
Oceanus
Volume 21, Number 3,

Oceanus®

The International Magazine of Marine Science

Volume 21, Number 3, Summer 1978

Published by Woods Hole Oceanographic Institution

The views expressed in *Oceanus* are those of the authors and do not necessarily reflect those of Woods Hole Oceanographic Institution.

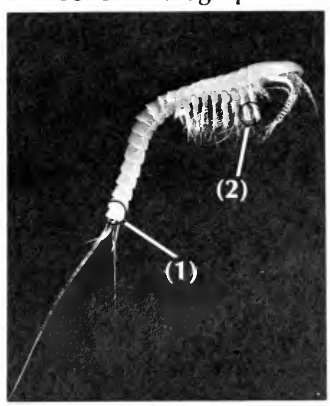
Editorial correspondence: *Oceanus,* Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Telephone (617) 548-1400.

Subscription correspondence: All subscriptions, single copy orders, and change-of-address information should be addressed to *Oceanus* Subscription Department, 1172 Commonwealth Avenue, Boston, Mass. 02134. Urgent subscription matters should be referred to our editorial office, listed above. Please make checks payable to Woods Hole Oceanographic Institution. Subscription rates: one year, $10; two years, $18. Subscribers outside the U.S. or Canada please add $2 *per year* handling charge; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Current copy price, $2.75; forty percent discount on current copy orders of five or more. When sending change of address, please include mailing label. Claims for missing numbers will not be honored later than 3 months after publication; foreign claims, 5 months. For information on back issues, see page 56.

Postmaster: Please send Form 3579 to *Oceanus,* Woods Hole, Massachusetts 02543.

Contents

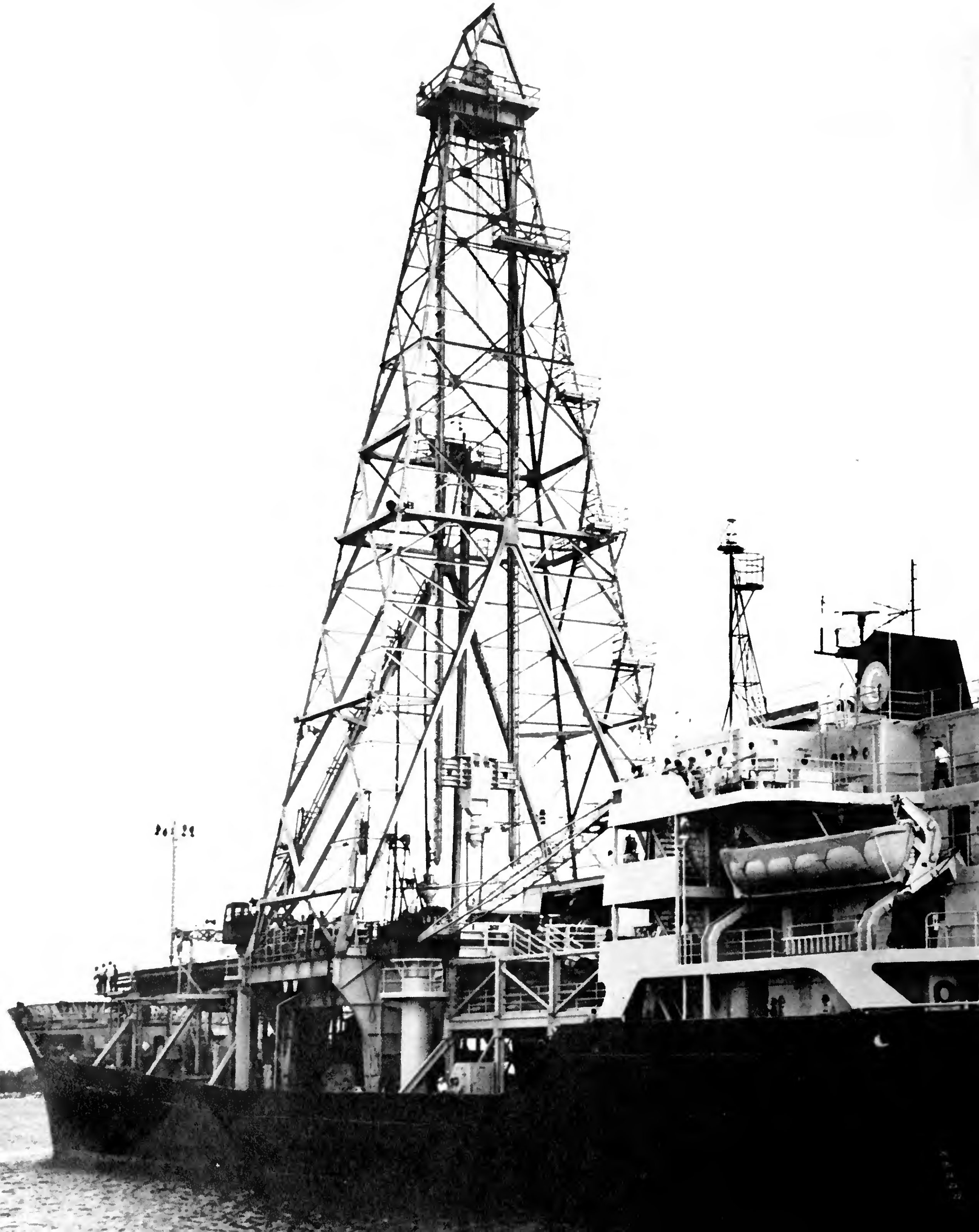
Cover Micrographs



FRONT COVER: Scanning electron micrograph of the comb-like spines (1) on a primitive crustacean, Cephalocarida *(picture of the animal above, adult size about 3 millimeters, was photographed from model at Smithsonian Institution – circles indicate areas of cover photographs). 4,000x. BACK: the tip of the tentacles (2) of the same animal. 500x. Cover photographs by Susumu Honjo (see article page 19).*

 Published quarterly by Woods Hole Oceanographic Institution, Woods Hole, Massachusetts 02543. Second-class postage paid at Falmouth, Massachusetts, and additional mailing points.

The Future of



Deep-Ocean Drilling

by J. R. Heirtzler and A. E. Maxwell

The International Program of Ocean Drilling (IPOD) — a joint research effort that has just completed a decade of important work — is at a critical juncture in its development. The marine scientific community is pausing to assess the many accomplishments of the program as well as objectives not obtained. In short, it is trying to determine whether drilling should continue, and if so, how and at what cost. Among the significant results of the program — which has been compared in importance with the first Challenger Expedition (1872-1876) that ushered in modern oceanography — have been data that support the theory of sea-floor spreading or plate tectonics, and indications of oil and metal deposits in the sediments at various coring sites. In addition, important information has been gathered relating to past climate periods — for example, it has been established that Antarctic glaciation has lasted more than 20 million years, or more than four times the age previously accepted. But the *Glomar Challenger* — the ship specially built for the project that has been used to drill more than 703 holes at 466 sites (as of Leg 61), along with sampling, measuring, and charting that has filled 42 volumes with data on underwater structure and sediment and basement rock composition — is generally felt not adequate to meet the deeper and more demanding drilling of the 1980s. And so thought is turning to use of a larger vessel — probably the salvage ship *Glomar Explorer* — to conduct the major drilling efforts of the next decade (Figure 1). Thus it is appropriate here to review the early years of the program, addressing the questions relevant to its future direction.

When the IPOD was implemented under its original name of Deep Sea Drilling Project (DSDP), its goals were to obtain samples of sediments from the world's ocean basins, and in the process, hopefully provide evidence to support the newly proposed plate tectonic or sea-floor spreading theory (see *Oceanus*, Winter 1974). On the early cruises of the *Glomar Challenger*, fossil-laden

The Glomar Challenger *— a 10,500-ton vessel, 400 feet long, with a beam of 65 feet and a loaded draft of 20 feet. The drilling derrick stands 194 feet above the waterline. She is owned by Global Marine of Los Angeles, California.*

sediment cores tended to support the theory, convincing many land geologists, stratigraphers, and micropaleontologists who had been hitherto wary of the idea. In the course of collecting and analyzing core sediments, much was learned about the processes inherent in ocean basin development, the structure and composition of the oceanic crust, and the age and history of the earth.

In fact, a major discovery occurred on the first voyage to the Gulf of Mexico: oil was found in sediment cores brought up from about 180 meters below the ocean floor. On later cruises, traces of hard minerals — iron, copper, chromium, and vanadium — were found. These discoveries have obvious significance as possible future energy and mineral sources. On the 13th cruise in 1970, another startling discovery was made. Salt deposits found in core samples, along with other data, led oceanographers to theorize that the Mediterranean six million years ago was not a sea, but a desert. But this was just the beginning: the data continued to accumulate, giving rise to several new concepts.

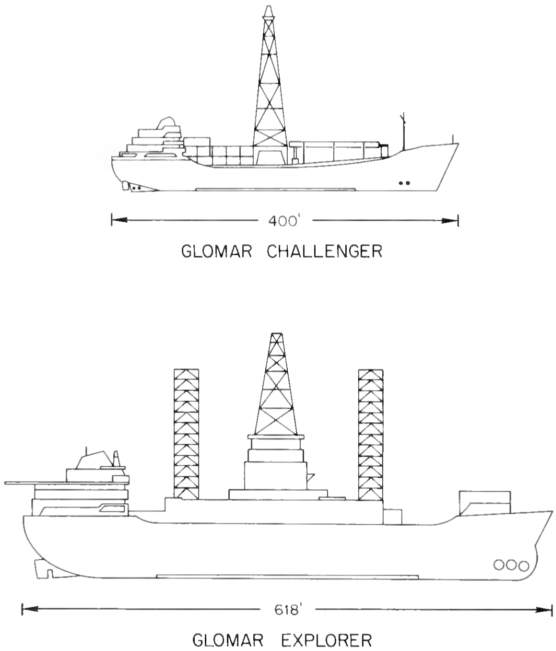


Figure 1. The Glomar Explorer *can handle more than 10 kilometers of drill pipe in contrast to the 7.6 kilometers for the* Glomar Challenger. *In addition, the* Explorer *can operate in waves that are 12 meters high and in winds of 65 knots, as well as in ice-covered polar seas. It is too large, however, to pass under bridges or to go through the Panama Canal.*

Deep-Sea Drilling as a Scientific Tool

It may not be immediately apparent that the processes that form the sea floor are more orderly and simple than those that shape and form the dry land. However, that is apparently the case. Since complex atmospheric forces have not disturbed it and man has not been there to change it artificially, the ocean floor geologic formations can be decoded to determine the earth's history.

During the last 50 years, the ocean floor has been studied with remote acoustic sensing equipment, with bottom instruments on cables, and with short corers that penetrate a few meters into the bottom. All of these provided a first impression of the nature of the ocean bottom/ocean water interface as it now exists.

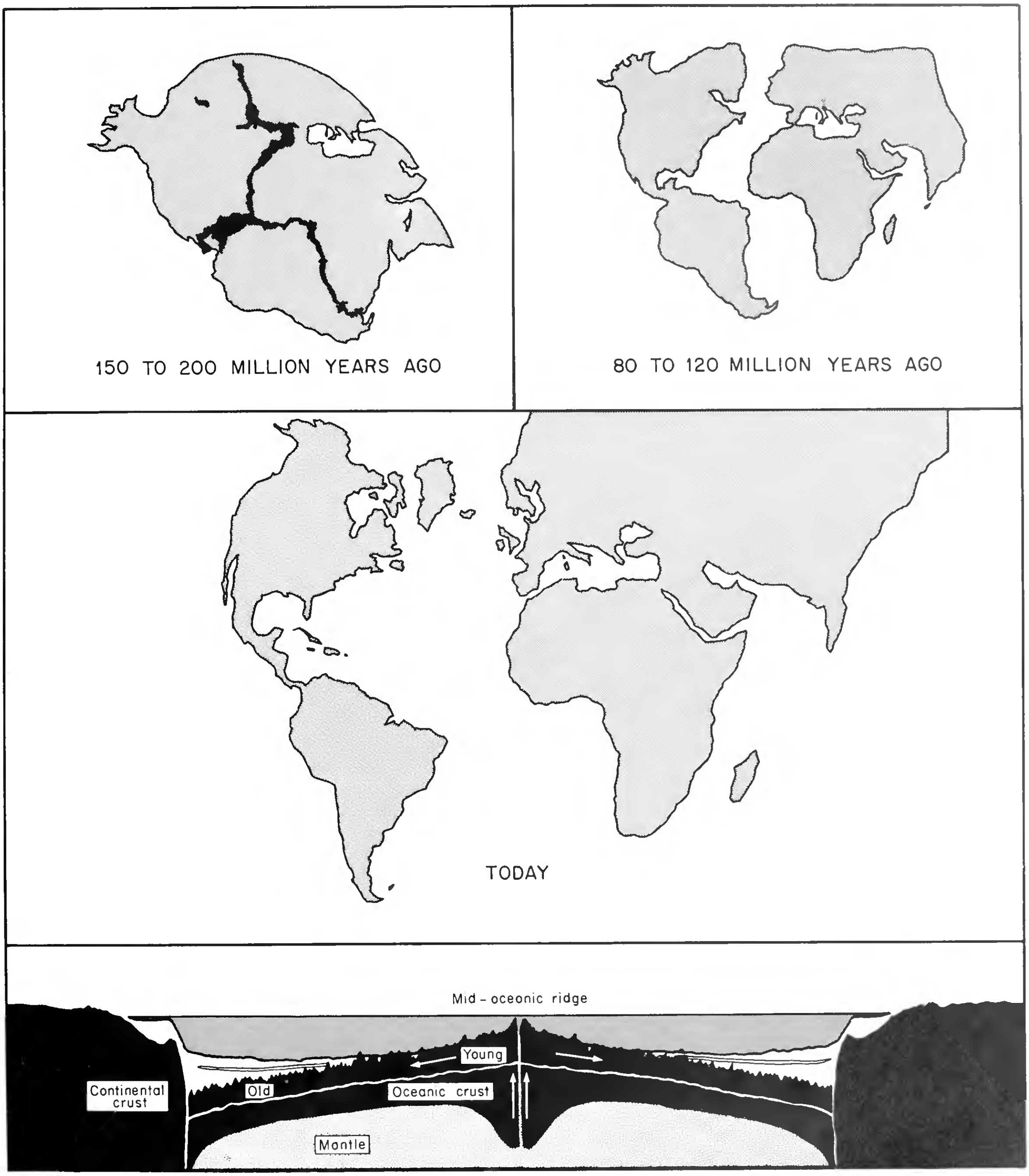
In some places, the ocean floor is eroded, revealing older sediments, but if one really wants information on the nature of the bottom, such as underlying rock formation, drilling is required. Drilling on the continental shelf in water depths of 200 meters or less has been undertaken by oil companies since the 1940s, but drilling in thousands of meters of water has only been attempted recently.

Deep-sea drilling began with Project Mohole, proposed in 1957 as an attempt to drill to the Mohorovičić discontinuity, which represents the boundary between the earth's crust and mantle. The project, funded by the National Science Foundation in 1961, drilled off the California coast, penetrating 300 meters of sediment in 1,000 meters of water. In later drilling off Guadalupe Island, samples of basaltic basement rock were recovered from under 183 meters of sediment in 3,570 meters of water. This represented the first successful attempt to explore the sea floor, utilizing deep-sea drilling techniques.

While in the process of choosing a site to drill to "Moho" northeast of Hawaii in 1966, the U.S. Congress discontinued funding for the project because of escalating costs. At this point, $25 million had been spent, and it was estimated that another $100 million would be needed to complete the job. Despite its early demise, the project produced technical developments that later proved useful to the Deep Sea Drilling Project as well as the offshore oil industry.

Two years prior to the Congressional action on Project Mohole, an organization was established called the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES). In 1965, this organization drilled 14 holes in the Blake Plateau — a large bottom feature off the southeast coast of the United States (see *Oceanus*, Winter, 1978). The success of this venture, undertaken at less cost than Project Mohole combined with the potential for significant scientific returns, was one of the chief factors that led the National Science Foundation to back the Deep Sea Drilling Project formally proposed by JOIDES in 1966. The *Glomar Challenger* was then ordered from Global Marine,

Continental Drift and Sea-Floor Spreading



The Deep Sea Drilling Project core results have provided support for the concepts of continental drift and sea-floor spreading. Note above the jigsaw puzzle fit that can be made of the Atlantic coastlines of Africa and South America. In 1885, Eduard Suess suggested that all the southern continents had once been joined as a supercontinent that he called "Gonwanaland." Some 30 years later it was proposed that there had been two continental masses, Laurasia in the north and Gonwanaland in the south. Over the years, however, many scientists remained skeptical because of a lack of clear-cut evidence. Supporting evidence for the continental drift theories began to emerge in the 1950s and 1960s with the discovery of rocks in Brazil that nearly matched others found in Gabon, West Africa. About the same time, sedimentary rocks, about 200 million years old, were found in Antarctica that contained fossil amphibians and reptiles found in other Gonwanaland continents. One of the problems with the continental drift concept was that no one had determined a reasonable mechanism for the movement of the continents. Thus the theory of sea-floor spreading (above) and plate tectonics emerged. Volcanic material is brought up in the center of the ridge, cools, and is forced away on either side by newer lava rising along the rift. The older crust is forced down again into the mantle in the deep oceanic trenches where it becomes part of a plate system. These plates are in motion relative to one another, either slowly moving apart with the creation of new crust, moving together with the destruction of old crust, or moving past one another.

Inc., beginning her first cruise in the Gulf of Mexico in July, 1968.

The JOIDES group initially consisted of four oceanographic institutions — the Lamont Geological Observatory of Columbia University (now Lamont-Doherty), the Institute of Marine Science of the University of Miami (now the Rosenstiel School of Marine and Atmospheric Science), the Scripps Institution of Oceanography of the University of California, and the Woods Hole Oceanographic Institution. Later, five more U.S. institutions were added — the departments of oceanography at the University of Rhode Island, the University of Washington, Oregon State University, and Texas A & M, and the Institute of Geophysics at the University of Hawaii. In 1974, the project became an international one when the Soviet Union, West Germany, France, Britain, and Japan signed up, each making a direct contribution of $1 million a year, plus much larger indirect ones. Beginning in November 1975, the DSDP was renamed the International Program of Ocean Drilling (IPOD). The title DSDP, however, was retained to identify the Scripps portion of the operations.

In 1976, the member institutions from the United States incorporated to form Joint Oceanographic Institutions (JOI). This was done to allow the group to enter into formal contracts with the government in connection with the program. JOIDES, including its foreign members, continued as a subgroup of JOI.

