	26 Oct	St. George's	Woods Hole		Katz
128	1 Nov	25 Nov	Woods Hole	Woods Hole	South of Halifax	Stanbrough
129	3 Dec	23 Dec	Woods Hole	Woods Hole	East of Bermuda	Bradley

R/V KNORR

Total Nautical Miles for 1975 — 30,563

Voyage No.	*Depart*	*Arrive*	*Ports*		*Area of Operations*	*Chief Scientist*
45	7 Jan	8 Jan	Woods Hole	Brooklyn	To shipyard	
	11 Jan	12 Jan	Brooklyn	Woods Hole	and return	
46	24 Jan	30 Jan	Woods Hole	Woods Hole	Continental Shelf	Barvenik
47-I	4 Feb	18 Feb	Woods Hole	St. George's	New York	Farrington
II	21 Feb	3 Mar	St. George's	Woods Hole	Gay Head-Bermuda Transit	Smith
48-I	7 Mar	21 Mar	Woods Hole	St. George's	North Atlantic	Worthington
II	23 Mar	7 Apr	St. George's	St. George's		Worthington
III	9 Apr	16 Apr	St. George's	Woods Hole		Worthington
49	21 Apr	19 May	Woods Hole	Woods Hole	East of Bermuda	Schmitz
50	7 Jun	9 Jun	Woods Hole	Woods Hole	Continental Slope	Hollister
51-I	11 Jun	6 Jul	Woods Hole	Ponta Delgada	Labrador Sea	Spencer
II	9 Jul	3 Aug	Ponta Delgada	Reykjavik	Mid Atlantic Ridge	Hollister
III	6 Aug	6 Sep	Reykjavik	Glasgow		Hollister
IV	16 Sep	9 Oct	Glasgow	Woods Hole	North Atlantic	Brewer
52-I	15 Oct	28 Oct	Woods Hole	St. George's	Gulf Stream	Sanford
II	30 Oct	31 Oct	St. George's	St. George's		
	31 Oct	11 Nov	St. George's	Woods Hole		Sanford
53	14 Nov	2 Dec	Woods Hole	Woods Hole	Sargasso Sea and Gulf Stream	Wiebe

R/V LULU AND DSRV ALVIN

Total Nautical Miles for 1975 — 6,420

LULU Voyage No.	*Depart*	*Arrive*	*Ports*		*ALVIN Dives*	*Area of Operations*	*Chief Scientist*
75	11 Feb	13 Feb	Woods Hole	Woods Hole		Gay Head	Rowe
76	24 Mar	4 Apr	Woods Hole	Nassau		Transit to Nassau	
	5 Apr	5 Apr	Nassau	Andros		Transit to Andros	
	10 Apr	10 Apr	Andros	Andros	1	Tongue of the Ocean	Shumaker
	11 Apr	11 Apr	Andros	Andros	1		Shumaker
	14 Apr	14 Apr	Andros	Clifton Pier		Transit to Clifton Pier	Wirsen
	17 Apr	17 Apr	Clifton Pier	Clifton Pier	1	Tongue of the Ocean	Wirsen
	18 Apr	18 Apr	Clifton Pier	Clifton Pier	1		Wirsen
	19 Apr	19 Apr	Clifton Pier	Clifton Pier	1		Wirsen
	20 Apr	20 Apr	Clifton Pier	Andros	1		Garner
	22 Apr	23 Apr	Andros	Andros	1		James (U. of Newfoundland)
	25 Apr	26 Apr	Andros	Andros	2		James
	27 Apr	27 Apr	Andros	Andros	1		Schlager (U. of Miami)
	28 Apr	28 Apr	Andros	Andros	1		Staiger (U. of Miami)
	29 Apr	2 May	Andros	Andros	3		Staiger
	6 May	7 May	Andros	Andros	2		Shumaker
	8 May	9 May	Andros	Andros	1		Shumaker
	15 May	16 May	Andros	Andros	1		Adams (NUSE)
	16 May	16 May	Andros	Nassau		Transit to Nassau	
	17 May	26 May	Nassau	Charleston	5	Abaco Canyon	Keller (NOAA)
	29 May	8 Jun	Charleston	Woods Hole	1	Off Charleston, S.C.	Lee (U. of Miami)
77	23 Jun	1 Jul	Woods Hole	Woods Hole	4	South of Nantucket	Uzmann (N.M.F.S.)
78	8 Jul	16 Jul	Woods Hole	Woods Hole	3	WHOI Bottom Stations	Rowe
79	23 Jul	4 Aug	Woods Hole	Woods Hole	10	New York Dump Sites	Cohen (NOAA)
80	12 Aug	18 Aug	Woods Hole	Woods Hole	4	Hudson Canyon Area	Cacchione
81	29 Aug	8 Sep	Woods Hole	Woods Hole	7	WHOI Bottom Stations	Sanders
82	28 Oct	28 Nov	Woods Hole	Newport, RI		Transit to shipyard	
	5 Nov	5 Nov	Newport, RI	Woods Hole		and return	
83-I	11 Dec	19 Dec	Woods Hole	Miami, Fla.		Transit to Miami	

R/V OCEANUS

Total Nautical Miles for 1975 — 2,573

Voyage No.	*Depart*	*Arrive*	*Ports*		*Area of Operation*	*Chief Scientist*
1	28 Oct	21 Nov	Sturgeon Bay, Wis.	Woods Hole	Ship Delivery Great Lakes, Gulfs of St. Lawrence & Maine	Burke