The Project

The funding, organization, and operation of this program is an interesting example of a joint international research effort. Financial contributions from foreign members are received at the National Science Foundation, where the funds are added to the U.S. contribution. Utilizing this international funding base, the NSF contracts with the DSDP office at Scripps for the ship operation, preparation of initial reports, and core repositories. The funds are also used to support the JOIDES advisory structure through a contract with JOI. However, each country separately funds surveys of proposed drill sites and the post-cruise study of samples.

The JOIDES advisory group consists of 250 members, who make up 23 committees and panels. This body drafts the scientific part of the IPOD proposals, defining drill ship objectives on each leg. It also appoints special committees, recommends sites to be surveyed and reviews safety factors, works out the drill ship schedule and provides for cruise staffing, recommends purchase of scientific equipment and special studies of samples, and oversees initial reports and matters relating to the curation of samples. While this may give the impression of administrative bureaucracy,

Table 1. Record as of Leg 60, May 1978.

1. **Completed 60 cruises of two months' duration in all oceans except the Arctic.**
2. **Drilled a total of 196,652 meters below sea floor at 466 sites (703 holes).**
3. **At single locations, penetration up to 1,741 meters of sediment, 700 meters of basaltic basement rock.**
4. **Longest drill string used 7,060 meters.**
5. **Recovered a total of 54,408 meters of cores, stored in two repositories.**
6. **More than 800 scientists have requested more than 90,000 samples.**
7. **More than 480 scientists have participated in *Glomar Challenger* cruises.**
8. **Forty-two volumes of initial reports have been published, deposited in 393 libraries worldwide.**

academic marine scientists rate this project (according to a recent study conducted by the University of Connecticut) first in quality of all marine geological and geophysical work funded by Federal funding agencies. Table 1 lists some of its accomplishments.

Few geological scientists doubt the success of the past decade of drilling, nor would they probably quarrel about the cost. However, the future requires a basic reappraisal. Among the questions that need to be answered are: Have the scientific results been worth the investment? Are future scientific achievements through continued drilling likely to provide significant advancement of the knowledge of the sea floor? Is present drilling technology adequate to meet future scientific requirements? What will the costs be? What priority does scientific drilling merit? These and similar questions must be answered by the scientific community to the satisfaction of government officials before any decision will be made about future drilling. Past successes have heavily depended on the availability of geological and geophysical information that was collected over many years in all areas of the oceans. These data allowed scientists to formulate many hypotheses concerning the age, structure, and history of the sea floor. Subsequent drilling data permitted geophysical measurements to be correlated with geological reality, thus confirming or modifying the earlier hypotheses. However, this reservoir of data has been virtually consumed during the decade. Therefore, future studies must give high priority to gathering new geophysical and geological data. With additional geophysical information, specific scientific objectives can be defined that can be only resolved by drilling (Figure 2).

A meeting was convened by JOIDES at Woods Hole, Massachusetts, in March, 1977, to identify more clearly the need and priorities for future deep-sea drilling and to assess new drilling technology. Participants included scientists from JOIDES and non-JOIDES institutions, representatives from industry and government, and members of foreign governments and institutions. At the meeting, scientific objectives were listed under four topics: passive margin, active margin, ocean crust, and paleoenvironment. It was stressed that drilling itself was not the objective, but merely a means to an end — that future drilling should attempt to solve specific scientific problems. In addition, the meeting determined that many future objectives would be unattainable using the *Glomar Challenger.* For example, the ship does not have the capability of handling riser pipe, thus providing for return circulation; or setting blowout preventors, essential when drilling in areas of potential hydrocarbon accumulation; or working in high latitudes with ice cover. In examining other available drilling ships, including those operated by industry, the meeting recommended that the government-owned *Glomar Explorer* be converted and used for drilling (Figure 1). The *Explorer,* 187 meters in length with a displacement nearly five times that of the *Challenger,* has a significantly better capability; it can handle about 4,000 meters of riser, has blowout prevention equipment, and can suspend nearly 12,000 meters of drilling pipe, compared with a maximum of 7,600 meters now possible with the *Challenger* (Figure 3). The *Explorer* also can be easily strengthened to work at anticipated sites in the South Atlantic that have ice conditions.

Participants at the meeting also recommended several alternative drilling programs for the future, which included various combinations of *Challenger* and *Explorer* drilling. For an optimum scientific program, it was suggested that the *Challenger* continue to drill through 1983, overlapping with an *Explorer* program, running from 1981 through 1987. In addition, the meeting recommended strong geophysical and sample analysis programs. The group stressed that continued drilling was dependent upon adequate support in this area. The estimated total cost of such a program was $396 million, excluding inflation and *Explorer* conversion costs estimated at $52 million.

The recommendations of the meeting at Woods Hole were subsequently approved and published by JOIDES in a document entitled "The Future of Scientific Ocean Drilling," which will serve as the basis for future planning. This has set the stage for a much broader evaluation of the program. The National Science Foundation has established scientific and engineering review panels. Similarly, there are committees within the National Academy of Sciences that are examining the program with a view to other scientific priorities. When these reviews are complete, their recommendations likely will be key factors in decisions relating to any future drilling.

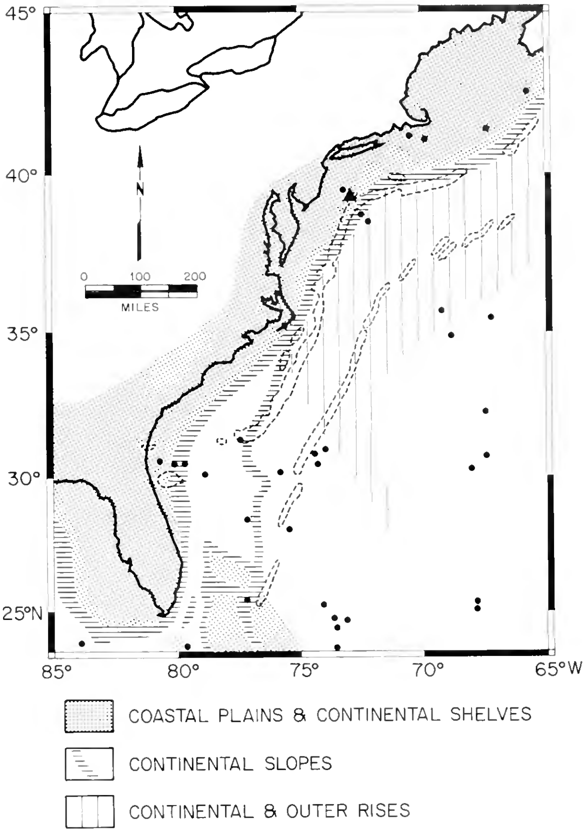


Figure 2. Continental shelves, slopes, and rises off eastern North America. Other plateaus, rises, and abyssal plains are unshaded. Dots indicate holes drilled in the area. The triangle is where six companies are now drilling for oil and gas off New Jersey. Elongated dashed areas represent the East Coast Magnetic Anomaly (toward the west) and the Blake Spur Magnetic Anomaly (toward the east). The edge of the North American continent is thought to lie somewhere between these two anomalies. (After K. O. Emery, in preparation)

The review process, too, will extend to other bodies beyond just the scientific community. A reappraisal of costs based on the Woods Hole recommendations puts a more realistic price tag on the program — $693 million in 1978 dollars, escalated at 7 percent per year for the period 1979 to 1988. Averaging out at about $70 million per year, this represents more than 75 percent of the present combined earth and ocean sciences research budgets of the National Science Foundation, or about 10 percent of the entire Foundation budget. The program thus requires new funds so as not to squeeze out other research programs. Consequently, the Office of Science and Technology Policy, the Office of Management and

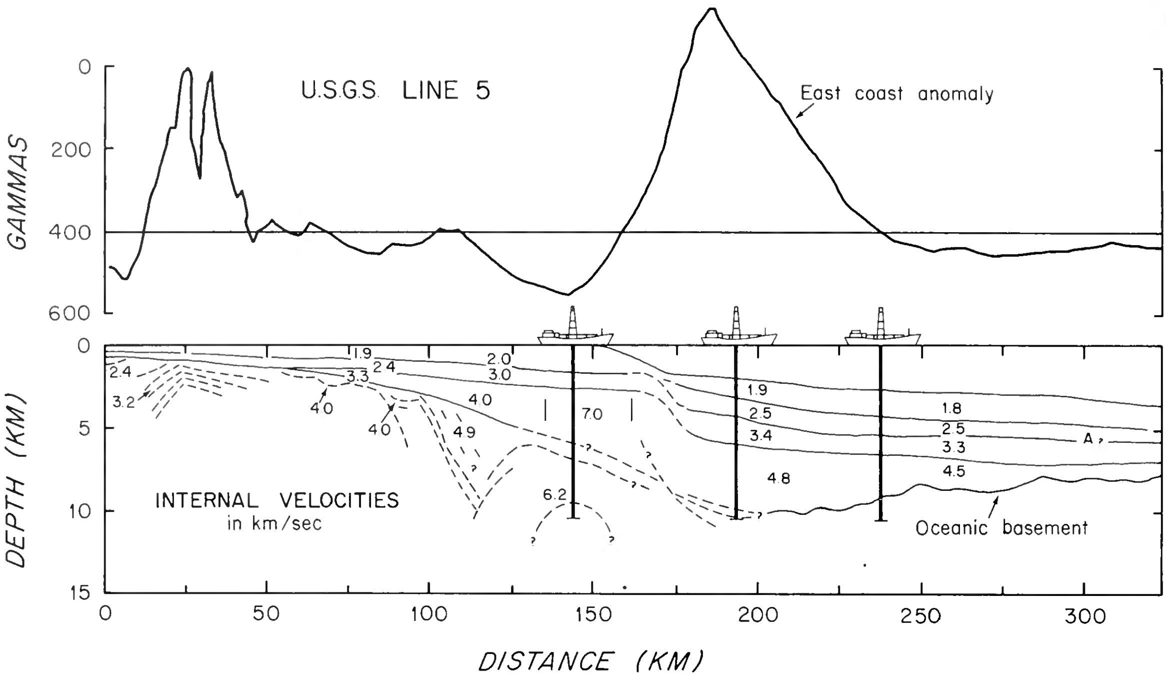


Figure 3. Geophysical profiles across the continental shelf, slope, and rise southeast from Cape Cod. Drilling with an Explorer-type vessel could reach structures down to 10 kilometers.

Budget, and the Congress all have begun their own investigations into the merits of the program.

Scientific Results Thus Far

The scientific accomplishments of the past decade of drilling fall under the topics of passive margins, active margins, ocean paleoenvironment, ocean crust, and downhole measurements.

Passive Margins

Passive continental margins are those where there is no spreading motion between the ocean and the adjoining continent. They are distinct from active margins, where the ocean floor goes under the continent, causing deep-sea trenches, earthquakes, and volcanoes. Both the North and South Atlantic margins are examples of passive margins. The North Atlantic margins are believed to have been created when a protocontinent rifted (split) and then spread about 180 million years ago.

The purpose of drilling on the passive continental margins is to determine how this initial rifting and spreading occurred and to understand the subsequent hiatuses in sediment deposition caused by climate, ocean circulation, sea-level changes, and the geology of the adjacent continents. Holes have been drilled in the Atlantic off eastern North America, Africa, the European continent near the Bay of Biscay, and the Rockall Plateau. The results were especially valuable where the sediments were thin and prograding (advancing on) the continent/ocean boundary. An example is on the Rockall Plateau, where we found evidence of subaerial (above sea level) relief during rifting. Lower Miocene hiatuses found on the Rockall Plateau (see *Oceanus,* Winter 1978) and in the Bay of Biscay correlate with deep boundary current seawater overflowing the Iceland-Faeroes Ridge. In both these drill sites, the carbonate content of the sediments relates to worldwide changes in the calcium carbonate compensation depth (the level below which the rate of calcium carbonate solution exceeds the rate of calcium carbonate deposition) and to transgressions and regressions on land.

Off northwest Africa and the eastern United States, the sediments are thicker than off Rockall and Biscay, frequently in excess of 10 kilometers near the continental margins. Because the *Glomar Challenger* does not have blowout prevention equipment, that ship cannot drill on the continental shelf, which contains thick sediment basins probably formed during rifting and initial spreading. On both sides of the North and South Atlantic, these areas are being drilled by petroleum companies. The *Challenger* has drilled on the outer continental margin and found rich organic layers. The possibility of petroleum deposits on the outer margin and beyond is thought to be good.

Active Margins

The drilling of active margin sites is a relatively recent activity. It requires a longer drill string for the greater depths of water found near the active trenches and margins. The sediment found on the landward side of the trenches is also of greater thickness.

The first major active margin drilling occurred in late 1977 in a traverse across the Japan Trench east of the island of Honshu. Some holes were not far from where a large earthquake occurred on June 11, 1978. Somewhat surprisingly, initial analyses of the cores had not revealed any oceanic sediments on the continental side of the trench, but revealed sediments with continental, rather than oceanic, affinities. It had been assumed that oceanic-type sediments would have been scraped off the oceanic basement rock as it was subducted under Japan. Not finding this prompted the overzealous *Japan Times* to run the headline "IPOD Survey Team Finds No Evidence Supporting Plate Tectonics Theory" — which, while true, does not disprove the plate tectonics theory. This voyage also determined that much of the sea floor west of the Japan Trench was once at or above sea level, emphasizing the great amount of vertical tectonics that occurs near active margins.

A second major traverse across an active margin occurred in the late winter and spring of this year. In this case, a traverse was made across the Mariana Trench westward to the South Philippine Sea basin. The analyses from these cruises were not completed at this writing. Other traverses will be made across the Middle America Trench off southern Mexico and Guatemala during the spring of 1979.

Ocean Paleoenvironment

Factors that influenced the oceans of the past include drifting continents, uplift and subsidence of the sea floor, and climatic changes. These factors, in turn, altered the biological, chemical, and physical oceanographic regimes of the oceans. While there is some discussion about which are the causes and which are the effects among some of these factors, the observational record is being rapidly filled in from the deep-sea drill cores. The lithologic and micropaleontologic records have revealed a number of highlights.

The oldest sea floor is early Mesozoic in age (somewhat more than 150 million years old). Most of the microorganisms that provide the basis for marine biostratigraphy (the correlation of structure by biological means) first appeared in the oceans at this time. Establishment of the continuity of evolving forms and the integration of them into biostratigraphic units has resulted from the core studies. In fact, because of the usefulness of the microfossils from the deep-sea drilling collection, paleontological reference centers have been established in Bern, Switzerland, and La Jolla, California. Additional centers are being considered worldwide.

Two central problems being studied through the use of this data are the changes from a warm ocean bottom water in the Early Cenozoic era to a colder ocean more recently (Figure 4), and a change from poor to well oxygenated water. There has been a very distinct cooling since the Late Eocene epoch (about 60 million years ago). Prior to that time, the high latitudes were warmer as was the ocean bottom (more than 10 degrees Celsius). Near the Eocene-Oligocene stratigraphic boundary there are widespread deep-sea unconformities and a rapid deepening of the calcium carbonate compensation depth by about 2 kilometers. This is probably related to changes in circumAntarctic currents due to the drift of Australia away from Antarctica and other continental reconfigurations.

Drilling has shown that the 3,800-kilometer long Ninetyeast Ridge in the Indian Ocean was originally an ocean island and seamount chain, but has sunk nearly 3,000 meters since the Cretaceous period. This, too, probably had a major influence on circumpolar seawater circulation.

Ocean Crust

Among the earliest successes of the Deep Sea Drilling Project was the verification and calibration of the magnetic reversal time scale for the last 70

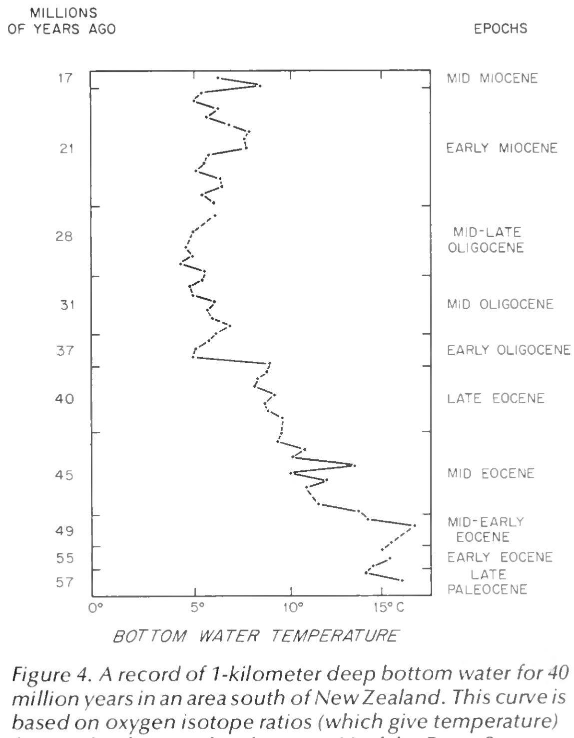
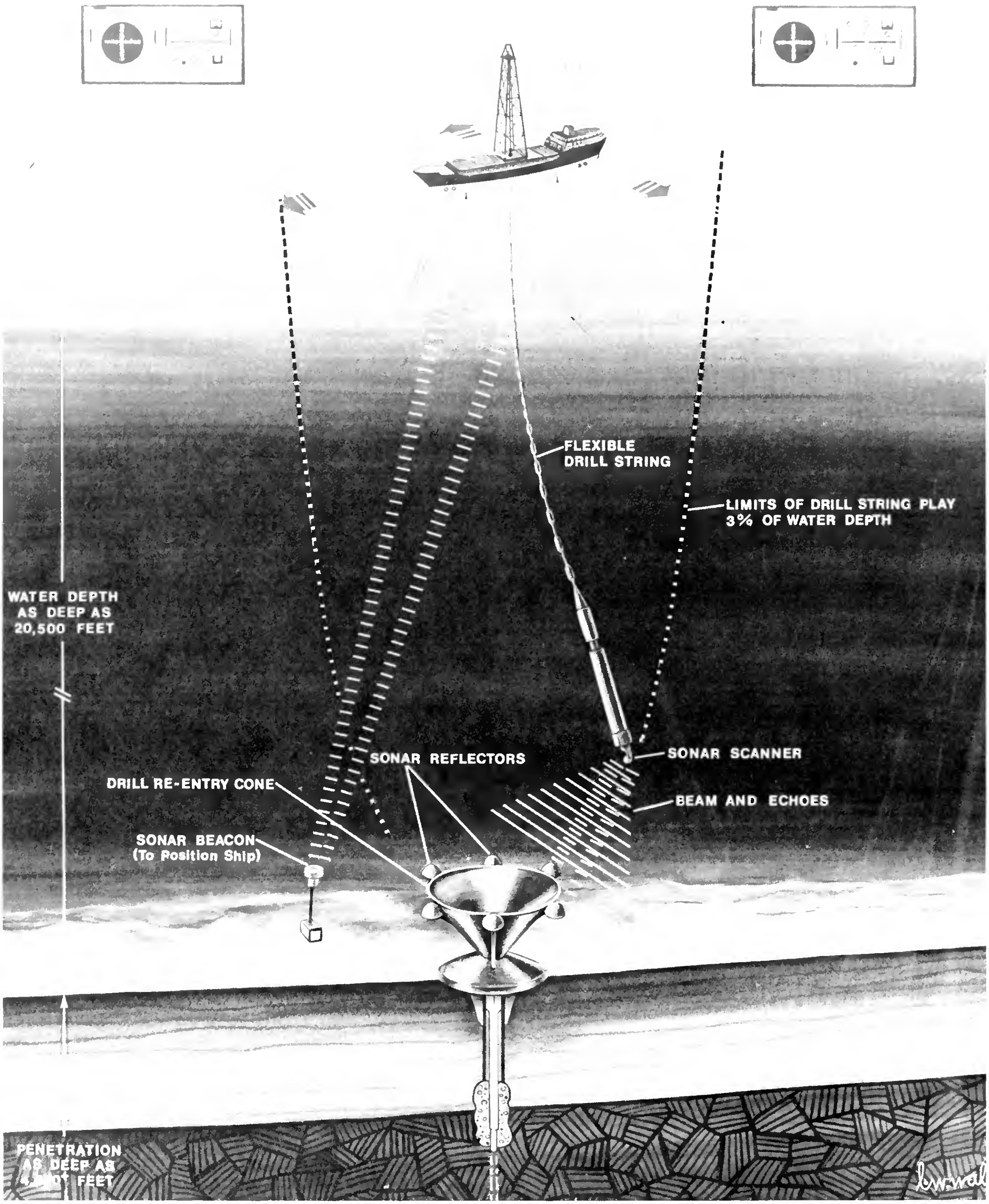


Figure 4. A record of 1-kilometer deep bottom water for 40 million years in an area south of New Zealand. This curve is based on oxygen isotope ratios (which give temperature) for benthic foraminifera from Leg 29 of the Deep Sea Drilling Project. (After Shackleton and Kennett, 1975)

Dynamic Positioning and Re-entry



The Glomar Challenger *uses "dynamic positioning" to hold station while drilling. Two thrusters forward and two aft, along with the vessel's two main propellers, are computer-controlled to hold position without anchors in water depths up to 6,000 meters so that drilling and coring can be accomplished. When a drill bit is worn out, the drill string is retracted, the bit changed and then returned to the same bore hole through a re-entry funnel placed on the ocean floor. High resolution scanning sonar is used to locate the funnel and to guide the drill string over it, which is maneuvered by a water jet. Operational re-entry was first achieved on Christmas Day, 1970, during Leg 15 in the Caribbean Sea. The relative position of bit and funnel are displayed at the surface on a Drill String Position Indicator Scope. The DSDP developed the re-entry technique because of being stopped short of scientific goals at many bore holes in the Atlantic and Pacific when the bit hit beds of flint-like rocks that dulled the bit and forced early abandonment of drill sites.*

million years. This was accomplished by a series of drill holes in the South Atlantic, which allowed dating of the sediments lying immediately above the basaltic basement rock by means of biostratigraphy, thereby determining the age of the crust. These ages could then be correlated with magnetic anomalies to yield a time scale that can be used to determine the worldwide rate of sea-floor spreading.

One of the major new challenges at the beginning of the International Program of Ocean Drilling in 1975 was to drill a kilometer or more into the basaltic basement rock or ocean crust. Up to that time, only a few tens of meters of basement rock had been recovered.

Recognizing that the generation of new ocean crust at the mid-ocean ridges was one of the fundamental geologic processes on earth, a program was devised to identify and study the igneous processes involved in formation, the possible modification of the crust by hydrothermal circulation, the nature of the magnetized rocks that give rise to linear magnetic anomalies, the aging of the crust away from the ridge axis, and other key problems about which there was no direct knowledge.

Six cruises have been made in the Atlantic and one in the Pacific to study these problems. Crust from about 10 to 110 million years of age was drilled in the Atlantic where sea-floor spreading is slow and young crust was drilled in the Pacific where spreading is faster. From the very beginning, this drilling program produced surprises.

The first discovery was that it was impossible to drill more than about 700 meters into the crust with the *Glomar Challenger,* because the crust was highly fractured with some layers broken down to sand-size pieces. The broken pieces bind the drill bit and prevent drilling. Fortunately, this is less of a problem in the older crust where cracks are filled. There also appears to be some evidence of hydrothermal circulation through the fragments (even away from the ridge axis). Future voyages will study these problems.

Study of the rocks has shown that in a single hole several primitive magma types can be present, which are not related to each other by crystal fractionation. Magnetization of the rocks is consistent only over depths of a few tens of meters: it varies down the hole, and the direction of magnetization is rarely what might be expected from the analysis of sea-level magnetic anomalies. Furthermore, the petrology and magnetic signature with depth may vary from one hole to another even when the holes are only 50 to 150 meters apart (Figure 5).

These new findings have precipitated new models of crustal genesis with a large statistical element built into them. The simplistic models that were originally proposed for global sea-floor spreading now need to be modified to include local variability. The use of submersibles to study rocks at mid-ocean spreading centers — such as in Project FAMOUS, the Cayman Trough and Galápagos projects (see *Oceanus,* Summer 1977) — has been of great assistance in trying to understand the spatial relationships of the newly determined geologic units.

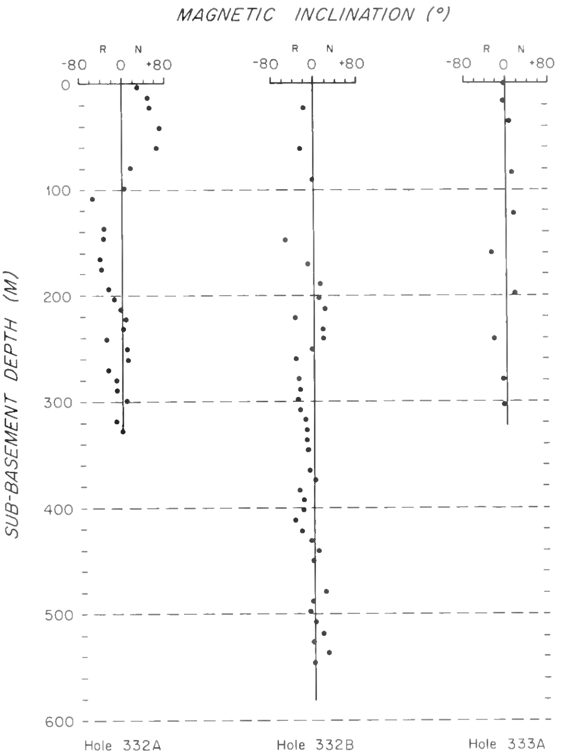


Figure 5. Observed magnetic inclinations from basement rock specimens from three nearby holes on Leg 37 of the Deep Sea Drilling Project in 1975. Hole 332B is only 100 meters from 332A and hole 333A is less than 10 kilometers from either of the other two. Note that rocks from the same depth are magnetized differently even though the holes are relatively close to each other. This illustrates the great heterogeneity of the basement.

Downhole Measurements

It is frequently difficult to relate the findings from a drill hole to the regional geology because the drilling provides such a small core sample. Accordingly, a downhole measurements program has been instituted to extend the base of knowledge out from the drill hole to tie in with regional geophysical surveys.

This program includes measuring the in situ acoustic wave velocity, density, porosity, temperature, electrical resistivity and radioactivity along the length of the hole. These measurements give continuity to the study of samples down the hole when recovery is incomplete and give average values for the sediments and rocks surrounding the hole (up to a few meters).

Another group of experiments has been undertaken to sense even further from the drill hole. Oblique seismic experiments using a geophone down the hole and firing explosive shots nearby have led to a better knowledge of local average seismic velocities and their anisotropy. Electrical experiments with widely separated electrodes are being made to extend the range of resistivity information. These and other experiments will be compared with the measurements previously mentioned and with similar measurements made on land in comparable geologic environments.

A third type of downhole experiment is presently being proposed. It includes instruments to be left in holes after the drilling ship departs. These include seismic sensors, strainmeters, and temperature and magnetic sensors. The experiments could also be expanded to include data on the diffusion of radioactive wastes. These instruments presently are all limited by battery life and the rate of data relay. The challenges should attract some of our best technical minds in the next few years.

A Summing Up

The JOIDES International Program of Ocean Drilling has completed its first decade. During this period, there have been notable achievements. Foremost are the scientific contributions to our understanding of the sea floor. This has allowed us to come to an understanding of the origin of mineral and petroleum resources. In addition, the program has been a model of international cooperation. It has brought together scientists from six countries in a unique management structure to provide scientific guidance to a complicated and expensive program. All six countries have participated in its financial support. Scientists from many countries have contributed to the results.

As the program enters its second decade, there are critical decisions to be made. Should the drilling continue in the face of the high technological costs that will be required to meet scientific objectives? Nearly $150 million has been spent and some $700 million will be needed for the next decade. In hindsight, the $125 million estimated to carry out the Mohole Project in 1966 does not seem unreasonable.

Earthquake and Crust Monitor

The National Science Foundation recently announced a plan to monitor earthquakes and study the earth's crust by installing a seismic device in a hole drilled 450 meters below the ocean floor.

The device, if successful, could be the start of a network of similar instruments placed at scattered undersea sites throughout the world. At present, there is a large land network of such devices called the Worldwide Seismic Net; the undersea project would be an extension of this network, giving scientists a type and quality of data not possible before.

The hole is scheduled to be drilled in November by the Glomar Challenger. *The device, an instrument package containing sensors and electronics, is the first of its kind to be placed under the sea floor. The hole will be drilled at a depth of 1,200 meters at the mouth of the Gulf of California, a site chosen because it is a small ocean basin being formed by a rifting of continental crust of the peninsula of Baja California away from the mainland of Mexico.*

The instrument package will be 10.1 centimeters in diameter and 4.5 meters long, an adaptation of seismic devices that have been placed on the ocean bottom in the past. The instruments in the hole will be wired to a recorder on the ocean bottom; the recorder can be brought to the surface for data recovery without disrupting the sensors.

In the final analysis though, the future of the drilling program will depend upon the quality of the science proposed and its economic and social implications.

J. R. Heirtzler, a Senior Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution, has been involved in the Deep Sea Drilling Project since 1969, and A. E. Maxwell, Provost of the Institution, since its inception. Heirtzler is presently Chairman of the JOIDES Planning Committee and Maxwell is Chairman of the organization's Executive Committee.

Helium Isotopes from the Solid Earth:

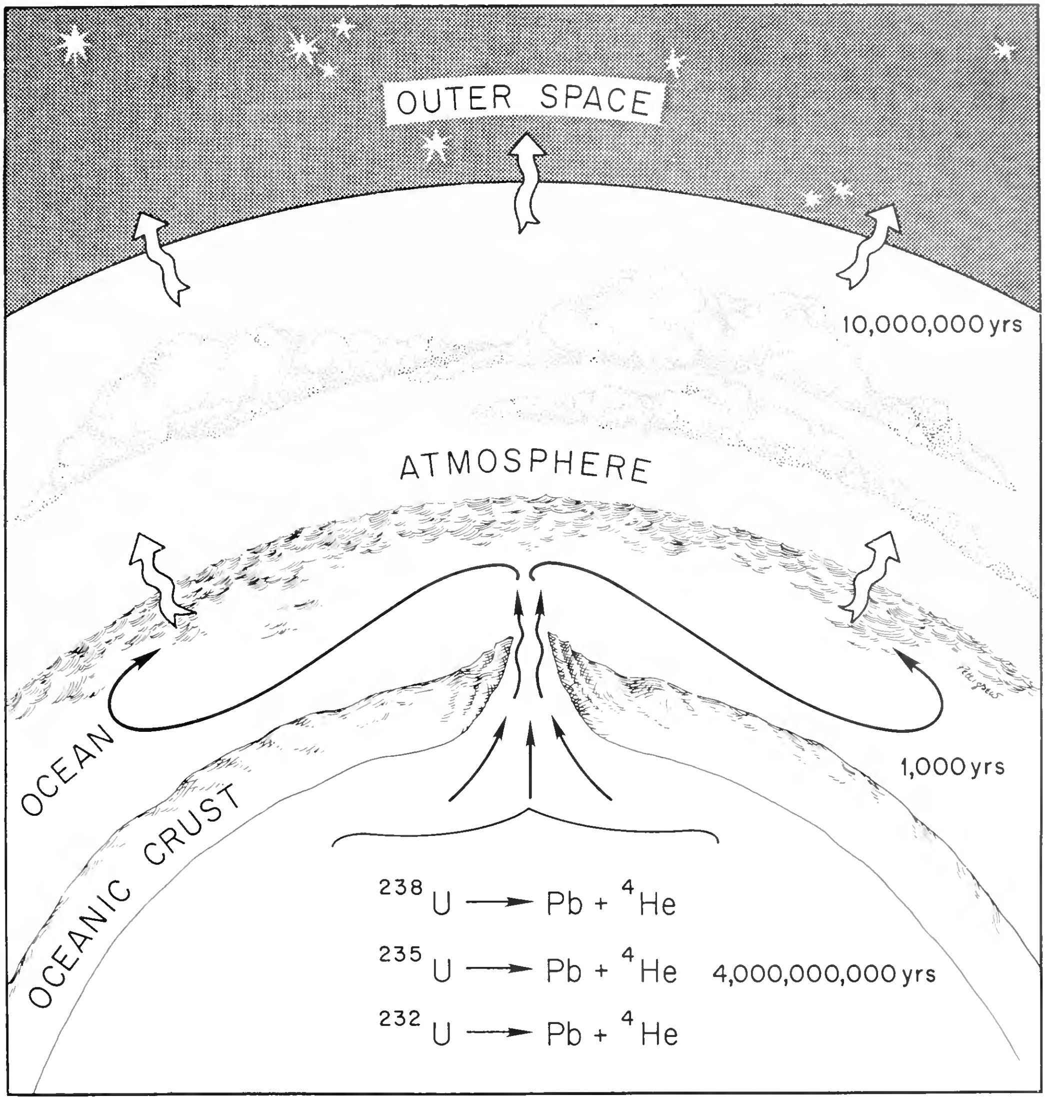


Figure 1. The geochemical cycle of helium. Long-lived radioactive substances, namely uranium and thorium isotopes, are continually decaying in the solid earth, becoming lead isotopes, but in the process producing helium atoms as a by-product. This helium escapes from the solid earth to the sea, then to the atmosphere, and eventually is lost into outer space. The numbers given are representative of the time which a given helium atom might spend in each stage of the cycle.

Up, Up, Up, and Away

by William J. Jenkins

Helium is the second lightest element. It is also the second most abundant element in the universe. In fact, next to hydrogen (the lightest element), it is the major constituent of stars. Yet despite its cosmic abundance, it is one of the rarer elements in the earth. For example, our atmosphere consists of only five parts per million helium; whereas, if it were present in its cosmic proportions, we would be breathing air that was more than 99.9 percent helium! Now, we could explain part of this deficiency by postulating that helium was inefficiently lost when the earth was formed. Since helium is chemically inert (it is the lightest of the noble* gases), it would not have been tightly tied to the small particles that combined to form the earth, and so a small amount of heating could have caused it to "boil" off and be lost forever. However, there is another process that accounts for the scarcity of helium.

Due to its light mass, helium tends to evaporate from the top of the earth's atmosphere, and is lost into interplanetary space. That is, a certain fraction (actually an incredibly small, but important fraction) of helium atoms achieve velocities in excess of the escape velocity** for the earth. These atoms obtain these speeds by a number of complicated processes; however, it is possible to calculate these effects, and thereby determine how rapidly we lose helium from our atmosphere. When these calculations are performed, we obtain the rather curious result that the residence time of helium in the atmosphere (the amount of helium in the atmosphere divided by the loss rate) is about 10 million years. This may sound like a long time, but when we consider that the earth is 4.5 *billion* years old, then this loss rate reduces the atmospheric helium inventory by a factor of 10^{-200} (a way of visualizing this figure is to consider that $10^{-2} = 1/100$ and $10^{-3} = 1/1{,}000$, and so on). We thus are faced with the problem of explaining why we still have so *much* helium!

To understand this embarrassment of riches, we must turn to the solid earth. When the earth was formed, it inherited a number of long-lived radioactive elements. It is ultimately these radioisotopes that provide the heat for the earth's volcanoes and global tectonics. What is important for our story is that most of these elements (thorium and uranium isotopes), in the process of radioactive decay, produce alpha particles (helium atoms) as a by-product. It is the leakage of this radiogenic helium from the solid earth that serves to maintain what little atmospheric helium inventory we have against loss into outer space. Figure 1 shows the geochemical cycle of helium. Helium atoms are produced by the decay of uranium and thorium in the solid earth. The bulk of the helium leaks into the oceans, primarily by upwelling of mantle material at sea-floor spreading centers and eventually (by bulk fluid motion and gas exchange) enters the atmosphere. The ultimate fate of this helium, once in the atmosphere, is evaporation into outer space.

So we have, at least in principle, an understanding of the geochemical cycle of helium. Or rather, *most* of the helium. Actually, helium consists of two isotopes. (The chemical nature of an element is governed by the number of protons in its nucleus. Hydrogen has one proton, helium two, lithium three, and so on. However, it is possible to have varying numbers of neutrons without changing the atom's chemical nature. Different atoms with different neutron numbers, but the same proton numbers are called isotopes.) We were dealing with helium-4 (^4He), which constitutes about 99.9999 percent of all helium. The remaining one millionth consists of the lighter isotope helium-3 (^3He — two protons and only one neutron). It may seem pointless to worry about such a small fraction, but this isotope has important consequences.

Although there is a process in the solid earth that produces a small amount of helium-3, there are none that produce significant amounts. This means that what helium-3 we see escaping from the earth must be primordial — that is, it was trapped when the earth was formed. This is of great interest to geochemists for two reasons. First, this is very clear evidence that the earth is still losing volatiles — that is, the earth's atmosphere and oceans are still in the process of formation. How rapidly the earth is degassing is the subject of considerable debate; we will discuss this later. Second, it is possible to determine the magnitude of this helium-3 flux. Once we know what the flux is, we can use it to calibrate other geochemical fluxes.

The question is: how does one measure the helium-3 flux? There is little doubt that such a flux exists. Excess helium-3 has been detected in hot springs, geothermal wells, fumaroles (vents), volcanoes, and in basaltic magma extruded onto the ocean floor. More importantly, this excess helium-3 has been seen in seawater throughout the entire Pacific and in all the other oceans. Recalling Figure 1, one realizes that the oceans act as an integrator for the helium flux. Since the oceans circulate on a time scale of about a thousand years, the deep waters will pick up many centuries worth of helium. In fact, we have used the oceans as a clock to time and amplify the helium-3 flux. This is done by using the observed distribution of excess helium-3 in the oceans coupled with what we have learned about the circulation of the oceans from radioisotopes, such as carbon-14. This flux calculation gives an estimated terrestrial helium-3 flux of about 4 atoms per square centimeter per second. This estimate is in very good agreement with independent, theoretical estimates of the loss rate of helium-3 from the atmosphere — a loss rate that must balance

*The "noble" or "inert" gases (helium, neon, argon, krypton, and xenon) are a group of elements that have no chemical affinities and therefore do not become involved in chemical reactions of bonding.

**As with rockets, or any projectile, there is a critical speed above which the projectile is travelling so fast that it will escape the gravitational pull of the earth.

the terrestrial input. Dividing this flux into the atmospheric inventory gives the residence time of helium-3 in the atmosphere to be about a million years. This shorter residence time (relative to helium-4, which is about 10 million years) is a result of the fact that helium-3 is lost at a disproportionately higher rate than helium-4, due to its lower mass. Of course, if helium-3 is *lost* at a disproportionately higher rate than its more abundant sibling, then it must be *gained* at a disproportionately greater rate. This is to say, the isotopic ratio ($^3He/^4He$) of helium coming from the deep earth is much higher (about 10 times higher!) than the atmospheric ratio. This way we can see very clear isotopic signatures where natural variations in the amount of helium might mask the primordial flux.

An additional flux of helium comes from the continental crust. As we understand it, the continental crust was created by magma that has worked its way up from the deep earth, cooling and degassing at the surface. Thus these rocks have given up their original helium-3 signal. However, the uranium and thorium isotopes concentrated in these rocks are continuously producing almost pure helium-4, so what helium is released from these rocks has an isotopic ratio ($^3He/^4He$) from 10 to 100 times lower than the atmosphere. That there is any helium-3 at all is the result of a secondary reaction on lithium nuclei caused by the radioactivity of the uranium and thorium isotopes.

So what we see in nature are three characteristically different kinds of helium, with very different isotopic ratios (see Table 1). The fact that they differ by factors of 10 (whereas we can measure these isotopic ratios to less than a percent) makes their detection very easy.

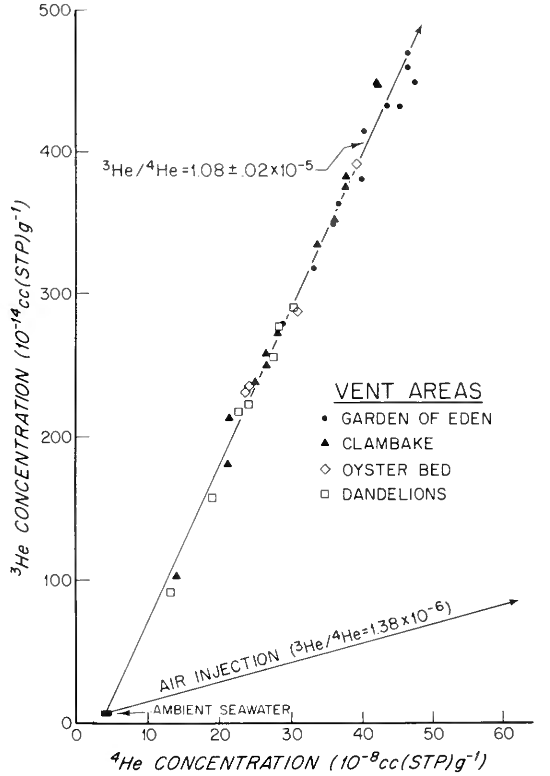


Figure 2. Observed ^3He and ^4He concentrations in the Galápagos submarine hydrothermal springs. Note the tight correlation about a straight line despite the nearly five-fold variation in concentrations. Compare the massive enrichment to background (ambient) concentrations in the darkened rectangle. The other trend line shows what would happen if the helium came from the atmosphere.

Helium From the Galápagos

We had learned from measuring the distribution of this primordial helium-3 excess in deep waters that a lot of the helium appeared to be coming from the eastern equatorial Pacific. This was not particularly surprising since this area was known to contain the fastest spreading ridges in the world. In keeping with this high tectonic activity, such as sea-floor spreading, it is natural to expect to see a lot of primordial helium. Consequently, when *Alvin* made its historic dives to the Galápagos submarine hot springs last year (see *Oceanus*, Summer 1977), we made sure to take samples for measurement of helium isotopes.

We were not disappointed. We found enormous enrichments of primordial helium in these samples (Figure 2). Some of the samples we analyzed were almost 100 times enriched in helium-3 and more than 10 times enriched in

Table 1: The kinds of helium seen in nature.

Type of Helium	Typical Places Observed	Isotopic ($^3He/^4He$) Ratio
Primordial	Volcanoes, hot springs, spreading ridges	1.5×10^{-5}
Atmospheric	In the air	1.4×10^{-6}
Continental	Natural gas wells, uranium mines	1×10^{-8} to 1×10^{-7}

helium-4 over background seawater. It happens that even the background seawater was almost 50 percent supersaturated in helium-3 — the highest enrichments seen in ocean waters to date. To get the perspective, note the small black rectangle in Figure 2, which represents the contents of background seawater.

As we expected, the isotopic ratio of this superabundance of helium was almost 10 times atmospheric. For comparison, a trend line is shown (Figure 2), which the helium data would follow if what we added was air.

The water from which this helium came also was noticeably warmer than surrounding seawater. This, too, is no surprise, since the helium is being carried up from below by molten rock. What was encouraging was the very distinct correlation between the temperature of the water and the amount of excess helium-3 in it (Figure 3). To see how useful this could be, we must digress a moment.

When new oceanic crust is formed by upwelling magma, it cools and spreads outward as it is displaced by more new magma: hence the concept of sea-floor spreading or plate tectonics. It is possible from simple models to predict the amount of heat yielded by this spreading crust, and the rate at which it is conductively cooled. However, when scientists measure the heat flow from the ocean floor, especially near the axis of this spreading, they see substantially lower levels of conducted heat (Figure 4). Because of this, it has been suggested, and subsequently shown, that this missing heat is carried away by hydrothermal convection of seawater. As the rocks form and cool, thermal stresses are set up that crack and fracture them. Seawater penetrates these cracks, pervading (some scientists believe) as deep as five kilometers. The seawater is heated by the upcoming hot magma and the surrounding rocks, and begins to rise — issuing forth on the ocean bottom as hot springs. Isotope and chemical data from the Galápagos expedition indicate that the rocks exchange heat and chemicals with the water at temperatures around 300 degrees Celsius, but by the time the water reaches the ocean floor, it has entrained and mixed with so much cold seawater that it is a tepid 20 degrees Celsius or so. A few meters above the ocean floor these plumes of hydrothermal water are so dilute that their temperatures are only a few thousandths of a degree above normal. Thus it is very difficult to see their impact by standard oceanographic sampling techniques.

Despite this anonymity, these quiet springs do carry a substantial fraction of heat away from the spreading ocean crust. Now, since we know the helium-3 flux (we can see it throughout the world oceans), we can use the observed heat/helium-3 ratio in the hydrothermal waters to extrapolate to a global scale convective hydrothermal heat flux. This

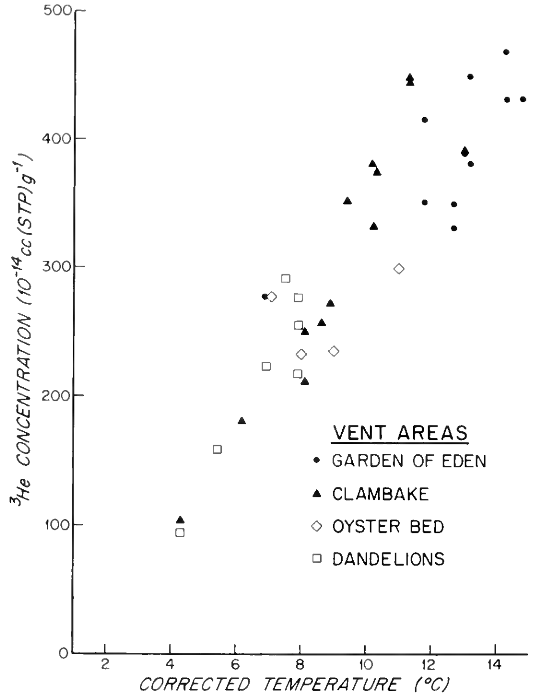


Figure 3. Observed heat/ ^3He correlation in the Galápagos submarine hydrothermal waters. The trend is definite, although scattered. The scatter is largely due to uncertainties in the temperature of the water, and to local variations in the heat/ ^3He ratio.

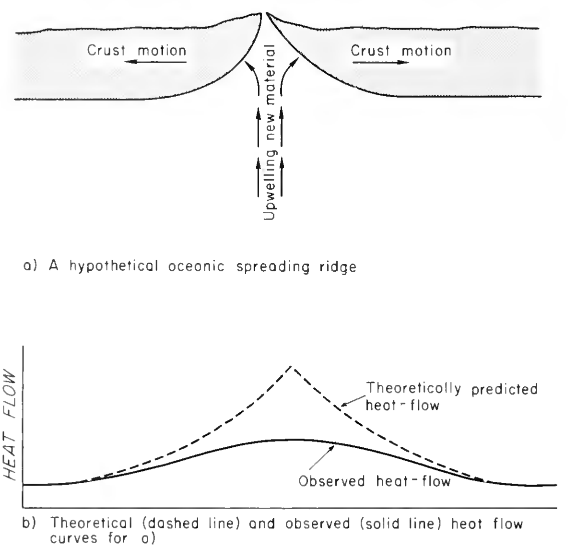


Figure 4. The difference between the observed (solid line) and theoretically predicted (dashed line) heat flow for a spreading ridge. The heat deficit, the area between the two lines, is the convective hydrothermal heat flux. This heat is carried away by seawater which permeates through fractured and cracked rocks and convects upward. It is this process that also carries chemicals to and from the freshly formed oceanic crustal rocks.

seems a rather brash thing to do, for we are dealing with only one small corner of the world, but, in defense of this, we pose the following argument. In such a situation, there is always enough seawater around. In addition, the processes that do transport the heat — namely convection and permeation — are likely self-limiting. That is, if less water reached the heat source, it would become hotter. But what water did penetrate would not only cause more fracturing (due to the greater thermal shock), but would be more violently convected, causing more water to be drawn in and balancing the system.

Returning to the data, we use the observed heat/helium-3 ratio (7.6×10^{-8} calories per atom of helium-3) and the observed helium-3 flux (2×10^{19} atoms per second) for the entire earth to estimate the convective hydrothermal heat flux to be 5×10^{19} calories per year. Various scientists have estimated this heat flux by subtracting their observed conductive heat flow data from the theoretical curve (Figure 4) and they obtain estimates from 4 to 6×10^{19} calories per year. Therefore, this represents the first experimental proof of their estimates.

Moreover, we can use the helium-3 data to look at chemical fluxes from the deep earth. Evidence from sedimentary records clearly indicates that the oceans are approximately in a chemically steady state — that is the relative abundance of dissolved chemicals in the oceans has not changed substantially in the last few hundreds of millions of years despite the fact that sediment is forming from the dissolved chemicals and that materials are being carried to the oceans by winds and rivers. What this means is that the fluxes into and out of the oceanic reservior must balance. Geochemists have been occupied with looking at these fluxes and trying to balance the oceanic budgets for each element. This works well for most elements: the river flux, as measured by the river water flow and the amount of chemicals contained in that flow, quite closely matches the sedimentary flux, as determined by measuring the rate of sedimentation and chemical composition of the sediments. Scientists have long recognized, however, that for certain elements (notably magnesium [Mg] and calcium [Ca]) the oceanic budgets need an additional source (for Ca) or sink (for Mg) to balance out. It has been suggested, and indeed determined by observation, that cooling rocks take up magnesium from seawater in return for calcium and other elements (see *Oceanus*, Summer 1977). Until now, it had not been possible to quantify these exchanges, but by correlating the observed chemical anomalies with the helium-3 anomalies in the same way as we did for heat, we can compute these chemical fluxes. The results (chemical measurements are still in progress at the Massachusetts Institute of Technology) are encouragingly close to what we need to balance the budgets, but with a few interesting surprises.

The Degassing of the Earth

As mentioned before, the presence of primordial helium-3 is the first real evidence that the earth is still degassing. Also, the measured helium-3 flux is the first hard number for the rate of degassing. You may ask why an oceanographer would be interested in such a thing, but it is by this process that the oceans and atmosphere were formed. All today's water and air used to be inside the solid earth, and were released in the process of the formation of the crust — that is, degassing. It then becomes of interest to ask ourselves: is it over? If not, how rapidly is this formation process taking place? How rapidly did it take place in the past?

The answers to these questions, and many more, are tied up in the geochemical budgets of not just helium, but many other elements; and in the complex physics and chemistry of the entire earth, solar system, and even the stars. To compound the difficulty, we are looking at the present — a relative snapshot — and trying to guess what has happened over the last four and a half billion years. Nonetheless, we do have some information available. We know the helium isotope fluxes, and we therefore know a good deal about the helium budgets. From global heat-flow measurements, we can learn something about the abundances of the radioactive elements, for it is these elements that provide the heat energy, and helium-4 for the earth's volcanism and tectonics. Thus we can set up a number of budgets which we must satisfy in order to explain the degassing of the earth. Then we test different theories on how the oceans evolved.

First, we suppose that the earth's degassing rate has been constant over all geologic time. When we try to balance the budgets, we find that we cannot simultaneously satisfy both the uranium and the helium budgets. What this tells us is that the rate at which the earth is degassing *must* have varied over the earth's history.

This is not surprising at all. The radioactive substances that produce the heat which drives the degassing process are themselves disappearing, and decreasing in concentration with time. As a result, we would quite naturally expect a decrease in degassing activity with time. When we apply a time varying (exponentially decreasing) degassing with time, we find a very good balance for our budgets. What is encouraging is that the time dependence which results quite naturally from this analysis is fairly similar to the time-dependence of the radioactive heat production (Figure 5).

This might be expected, as the earth will try to "thermostat" itself. If there is a great amount of heat production in a parcel of mantle material, it will become very warm and expand. As with Archimedes' principle,* it will try to float (or at least

*A body floating in a fluid displaces a weight of fluid equal to its own weight. If the density of the body is lighter than that of the fluid, the body will feel an upward force, or buoyancy.

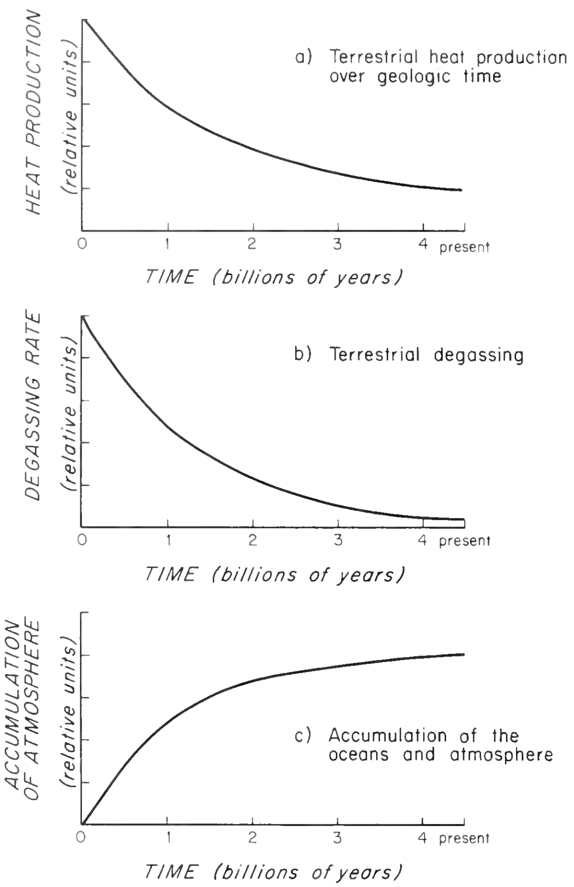


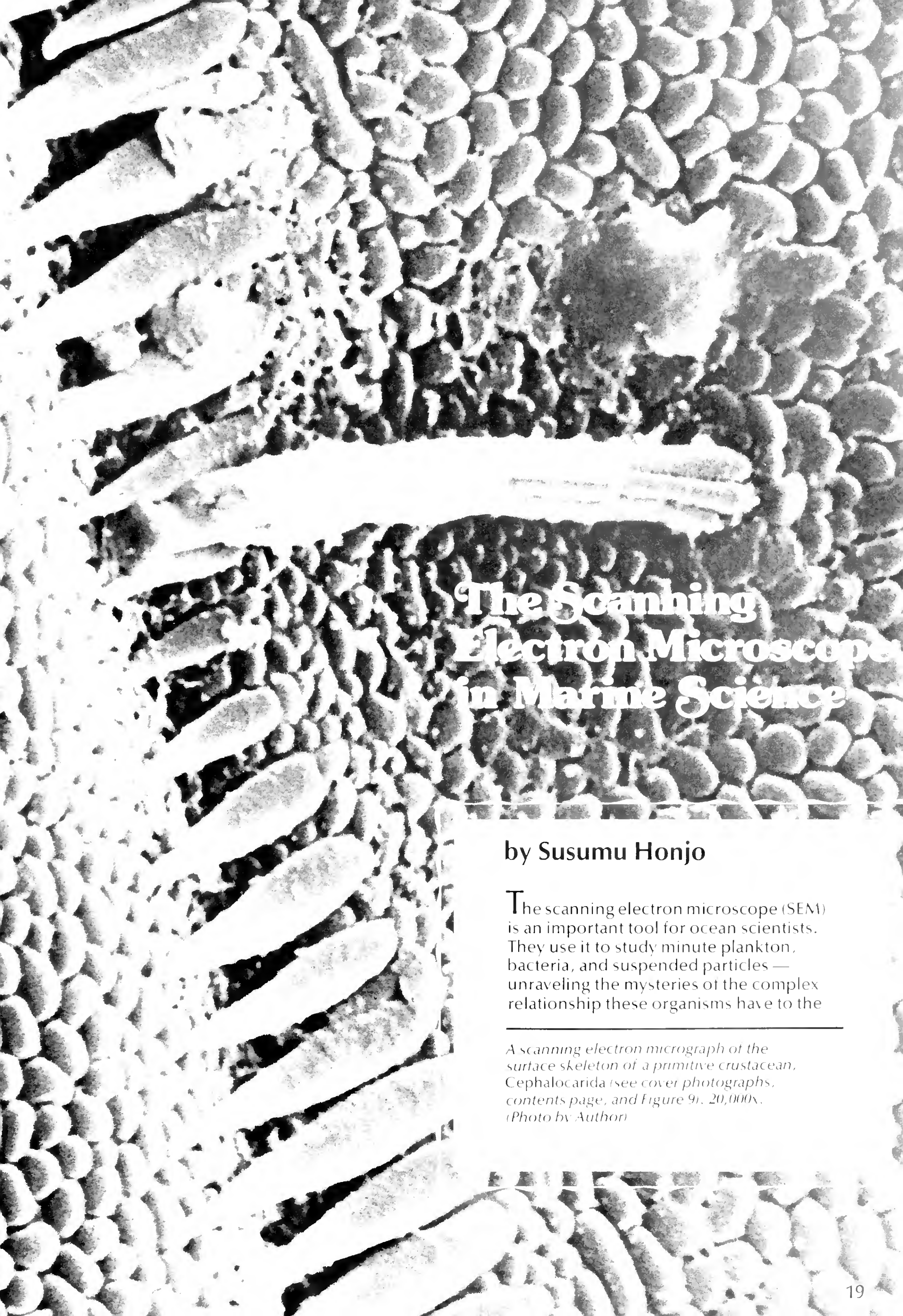
Figure 5. The degassing of the earth. The theoretical calculations of the helium and uranium budgets produce a degassing curve for the earth (b), which looks quite similar to the heat production curve (a). Figure (c) shows the growth of the oceans and atmosphere that would result from the calculated degassing curve (b).

rise). In addition, the material will become less viscous, so that the motion will be enhanced. Consequently, a higher heat production will lead to more vigorous convection — and hence more rapid degassing. So what we see, or at least predict, is a more rapid accumulation of the oceans in the first half of the earth's history coupled with a more gradual, but still on-going accumulation in the latter half.

We can test this theory against an additional budget: that of argon-40 (^{40}Ar). This is the third most abundant gas in our atmosphere (about 1 percent of air by volume is argon), and is almost totally derived by the decay of potassium (^{40}K). Unlike helium, argon-40 cannot escape the atmosphere once it is degassed from the solid earth, so that it represents an integrator of the degassing process. When we do try to balance the argon-40 budget, we find we must account for the portion produced in the continental crust, for not all of it is retained in the rocks where it is formed (about half escapes). When we do this, we find remarkably good agreement with what we see. This tells us that we are indeed on the right track.

Unfortunately, the story does not end here, because inevitably we will have to balance and explain the budgets of all the elements, resolving our predictions with the physics and chemistry of the earth. There may never be an ultimate answer or test to our questions, for we are delving into a highly speculative and uncertain area of geochemistry. But perhaps that is what makes it so rewarding.

William J. Jenkins is an Assistant Scientist in the Chemistry Department at the Woods Hole Oceanographic Institution.

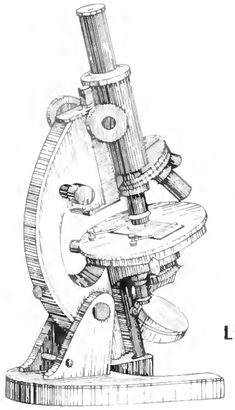


The Scanning Electron Microscope in Marine Science

by Susumu Honjo

The scanning electron microscope (SEM) is an important tool for ocean scientists. They use it to study minute plankton, bacteria, and suspended particles — unraveling the mysteries of the complex relationship these organisms have to the

A scanning electron micrograph of the surface skeleton of a primitive crustacean, Cephalocarida (see cover photographs, contents page, and Figure 9). 20,000x. (Photo by Author)



Light Microscope

environments they inhabit. The SEM also is a sensitive instrument for assessing the slow but important chemical reactions of seawater with minerals, and the path of surplus nutrients from the surface layer to the deep ocean floor. Ocean micropaleontologists use it to study microfossils in the deep-sea sediment, reconstructing past climate epochs and estimating future changes. In a sense, the user of the SEM is an explorer, seeking to uncover the fine details of the world of marine matter. In addition to revealing this ultrastructure, the photographs produced by the scanning electron microscope often are exquisitely abstract in an artistic sense.

There are three basic types of microscopes — the light microscope, the conventional electron microscope (often referred to as the transmission electron microscope), and the scanning electron microscope. It should be stressed that these instruments do not compete with each other, but, in fact, complement each other by supplying the scientist with different kinds of information. One of the major features that sets the scanning electron microscope apart from the light microscope and the conventional electron microscope is that it produces three-dimensional images, whereas the two other microscopes generally produce two-dimensional ones.

The light microscope — first built in the 16th century — presents an image in two dimensions because it has a very limited depth of field, focusing sharply in only one plane. In essence it is limited by the fundamental nature of light, which imposes a limit on the resolution of images. This means that it cannot separate dots that are closer together than 2,000 or 3,000 angstroms (1 angstrom is 1/10,000 of a micrometer). The light microscope works best with thin samples viewed by transmitted light, or with flatter samples, viewed by reflected light.

The technical development of the conventional electron microscope gave scientists clearer access to the world between the cellular and molecular realms of existence. The best transmission electron microscopes have a resolution of between two and five angstroms, so that the maximum effective magnification exceeds a million diameters. Although the physical concepts upon which electron microscopy are based can be traced to the 19th century, two important events in the early 1900s led directly to the building of the electron microscope. The first was de Broglie's theory that a moving electron might have the properties of a light-like wave. The second was a demonstration by Busch that suitably shaped magnetic or electrostatic fields could be used as true lenses to focus an electron beam to produce an image.

It was not, however, until the mid-1930s when scientists were studying the functions of the cathode ray tube that the electron beam was harnessed for use in the electron microscope. The shorter the wavelength used in microscopy, the higher the potential resolution. The transmission electron microscope achieves much higher resolution than the light microscope because electrons when subjected to high voltage (say 100,000 volts) have wavelengths several orders of magnitude shorter than visible light. Actually the function of an electron microscope is the same as the light microscope. The latter makes use of glass lenses to focus light, while the former incorporates electromagnetic coils to deflect the electron beam.

One feature of the transmission electron microscope is that the inside of the scope has to be kept in a very high vacuum to prevent the beam from being intercepted by air molecules. This is also one of the disadvantages of the microscope in that any sample has to go into the high vacuum area, exposing it to the bombardment of the electron beam. The transmission electron microscope requires thinner samples than the light microscope because only those electrons that emerge from the specimen with a narrow range of energies can be focused in a single image plane by the magnetic field of the objective lens. In most cases, it is the electrons that have been deflected but not changed in energy that are utilized to form the image. The thicker the specimen, the more likely is an electron to lose energy as it passes through. This is why the sample for transmission electron microscopy must be very thin, usually not more than 800 angstroms thick. It must be completely dehydrated, with all volatile matter removed. This severely limits the kinds of objects that can be observed without preparation and special preservation — in our case microskeletons of marine organisms, such as diatoms and coccoliths, which are essentially made of hard minerals. The resulting image produced by the transmission electron microscope tends to be a "shadow graph," a map, in effect, of the mass density of the specimen (Figure 1).

Diatoms are microscopic algae. Since the 19th century, their regularly spaced siliceous frustules have been used to check the resolution of the light microscope. The diatom also was the common object used by physicists and engineers in

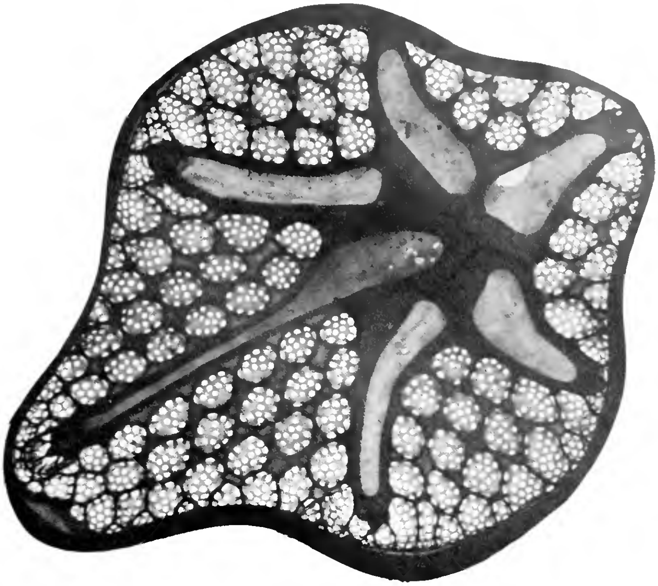


Figure 1. Transmission electron "shadow graph" of a valve of a diatom, Thalsassiosira, *suspended at 3,000 meters in the central Pacific. Magnification 2,000x. (Photo by Author)*

the early stages of electron microscope development. Systematic studies of diatoms and coccoliths (minute calcite scales of marine algae) also were accomplished shortly after this period. It was not, however, until the development of a complex replication technique that sedimentary rock could be brought under the electron microscope. The process involves replicating samples with a thin film of carbon by vacuum evaporation. It has been a standard technique for many years (Figures 2 and 3).

The scanning electron microscope developed rapidly in the years after World War II. By the mid-1960s, it was ready to serve applied science. The microscope is able to provide three-dimensional images because generally it records not the electrons passing through the sample but the secondary electrons that are released from the specimen as a result of its interaction with the primary electron beam. Usually, only those secondary electrons originating near the surface of the specimen are seen; the sample therefore can be of any size and thickness that will fit in the instrument's evacuated sample chamber. The secondary electrons are not focused but are simply collected in a device known as an electron detector where they are amplified, producing a signal that is relayed to the cathode ray tube to create the image. With the scanning electron microscope, a microscopist can start from a tangible image at hand-lens range and zoom up to a magnification of 100,000x, with a routinely obtainable resolution of 100 Å. Ordinary electron microscopes are incapable of operating at less than a few hundred magnifications. Because thin specimen slices are not required, the preparation of samples for the scanning electron microscope is generally much simpler than it is for the light microscope or the transmission electron microscope.

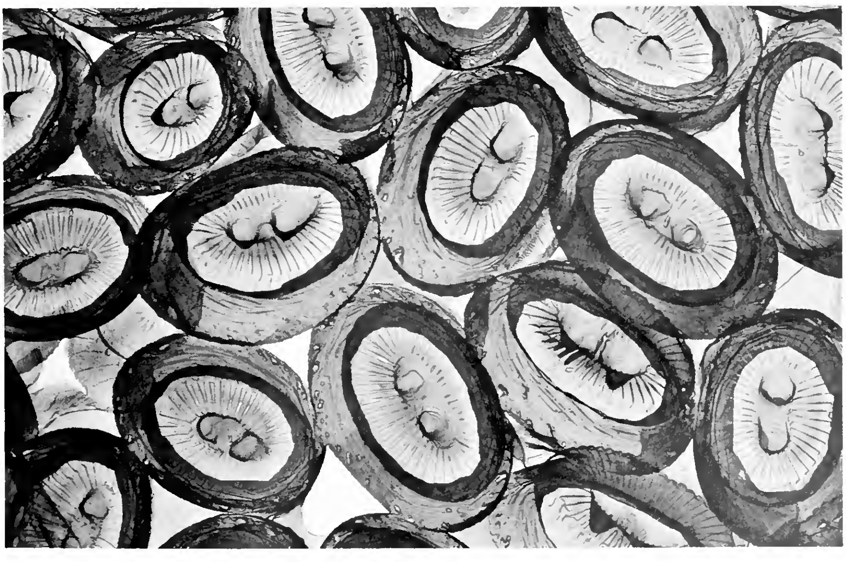
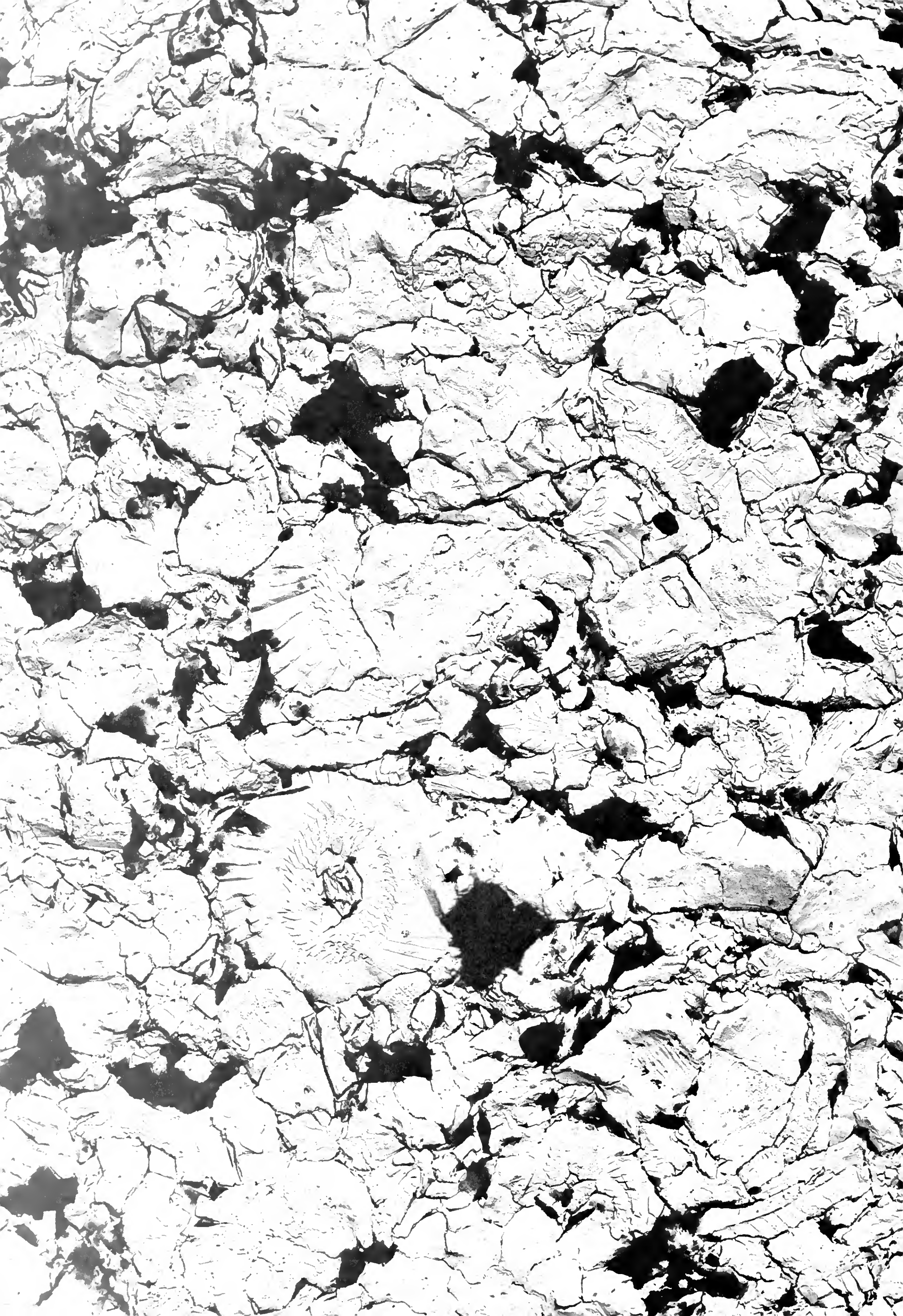


Figure 2. Transmission electron micrograph of carbon film replication of coccoliths, Syracosphaera, *from the central Pacific. Magnification 10,000x. (Photo by Hisatake Okada)*



How the SEM Works

In scanning electron microscopy, the sample is scanned by a focused electron beam and the image that results is formed by a technique similar to that used in television sets. There are two major differences. First, the standard TV picture is made up of 525 horizontal lines, whereas the SEM image can be adjusted from 100 lines to more than 1,000. This finer scan is used to produce the micrograph. Second, the rate of the SEM scan is often slower than the scanning rate in television. Thus the resulting micrograph is an image produced by a slow-moving electron beam. While one can speed up the scanning pattern for visual inspection, a time exposure of several minutes is often needed to obtain high-resolution micrographs of the best quality. A diagram of the instrument is shown in Figure 4. Electron lenses (L) focus the primary electron beam (PE) down to a diameter of approximately 50 to 100 Å on the surface of the specimen. This beam is deflected by two pairs of coils (C) in combination with the deflection control (DC) to perform a square scanning motion by moving line after line across the specimen surface (between 1,000 and 2,500 lines per frame). When the surface of the specimen is hit by the electron probe, it generates what is known as "slow" (low energy) secondary electrons (SE) that belong to the surface of the object. At the same time, "fast" (high energy) backscatter electrons (BE) are generated. Both types of electrons are collected in an electron detector (D). The slow secondary electrons are attracted by the positive field of the detector and are accelerated in the detector. The electrons impinge on the surface of a scintillator (SC) and generate photons. These are directed into a photomultiplier (PM) by means of a light guide (LG), where they release electrons that are instantly multiplied. The photomultiplier signal is then put into an amplifier system (A), whose output governs the intensity of the electron beam of the display cathode ray tube (CRT). On the video screen of the CRT, an image is built up in synchronism with the scanning movement of the initial electron beam on the specimen surface. The image represents the projection of the specimen surface as seen from a perspective along the center of the electron beam. Every location on the surface is represented by an image point on the video screen. Areas of high secondary electron emission are light and vice versa. The resolution of the picture is defined by the size of the primary electron beam; to a certain point, the smaller the diameter of the electron probe, the better the resolution. The magnification is changed by scanning different size areas of the specimen and displaying the signal on the same size video tube.

Figure 3. Electron micrograph of plastic-carbon film replication of Miocene fine-grain carbonate rock deposited in the deep-sea environment off the northwest Spanish coast. 5,000x. (Photo by Author)

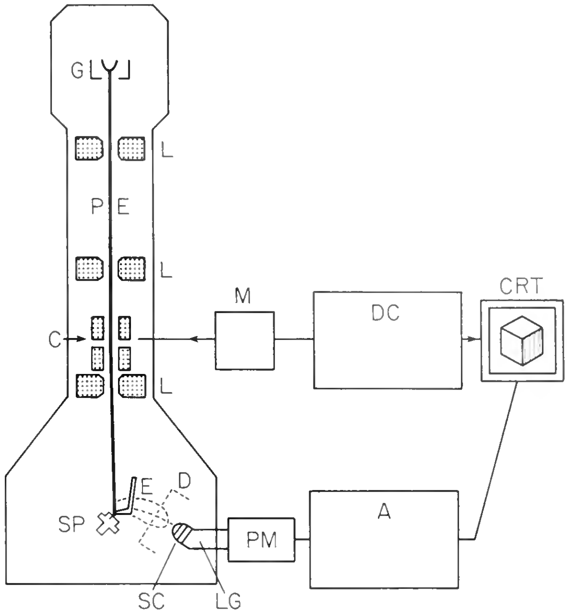
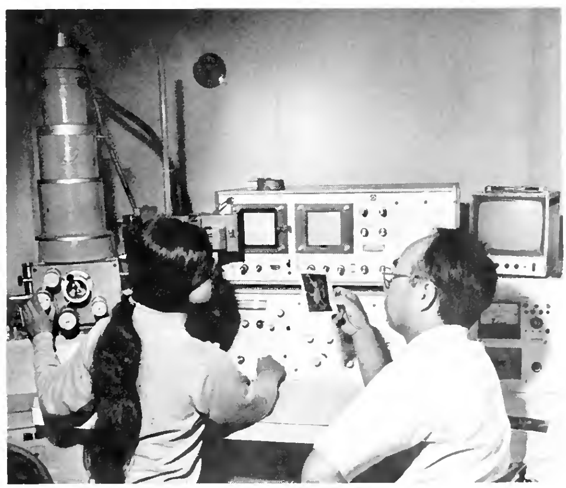


Figure 4. The scanning electron microscope. A = signal amplifier; C = scanning coils; CRT = cathode ray tube with video screen; D = electron detector; DC = deflection control; E = emitted electrons; G = electron gun; L = electron lenses; LG = light guide; M = magnification control; PE = primary electron beam; PM = photomultiplier; SC = scintillator; SP = specimen. (After G. Pfefferkorn, 1975)



The author, right, and assistant examine scanning electron micrograph in SEM facility at the Woods Hole Oceanographic Institution.

Examples of Research Projects

The deep sea is a severe environment. It is a world of total darkness, constant low temperatures, and

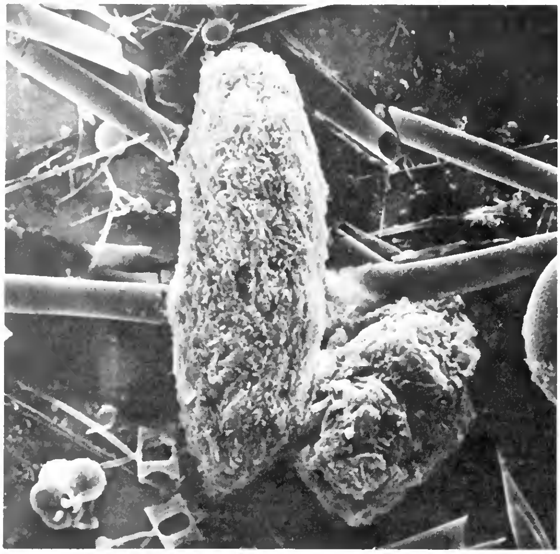
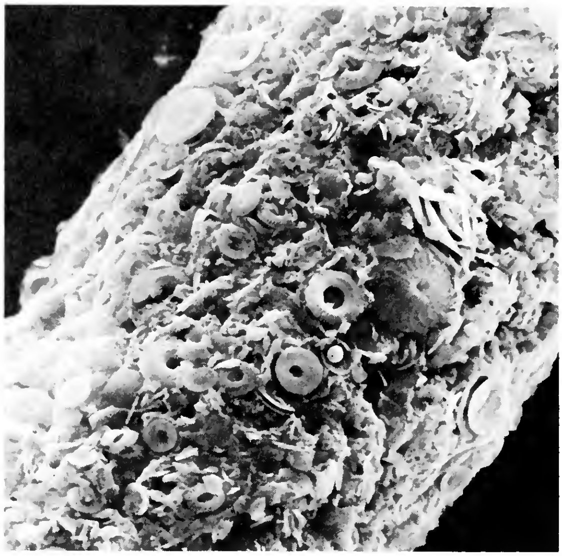



Figure 5. At left, scanning electron micrograph of sediment gathered by sediment trap experiment in Sargasso Sea at 5,300 meters. Oval object is the fecal pellet of a small zooplankton produced in surface waters. It contains coccoliths, clay minerals and a large amount of undigested organic matter from phytoplankton. 400x. At right, a closeup of a fecal pellet. 4,000x. (Photos by Margaret Goreau)

great pressures. Despite this, a large number of animals live there. All their energy needs depend on food produced in shallow or surface waters. But how does this food get to the bottom? It has been found that the surplus of food contained in the feces of zooplankton plays an important role in transporting energy from the productive surface waters to the abyss (see *Oceanus*, Winter 1978).

Through the use of electron microscopes at the Woods Hole Oceanographic Institution, the contents of these "fecal packages" have been exposed in detail (Figure 5). First, large numbers of nutrient-rich submicroscopic plant pigments were found. In some areas of the ocean, such as the Sargasso Sea, these pigments are the major source of nutrients and energy in the deep sea.

The remains of coccoliths (submicroscopic calcite discs produced by marine algae in surface water) are abundant in abyssal sediments (Figure 6). In some areas it has been estimated that nearly half of the sediment is made up of the remains of coccoliths. For a long time, geologists did not understand how this coccolith ooze was deposited at the deep-sea bottom. The discs are so small that it would take them tens of years to reach the bottom in several thousands meters of water. Seawater below a few thousand meters in the Atlantic and several hundred meters in the Pacific is undersaturated in respect to calcite. Thus it would seem that coccoliths, enroute to the bottom for burial in waters deeper than the saturation depth, could not survive the dissolution process. But quite the contrary is true: the coccoliths found in the deep sea are often well preserved, showing little or no sign of dissolution on their delicate architecture.

How coccoliths get from the surface to the bottom is now known, thanks to the scanning electron microscope. Zooplankton fecal pellets are often packed with coccoliths. The animals graze on phytoplankton and the indigestible coccoliths are wrapped into the pellet, which sinks quickly (within a few weeks) to the bottom. We have also found that the pellets contain clay minerals that are transported from arid lands by winds in the atmosphere and then deposited in the surface waters of the ocean.

The other major materials found in coccolith ooze on the bottom are tiny planktonic foraminifera shells, usually the source of calcium carbonate. These protozoan remains are relatively numerous in surface waters and sink rapidly by themselves. As coccoliths also apparently sink fast via fecal pellets, we have reached an important conclusion: the dissolution of carbonates does not take place in the water column, as previously thought, but occurs after arrival on the deep ocean floor. The dissolution of coccolith and foraminifera particles provides the natural lime that neutralizes the excess acidity of seawater. Information concerning where and how rapidly these particles dissolve has a bearing on the global climate situation, specifically the increased carbon dioxide levels in the atmosphere, which have been attributed to the burning of fossil fuels and the worldwide destruction of forests. The scanning electron

Figure 6. Scanning electron micrograph of coccolith ooze from the Rio Grande Rise in the South Pacific at 2,000 meters. 3,000x. (Photo by Margaret Goreau)

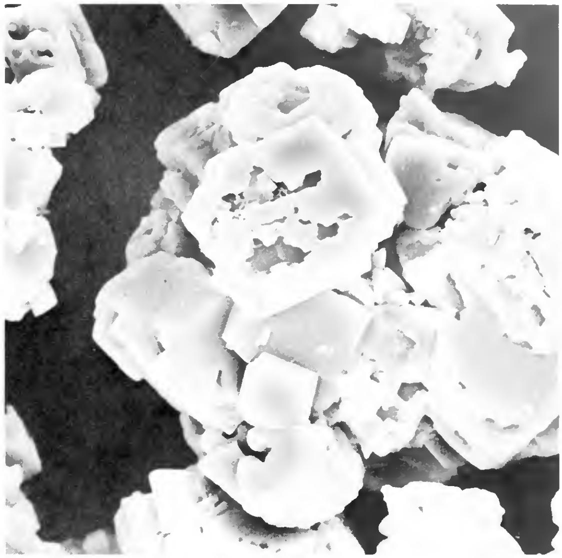


Figure 7. Dissolution on a calcite crystal deployed at 5,000 meters for three months in the Sargasso Sea, using taut mooring line. Magnification 3,000x. (Photo by Margaret Goreau)

microscope is a very sensitive method for assessing the rate of dissolution or precipitation of minerals in the ocean (Figure 7). Samples are collected at various depths through the use of mooring devices.

A variety of plastic filters have been devised to observe the many microscopic particles that seawater contains. For example, when a liter of water is collected from the Sargasso Sea (where the water is regarded as the cleanest in the world), it is passed through a filter with a pore size of 0.5 micrometers. The number of particles that remain on the filter usually exceeds 10,000. The weight of the particles is as small as 10^{-10} to 10^{-12} grams but they fall within a "comfortable range" for observation with the SEM. Clay particles, coccoliths, and debris from organisms are the major constituents of the suspended particles in the open sea (Figure 8). Nearshore waters contain greater numbers and varieties of particles. The species composition of suspended particles is more or less uniform throughout the deep-water column. This suggests that many particles are transported rapidly from the surface by large objects, such as fecal pellets. Their disintegration on the way down results in the suspension of small particles. Thus a particle found at extreme depth is not necessarily older than one from shallow water and vice versa.

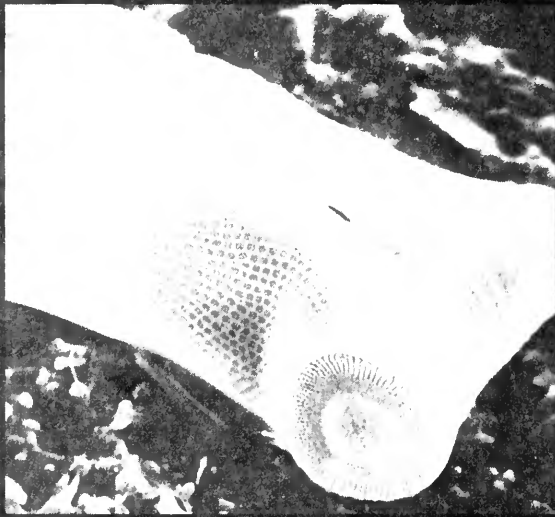
Quite often particles are found whose origin is hard to determine even when using the scanning electron microscope. For example, a piece of molted shell from a small crustacean looks very much like a clay particle. However, the energy dispersive X-ray microprobe, a common accessory of SEM, can reveal the elemental composition of an object almost instantaneously. When the primary electron beam bombards the object's surface, it emits a fluorescent X-ray radiation along with the secondary electrons. The pulse of this X-ray emission is then converted to electrons by a semiconductor detector. The pulses are measured and counted by a computer called a multichannel analyzer. The result — the buildup of a spectrum count versus X-ray energy — is either displayed on a TV screen or printed out. This technique allows the scientist to semiquantitatively analyze areas on the surface of an object as small as 0.1 micrometers square while still observing the image of the area as a whole.

The computer processing of the scanning electron microscope image also has enabled scientists to make an efficient statistical analysis of an object. Information relating to the number, projected area, and morphological details of suspended particles collected on a filter, for example, can be automatically gathered during the viewing process with the aid of a computer connected to the final display circuit. When this method is combined with the energy dispersive X-ray analysis through a computer editing process, what results is a large, high quality data bank on the composition of suspended particles in the ocean.

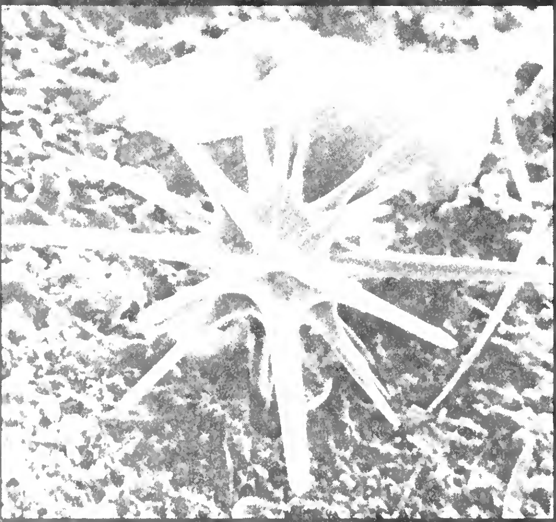
Marine biologists have been turning more and more to the SEM in their study of zooplankton, phytoplankton, and bacteria (Figure 9). But for a long while they were stymied in the preparation of samples for the instrument.

Examples of Suspended Particles

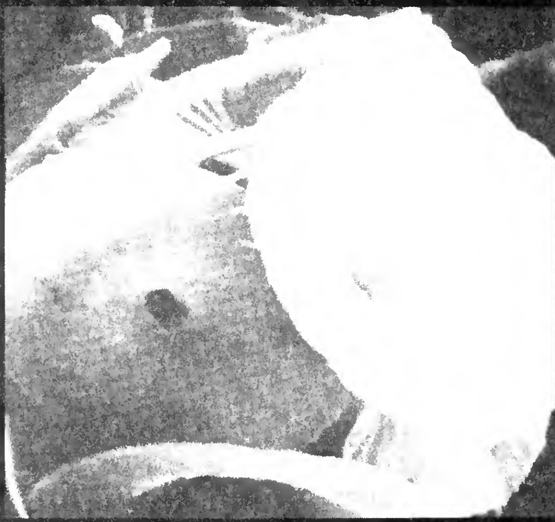
Dinoflagellate. 1,000x.



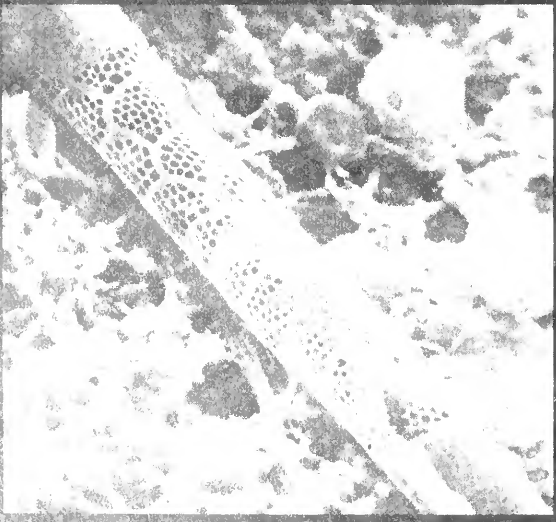
Sponge particle. 3,000x.



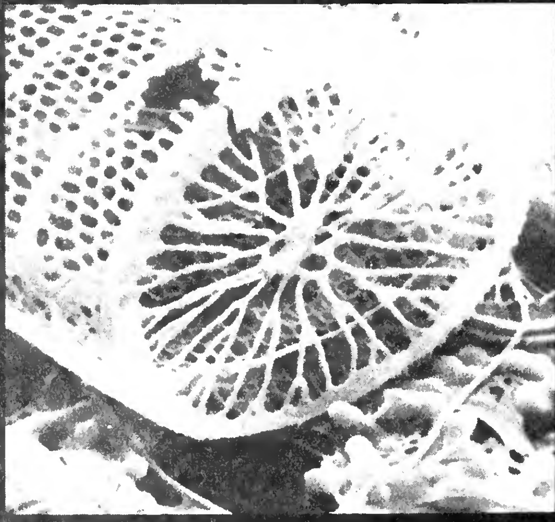
Acantharia skeleton. 2,500x.



Trumpet-shaped coccolith. 5,000x.

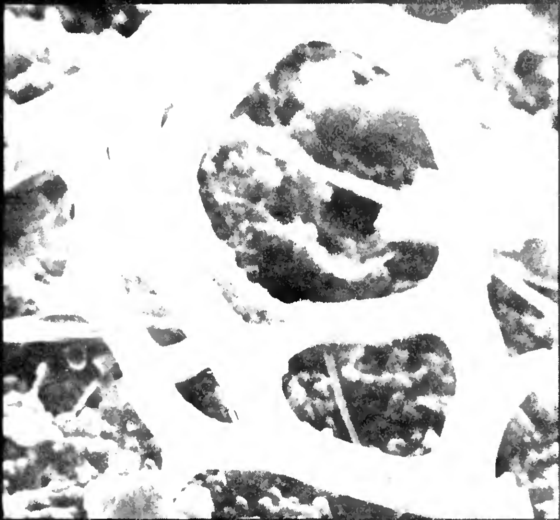


Unusual diatom. 1,000x.

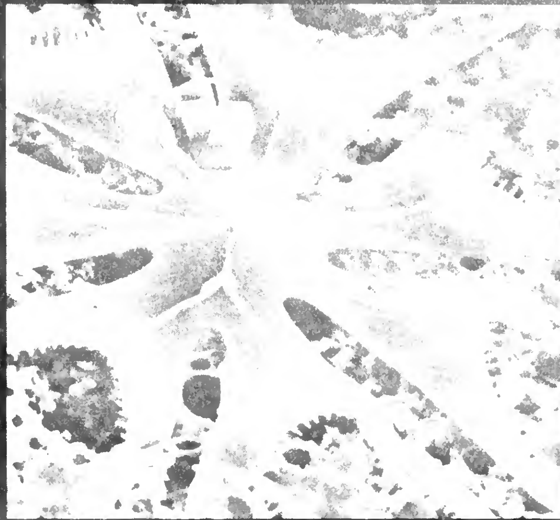


Part of diatom at left. 3,000x.

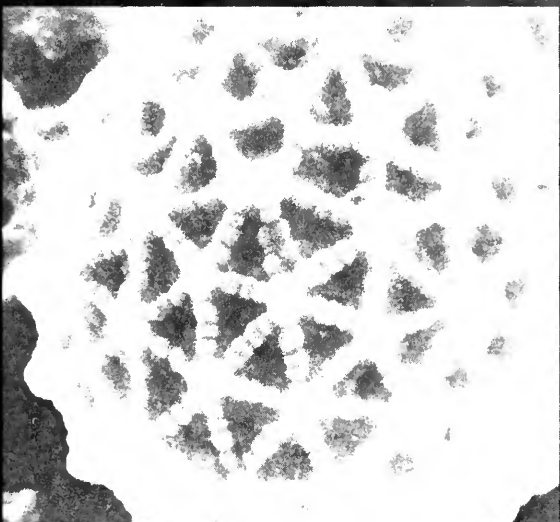
from the Western Pacific Ocean (Figure 8)



Silicaflagellate skeleton. 3,000x.

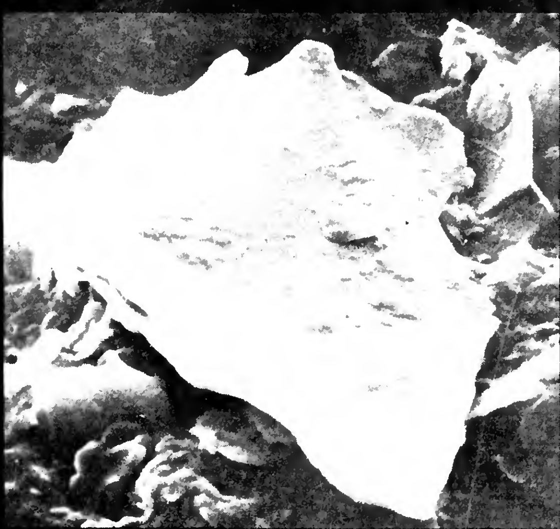


Unidentified particle. 2,000x.



Surface of unicell plankton. 4,000x.

Diatom. 2,500x.



Clay particle. 5,000x.

Spiral coccolith. 3,000x.

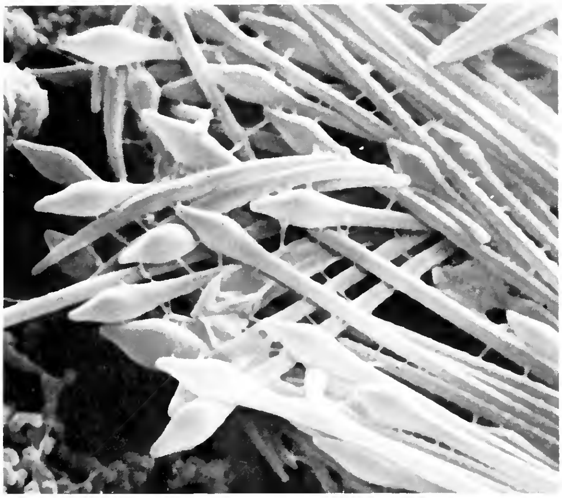
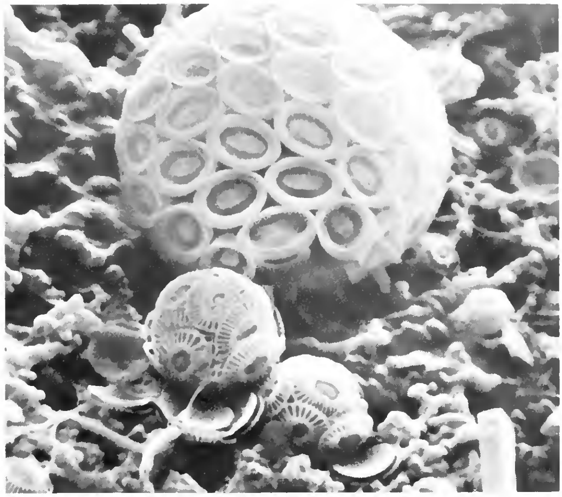
Figure 9. A scanning electron micrograph of part of the mouth of a primitive crustacean, Cephalocarida *(see cover photographs, contents page, and first page of this article). 1,000x. (Photo by Author)*

Generally speaking, marine organisms are separated from the surrounding seawater by a thin membrane of delicate tissues. To observe them under the SEM, they have to be completely dehydrated. So the problem was how to view the specimen as if it were still in its natural habitat, seawater. When seawater evaporates, the specimen is affected by high surface tension as great as several hundred kilograms per square meter, usually resulting in surface distortion. In the early 1950s, a technique called the critical point drying method was developed to solve the problem. Essentially, the method avoids the distortion that is produced by the passage of an air/liquid interface through the specimen. After critical point drying, the specimen is usually coated with a thin layer of metal either by evaporation or a technique known as sputtering. The purpose of the coat is two-fold: one, it renders the surface of the specimen conductive so that no excess electrical charge is built up; and, two, it enhances the production of secondary electrons, which are harnessed to form the image.

Future Trends

The engineering development of the scanning electron microscope is still growing rapidly. High resolution instruments capable of resolving objects as small as 30 A are already on the market. And with the aid of microelectronics, the operation of the SEM is becoming simpler and more efficient. Some manufacturers have marketed a semi-portable microscope as small as a medium-sized television set.

In the marine science field, the method has a



At left, an unusual radiolarian skeleton from the Sargasso Sea. 3,000x. Right, two species of coccolithophorids from the central South Pacific. 3,000x. (Photos by Tadashi Otaka)

bright future. Although there are still technical difficulties to overcome, there are also some exciting challenges to meet. For example, a device is being developed that will allow the deep submersible vessel *Alvin,* operated by the Woods Hole Oceanographic Institution, to collect sediment samples at the sediment/water interface for a multi-discipline deep-sea research project called Low Energy Benthic Boundary Layer Exploration (LEBBLE). The technique calls for human observation (through the submersible's portholes) of the sampling process, which involves partly preparing specimens in situ (at 4,000 meters in the Panama Basin) for the scanning electron microscope. This will provide ocean scientists a chance to see what the bottom of the abyss looks like under great magnification, which in turn will provide important information to answer the basic question of how it is formed.

Susumu Honjo is an Associate Scientist in the Department of Geology and Geophysics at the Woods Hole Oceanographic Institution.

The majority of research programs being conducted at the Electron Microscope Facility of the Woods Hole Oceanographic Institution are supported by the Oceanography Section of the National Science Foundation.

Seagrasses and the Coastal

Nearly half the population of the United States is living adjacent to coastal waters or to the shores of the Great Lakes. This percentage almost certainly will continue to increase during the 1980s. The coastal environment, however, really constitutes a very small area. It has been estimated that all harbors, estuaries, and nearshore coastal waters of the world make up no more than 1 percent of the surface area of the world's oceans. Yet it is this nearshore fringe that is colonized by one or more of the most highly productive ecosystems in the world. These ecosystems are dominated by submerged or semi-submerged plants. Only in the Arctic or Antarctic are these ecosystems absent. Because these vascular plants exist in relatively shallow water along the coastal fringe, they are subject to increasing stresses caused by man and his growing, diversified needs. The continued multiplicity of demands upon estuarine and coastal environments as producers of food, avenues of transportation, receptacles of wastes, living space, and sources of recreational or aesthetic pleasure makes it imperative that we understand the functioning of these nearshore ecosystems, with their attendant frailties and strengths. This knowledge is essential if we are to manage these ecosystems wisely so that we can derive maximum benefits from them.

Coastal Ecosystems

Several different coastal ecosystems exist in the tropics and temperate zones of the world. In the tropics, for example, extensive mangrove systems are present, whereas in temperate zones one finds massive kelp and marsh systems. Beyond the coastal fringe that supports the mangrove and marsh systems are vast meadows of one or more species of grass-like plants. These are rooted in soft, sandy, or muddy bottoms. Horizontal stems in the sediment, known as rhizomes, send erect, leafy

Figure 1. Eelgrass, Zostera marina, *in Puget Sound, Washington. Note the snails, which eat the leaves. (Photo by Author)*

by Ronald C. Phillips

shoots into the water. The stalks are often dense, with leaves so long that they resemble vast meadows of waving wheat or oats. These plants are called seagrasses (Figures 1 and 2).

There are few parts of the world's coastal zone where one or more species of seagrasses do not grow (Figure 3). It is becoming clear that seagrass meadows form one of the most productive natural ecosystems on earth (Table 1), and that they contain a wide variety of marine life. Bostwick Ketchum of the Woods Hole Oceanographic Institution has estimated that 80 to 90 percent of the commercial and sport fishes depend on estuaries for part or all of their life cycle. Estuaries typically support large seagrass meadows. The problem is that until recent years the presence and importance of these meadows went virtually unrecognized. This was due in large measure to the training of marine scientists, who usually viewed the ocean as a deep-water mass. Marine biologists, who have worked in and around seagrass meadows, mainly have been interested in particular algae or animals that live there. Fishery biologists have been interested largely in the shellfish or fish stocks directly or indirectly associated with the meadows. It has only been since the mid-1960s that oceanographers have begun to include the shallow benthic coastal zone as a part of the ocean system. It is now known that seagrasses form a discrete ecosystem that traps material from the land and exports great quantities of plant and animal products to the open sea. These products range from whole leaf and rhizome material, to particulate detritus, to dissolved organic matter that is used to support oceanic phytoplankton. This latter component forms the base of the food chain of the oceanic offshore fisheries.

The leaves and rhizomes of turtle grass, *Thalassia testudinum*, for example, have been transported to deep trenches, such as those off

Figure 2. Turtle grass, Thalassia testudinum, *in Panama. These grasses are commonly eaten by* Diadema *that move off adjacent coral reefs at night to eat blades, then move back to the reefs at daybreak. The urchins cause a "halo zone" of closely cropped leaves around the base of the reef. (Photo by Author)*

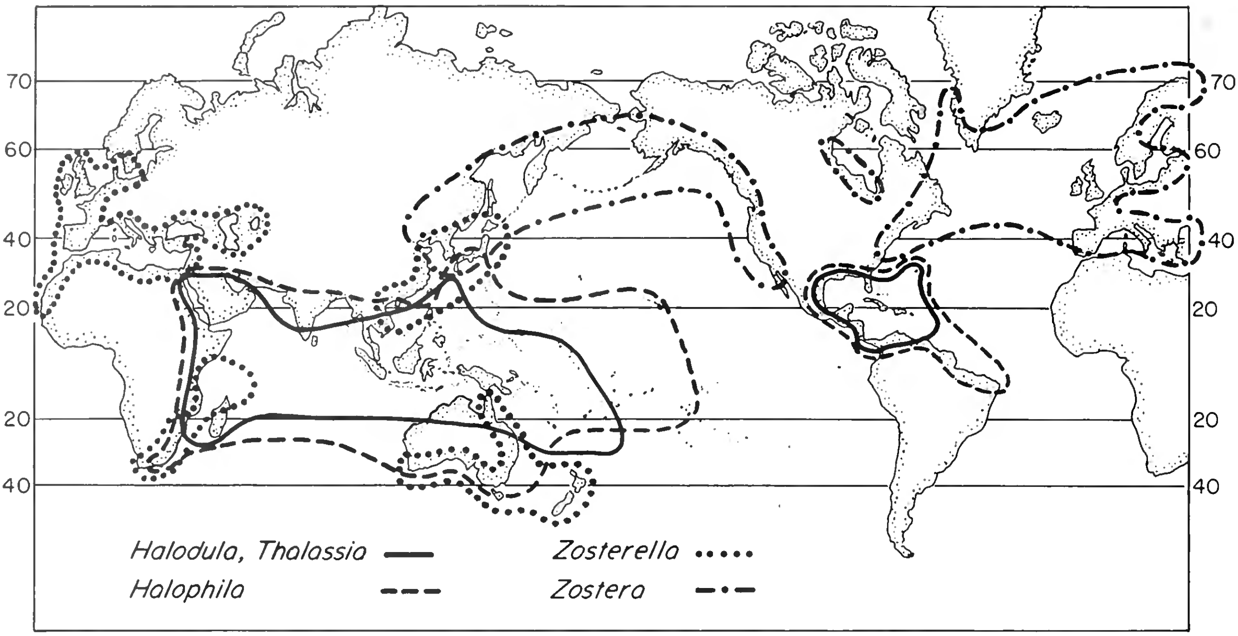


Figure 3. The distribution of selected genera of seagrasses. These genera have distributions so broad that they exceed the more restricted distribution of lesser genera. (Adapted from C. den Hartog, 1970)

Puerto Rico, and have been found down to 8,900 meters. This material is eaten by a variety of isopods, amphipods, annelids, gastropods, and bivalves. Thus the seagrass ecosystem may be described as a trap or filter, as well as a pump that links the land to open oceanic masses.

The Seagrass Ecosystem

There are approximately 45 species of seagrasses in the world's oceans, falling into two families and 12 genera. All are monocots (having a single seed in a leaf). The family *Potamogetonaceae* contains 9 genera and 34 species. The family *Hydrocharitaceae* contains 3 genera and 11 species. Most seagrasses have submerged flowers, with pollination occurring underwater.

By their presence on a landscape of relatively uniform relief, seagrasses create a diversity of habitats and substrates, providing a structured habitat from a structureless one. In 1937, R.C. Stauffer subdivided the eelgrass invertebrate community into four categories: 1) on the plants; 2) among the plants; 3) on the mud surface; and 4) in the mud. Only the two latter categories of animals would be present without the plants. Since many of the animals in these categories are either protected from wave action by the plant cover or are associated with the roots, it is probable that the species list in categories three and four would be considerably reduced if seagrasses were absent.

Because of their structure and physiology, seagrasses perform a wide assortment of biological and physical functions in the coastal environment. These functions were summarized in 1969 by E.J.F. Wood, W.E. Odum, and J.C. Zieman:

1. Eelgrass, a north temperate seagrass, has a high growth rate, producing on the average about 300 to 600 grams dry weight per square meter per year, not including root production.

2. The leaves support large numbers of epiphytic organisms (other plants attached to the eelgrass, not growing parasitically but using them for support), with a total biomass approaching that of the plants themselves. This diversity is possible because of the abundance of oxygen, nutrients, and food provided by the plants. Thus seagrass meadows provide a stable, benign, and predictable environment in which a great variety of organisms can grow.

3. Although a few organisms may feed directly on the eelgrass and several may graze on the epiphytes, the major food chains are based on eelgrass detritus and its resident microbes.

4. The organic matter in the detritus and in decaying roots indicates sulfate reduction and maintains an active sulfur cycle.

5. The roots bind the sediments together, and, with the protection afforded by leaves, surface

Table 1: Comparative average productivities of selected seagrasses and crop plants. (After McRoy and McMillan, 1977; Odum, 1959)

Species	Locality	Productivity (g C/m²/day)	Annual Productivity (g C/m²)
Seagrasses			
Thalassia testudinum	Puerto Rico	2.4-4.5	600-1125
(assume growing season	Florida	0.35-16	88-4000
of 250 days)	Texas	0.9-9.0	225-2250
Halodule wrightii (assume growing season of 120 days)	North Carolina	0.48-2.0	72-240
Zostera marina	Denmark	2.0-7.3	240-1095
(assume growing season	Rhode Island	0.4-2.9	60-435
of 120 days)	North Carolina	0.2-1.7	30-255
	Washington	0.6-4.0	90-600
	Alaska	3.3-8.0	495-1200
Cultivated Crops			
Wheat	World Average	0.94	344
Corn	World Average	1.13	412
Rice	World Average	1.36	497
Hay	U.S. Average	1.15	420
Sugar Beets	World Average	2.10	765
Sugar Cane	World Average	4.73	1725

erosion is reduced, thereby preserving the microbial flora of the sediment and the sediment/water interface. Since seagrass rhizomes form a dense, interlacing mat, and the leaves form a dense baffle, the plants are so effective in their hold on the bottom that they persist during tropical hurricanes, despite wave action caused by 150-knot winds.

6. The leaves retard currents and increase sedimentation of organic and inorganic materials around the plants.

7. Eelgrass absorbs nutrients through the leaves and roots; nitrogen and phosphorus can be returned to the water column from sediments via seagrasses.

Ecology of Seagrasses

Seagrasses tolerate a wide range of salinities from 6 ‰ (parts per thousand) to 60 ‰ (they even will tolerate fresh water for short periods). For eelgrass in the north-temperate zone, *Zostera marina*, the optimum range appears to be 10 to 30 ‰. For turtle grass in the tropics, *Thalassia testudinum*, the range is 20 to 35 ‰. For shoal grass in the tropics, *Halodule wrightii*, a pioneering and more adaptable species, the salinity range extends from 20 to 60 ‰.

Seagrasses also tolerate a wide range of water temperatures, varying from 0 to 40 degrees Celsius. The optimum temperature for growth and development of a species seems to depend on its specific location. It is likely that seagrasses form biotypes adapted to a local suite of salinity, temperature, nutrient, and weather conditions. Thus in Puget Sound, Washington, eelgrass grows, flowers, and develops seeds in a water temperature range of 6 to 13 degrees Celsius, whereas in Beaufort, North Carolina, the range is 0 to 33 degrees Celsius. The same is true for the two North American tropical species, *Thalassia* and *Halodule*. In the northern Gulf of Mexico, the temperature range is 7 to 32 degrees Celsius, whereas in southern Florida it varies between 17 to 32 degrees Celsius. At St. Croix, U.S. Virgin Islands, the range is 23 to 30 degrees Celsius.

The depth distribution of seagrasses depends on many interrelated factors — depth, waves, currents, substrate, turbidity, and light penetration. The plants usually occur from low tide down to about 10 meters. In the temperate zone, eelgrass maintains limited intertidal stocks, whereas in the tropics only shoal grass grows in sparse amounts in the intertidal zone. In some areas, eelgrass (San Diego Trench) and turtle grass (Bahamas) have been observed at depths of 30 meters. This lower limit is probably established by a combination of minimum light intensities and suitable substrate. Seagrasses may be restricted to less than 1 meter where waves stir up a muddy bottom.

Almost all species occur on unconsolidated muddy sand substrates, thus occupying a habitat virtually uncontested by benthic algae. In the tropics, species of the green algal families *Codiaceae* and *Caulerpaceae* grow on a muddy sand substrate. These algae are often abundant in a dense seagrass meadow. Only species of *Phyllospadix* in the North Pacific and *Posidonia* in Australia and Tasmania grow attached to rocky substrates. The substrates vary from coarse sand to almost liquid mud. The normal substrate is a reducing one beneath an oxidized surface layer. Cuts made by boat propellers in shallow-water meadows show how the union between seagrasses and their substrate can be disrupted. In some areas, such cuts are still noticeable up to 15 years after the act.

Seagrass Productivity

A probable key to the diversity of plants and animals in seagrass meadows is their productivity (Table 1). Representative values of annual production of *Thalassia* in the Caribbean range from 88 to 4,000 grams of carbon per square meter. Annual values for *Zostera* range from 6 to 1,200 grams of carbon per square meter. Thus seagrasses can grow as fast as cultivated corn or rice, hayfields, or tall grass prairies (corn annually produces 412 grams of carbon per square meter and rice, 497). On an areal basis, seagrass production rates can be higher than phytoplankton production off Peru, one of the most productive areas in the world's oceans. Since seagrasses are located in the nearshore coastal fringe, which also supports other shallow-water ecosystems, seagrass production is supplemented by that of benthic microalgae, macroalgae, epiphytes, phytoplankton, marshes, mangroves, and (in some areas) coral reefs.

Several components of the seagrass ecosystem have been found to be contributors to carbon cycling. The epiphytic flora on seagrasses can be diverse and very abundant, causing leaves to break or to be shaded from sufficient light, preventing photosynthesis. C. den Hartog published a list in 1970 of up to 200 algal species epiphytic on eelgrass alone. This productivity was measured at 20 percent of the mean annual net production of *Thalassia* in Florida (200 grams of carbon per square meter per year) and at about 25 percent of the annual production of *Zostera* in North Carolina. In addition, seagrasses excrete a considerable quantity of dissolved organic carbon (DOC) into the water mass, which is then available for uptake by other local plants or for export offshore. It was found that eelgrass and its epiphytes contributed almost 15 percent of the total DOC in the estuarine system near Beaufort, North Carolina. The conclusion was that these plants are an important part of the carbon cycle in an estuary.

Seagrasses produce and consume great quantities of oxygen. A study done in Holland in 1935 showed a supersaturation of the waters over the plants of 260 percent in mid-afternoon. At night the waters became anoxic. In Florida, *Thalassia* leaves during the day swell as much as 200 to 250 percent of their early morning volume due to the internal production of oxygen. Since the leaves lack stomata, the oxygen is forced out of the leaves at the edges in long streams. Moreover in a shallow, calm meadow, with little water flow, it is possible to hear a hissing from the rapid bubbling. The appearance, as described by one researcher, is akin to that of a "newly opened bottle of beer!"

Animal Diversity

Some of the earliest studies conducted on animal life in the seagrass ecosystem were done at the Biological Station in Copenhagen, Denmark. The first was a report by C.G.J. Petersen in 1891, stating his belief that fish abundance in Denmark was due to eelgrass. Other Danish scientists, working from the same station, concluded that the eelgrass belt was faunistically the richest in their fjords. The water over the plants teemed with small crustaceans, molluscs, and fish. Outside this plant belt the fauna was much poorer. Much the same findings have been reported for eelgrass meadows in the United States and Japan. A typical animal list would include ciliates and flagellates, hydroids, polychaetes, coelenterates, snails, clams, scallops, shrimp, amphipods, isopods, bryozoans, opistobranchs, crabs, copepods, nematodes, echinoderms (such as sea urchins and starfish), lamellibranchs, ostracods, and pycnogonids. A diversity of fish and wildfowl also inhabit eelgrass meadows. Tropical meadows support the same diversity and abundance of animals. In addition, tropical turtle-grass meadows often support populations of green, loggerhead, and hawksbill turtles, as well as dugongs and manatees, all of which eat the seagrasses (Figure 4).

Many animals occupy a seagrass meadow as larvae only (crabs, scallops, and fish), while others pass through either as zooplankton or as migrating fish. A number of animals, many of which are food animals, live in the seagrass beds throughout their life, such as clams, shrimp, crabs, and various fish (Figure 5).

The importance of seagrass systems, however, does not lie only in their direct food value to animals. They also provide a habitat for the growth of both commercial and noncommercial fish and invertebrates, while providing protection from predators (Figures 6 and 7). Thus seagrass meadows act as a nursery, as well as being one of the most valuable marine resources in terms of overall coastal ecology and fisheries production. In 1918,

Figure 4. Loggerhead turtle caught in eelgrass meadow at Puenta Chueca in the Gulf of California. (Photo by Tom Backman)

Petersen, summarizing the work of three other scientists on the eelgrass ecosystem in the Kattegat region of Denmark, reported that detritus formed from eelgrass served as the basis for several invertebrate communities, and that this ultimately led to several species of food fish important to the Danish economy. These conclusions were challenged in 1931, when a massive die-off of 90 to 100 percent of the eelgrass in the North Atlantic occurred. Exactly why the eelgrass died out is still a matter of conjecture.

Following the die-off, most of the animals associated with eelgrass — such as scallops, clams, crabs, and waterfowl — disappeared. In some areas, black brant geese populations diminished by up to 90 percent. Fish populations fell off sharply but not as drastically as Petersen might have predicted. It is now believed that the rich organic sediment built up by the eelgrass system over the years, but devoid of the plant cover, began to release nutrients into the water mass, thus cushioning an immediate impact on the fisheries.

Food Chains

The most important role of seagrasses in the food chain is the death and decomposition of the living plants to form detritus (Figure 8). A variety of investigators, including several of the early Danish group to more contemporary scientists working in the northeastern United States, California, and Japan, have concluded that detritus is probably the single most important item at the base of food chains in intertidal and shallow subtidal communities.

Evidence is accumulating, however, that detritus *per se* is not the primary source of food when it is ingested by the teeming masses of clams, oysters, worms, and crustaceans — the detritivores. Other researchers have shown that detritus is a substrate for large numbers of bacteria, which are the real food for detritivores, allowing many marine invertebrates to live almost indefinitely on an exclusive diet of bacteria.

A general food chain is shown in Figure 9. The bacterivorous fauna include zooflagellates (protozoans), and some species of ciliates and rotifers, while the carnivorous microfauna include ciliates, rotifers, and turbellarians. The detritus feeders include amphipods, gastropods, bivalves, polychaetes, and oligochaetes. These chains are long and complex. It appears that many of the food animals gathered in the inshore coastal environment result from detritus food chains that are associated with seagrass meadows.

There is an important relationship between seagrass detritus formation and nutrient cycling within and across ecosystem boundaries. The plants themselves absorb phosphorus, nitrogen, sulfur, and carbon through the roots and, to some extent, through the leaves, pumping them into the water mass where they can be used by epiphytes and phytoplankton. Particulate detritus is poor in essential nutrients, while bacteria contain very high amounts of phosphorus and nitrogen. Bacteria absorb nutrients from the water and, while acting on the detritus, enrich it with nitrogen and phosphorus. Mineral nutrients cycle between bacteria and animals, the latter remineralizing the nutrients by digesting the bacteria. At the same time, the seagrass plants are excreting dissolved

Figure 5. Dungeness crab, Cancer magister, *found in eelgrass meadow in Puget Sound. (Photo by Author)*

Figure 6. Simpson's sunstar, Solaster simpsonii, *in eelgrass meadows in Puget Sound, Washington. This starfish forages for clams among the plants. (Photo by Author)*

Figure 7. Sand dollars, Dendraster sp., *are often found on sand adjacent to meadows in Puget Sound, where they dig, undercut, and uproot the eelgrass. If the animals are excluded by cages, the eelgrass returns to the denuded patch. (Photo by Author)*

organic carbon (DOC) and matter (DOM) into the water column. These are available to epiphytes on the seagrasses, benthic macroalgae and microalgae in the meadows, as well as phytoplankton in and outside the ecosystem.

The detritus is involved in a complex chemistry of nutrient cycling in the substrates of a seagrass meadow. Because of the quantity of dead leaf material falling from the plants and the rate of its decomposition by bacteria, sediments in a meadow become reducing below a very shallow oxidized layer. In turn, because of this and an abundance of sulfur bacteria, the sediments tend to be dominated by the sulfur cycle. This is related to a rich microflora and microfauna.

Sediment Stabilization

All research indicates that seagrass leaves in a meadow act as a baffle that increases the rate of particulate sedimentation, preferentially concentrating the finer particle sizes and stabilizing the underlying sedimentary deposits. This occurs through the entrapment of water-borne particles by the leaf blades, the formation and retention of particles produced within the meadows, and the binding and stabilization of the substrate by the rhizome and root systems. These effects can be local or widespread. Two examples of the long-term, widespread influence of seagrasses on sedimentation and stabilization are the carbonate bank along the eastern margin of Shark Bay in Western Australia, and the grass-bound "mattes" on the Mediterranean coast of France.

The effect of seagrass meadows on sediment stabilization is well documented. When the eelgrass disappeared in 1931, sand banks formerly covered by the grass in Salcombe Harbor, England, were lowered by 30 centimeters or more almost overnight. Many species of filter-feeding invertebrates and molluscs, and several flatfish also disappeared. Several people have observed that *Thalassia* meadows suffer little damage from

Figure 8. Detached seagrass leaves often pile up on a beach, where they are mechanically ground up into particulate matter called detritus. This detritus and other dissolved materials released in the process float back to sea and form the basis of long, complex food chains. (Photo by Author)

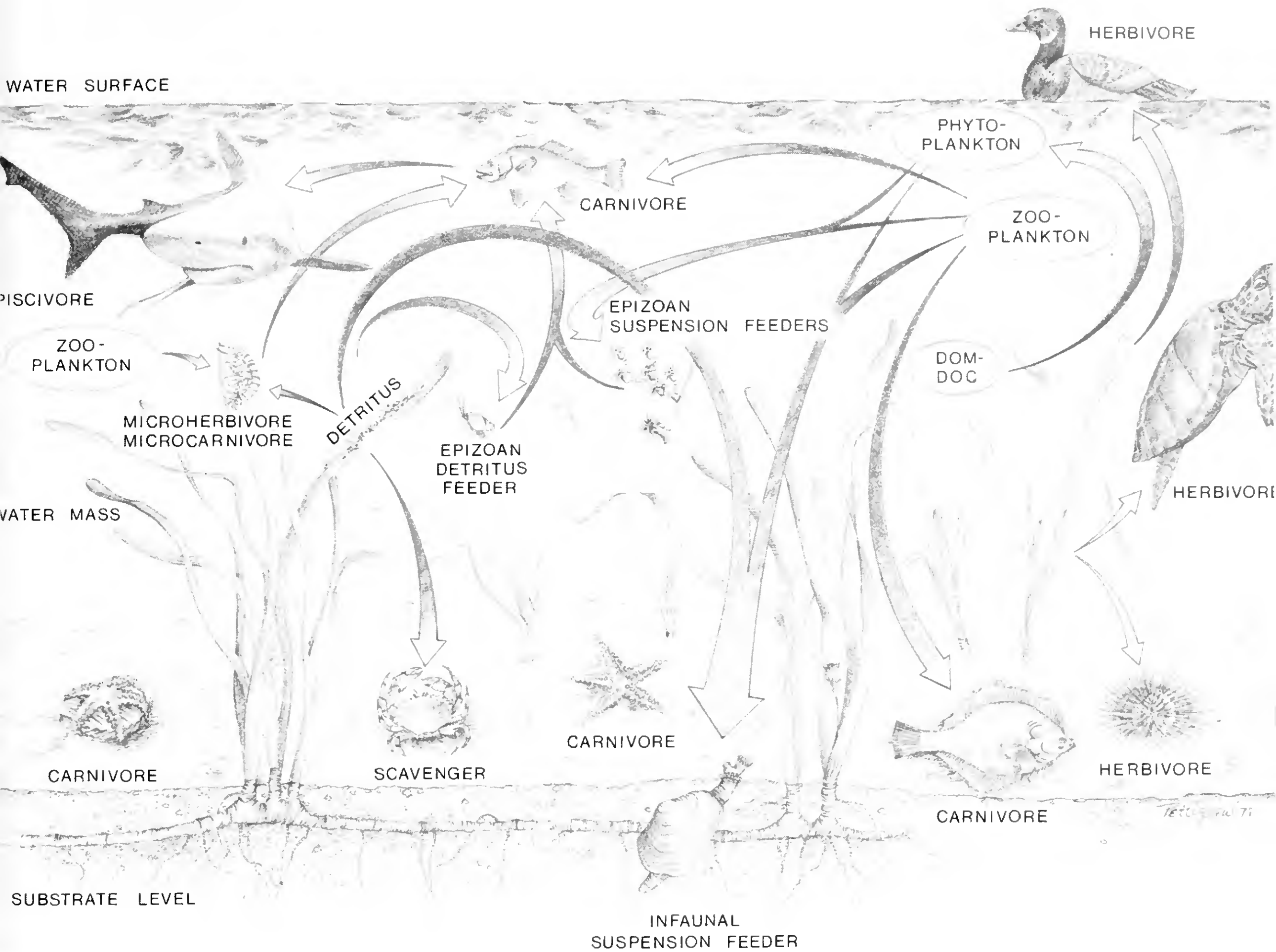


Figure 9. Generalized food chain for seagrasses. (Adapted from J. C. Ogden, in press. Drawing by Trish Pettigrew)

hurricanes (some of which produce 150-knot winds) in Florida and Texas. Bottom areas recover quickly due to a rapid growth rate of leaves (up to 25-millimeter increments per week), and the sediment remains intact. Up to 10 to 20 centimeters of sediment have eroded from unvegetated sand banks following a single storm in Chesapeake Bay, Maryland, while little, if any, disappeared from within an eelgrass meadow.

Sediment stability is a function of density and the species of seagrass. *Thalassia* (wide, flat blade) is more effective at binding sediment than is *Syringodium* (narrow, terete blade). Observations indicate there is a decreasing density of plants and an increasing amount of sediment removed by turbulent water as one moves closer to the edge of an eelgrass meadow. Also there is a positive correlation between sediment stability and invertebrate diversity.

Strengths and Frailties

Almost all species of seagrasses grow on unconsolidated substrates. There is evidence that the plants function not only to stabilize the physical milieu of their environment, but that they also originate, drive, and coordinate a great diversity of chemical and biological events. The very dense mat of roots and rhizomes binds sediments, while the dense meadow of leaves acts as a baffle to surges and currents. This promotes and accelerates sedimentation of plankton, epibiota, and seagrass detritus. In turn, this leads to complex chemical cycles of gases and nutrients, trophic webs, and a high level of primary and secondary productivity.

Despite the ability of seagrasses to adapt to a fluctuating environment, several human-related activities threaten these hearty plants. Dredging poses the greatest danger. Not only are the plants removed, but the physical, biological, and chemical structures of the ecosystem are changed. Sediments may bury plants, but can also reduce plant density. This could result from sediment accumulation alone or in concert with an increased water turbidity. Sediment textures change from a mixture of sand and fine silts to sand, while chemistry changes from a reduced to a highly oxidized state. Lacking a cover to reduce erosion, the water over unconsolidated substrates turns from crystal clear to very turbid. The influence of turbid water on seagrass growth appears to be the same for all seagrasses. Where very turbid water prevails, *Thalassia* and *Zostera* are limited to a maximum depth of 3 meters, while populations of both have been observed down to 30 meters where the water is clear. Several studies have documented the drastic reduction in fauna, macroinvertebrates, and fishery products in both tropical and temperate seagrass meadows following dredging.

The reasons for dredging in the inshore coastal environment are varied. Since shipping and boating are necessary, maintenance dredging must be done to keep channels open. When this happens near seagrasses, large quantities of silt are deposited over indigenous seagrass meadows accompanied by turbid water over the plants. The greatest amount of dredging, however, involves the creation of new real estate. This became a serious problem in Florida in the mid-1950s; in the Tampa Bay area, for example, vast acreage was dredged and smothered by silt. More recently, dredging in seagrasses near coral reefs in southern Florida has increased. In fact, dredging has increased on a broad scale worldwide. Seagrass meadows and coral reef systems are currently being threatened in several areas where ports are planned to receive oil supertankers. Channels that are normally 35 feet deep for most shipping must be lowered to 70 feet. These channels also must be greatly lengthened, which results in continuous maintenance dredging.

The use of the hydraulic clam dredge also is increasing. It is indeed an economical method of harvesting clams from a seagrass meadow, but a destructive one since it blasts sediments to a depth of 45 centimeters. Most seagrass rhizome mats are located at a maximum depth of 15 centimeters. This type of dredging has been done in *Thalassia* and *Zostera* meadows in such diverse areas as Florida and Washington, respectively.

Thermal effluents also have a critical effect on seagrasses. All seagrasses appear to have upper and lower temperature tolerance levels. The upper level for eelgrass is 30 degrees Celsius; turtle grass approaches 35 degrees. Above such levels, leaf kill and plant death set in. Jay Zieman of the University of Virginia and Anitra Thorhaug of Florida International University have documented the extensive damage done to *Thalassia* in Biscayne Bay by heated effluents from two fossil fuel and two nuclear power plants at Turkey Point. Water near the plants in Biscayne Bay was raised up to 5 degrees Celsius above the ambient temperature. All plants in an area of about 9.3 hectares off the mouth of the discharge canal disappeared, while those in an area 30 hectares farther out declined by about 50 percent. The animal communities associated with these meadows also disappeared. Sediments off the fossil fuel plants also contained much higher levels of nickel, copper, vanadium, lead, cadmium, zinc, and iron than those not affected by the thermal plumes in Biscayne Bay.

In recent years, humans have dumped increasingly greater amounts of heavy metals, oil products, synthetics (such as DDE, DDT, and chlorinated hydrocarbons), solid wastes, domestic pollution, pesticides, detergents, fertilizers, and pharmaceuticals into the shallow waters of our inshore coastal areas. There has been little concern about the presence or absence of plant communities in these areas or for the impacts of these pollutants on them.

Solid wastes and domestic sewage adversely affect seagrass ecosystems by increasing sedimentation too quickly and by decreasing light penetration in the water. Studies are lacking on turtle grass and eelgrass but a team of scientists in England has determined that *Zostera noltii* can only tolerate changes of $\pm$ 7 centimeters per year or 3 centimeters per week. Meadows can be smothered by too much silt caused by upland erosion and runoff or dredging. For example, eelgrass meadows in Newport Bay, California, were reduced to isolated patches after dredging caused the plants to be smothered.

There is accumulating evidence that oil spilled in the sea damages both seagrasses and the surrounding community. This is presently the subject of on-going research. Certainly, oil kills seabirds and interferes with the development of animals, such as marsh crabs and some fish. Crude oil spillage on the south coast of Puerto Rico resulted in severe and long-lasting damage to tropical meadows of *Thalassia*. Following a crude oil spill at Santa Barbara, California, on January 28, 1969, it was reported that heavily coated leaves of *Phyllospadix torreyi*, a rock-inhabiting seagrass, were killed when oil made direct contact with air-exposed leaves at low tide. Plants located in 10 centimeters of water were protected from the damaging effects of the oil. Another study found that oil adhered to the leaves of this seagrass, subsequently killing them. It was also reported that the oil moved into the sediments, where it had a severe effect on the invertebrates, consequently moving up the food chain to humans. New leaves grew when the oil in the water was removed. Thus, except for the long-term residual effect of oil on the benthic animal community and its passage through the food chains, there was little noticeable effect of spilled oil on the seagrasses themselves.

Restoration of Seagrasses

Following the massive die-off of eelgrass in the North Atlantic in 1931, experimental work began on restoration methods to accelerate the normal 30-year period required for recovery. Early attempts

Figure 10. Eelgrass fixed serially to an iron rod and transplanted from the intertidal to a subtidal site in Puget Sound, Washington, in February, 1965. (Photo by Author)

Figure 11. The same site as Figure 10, but in September 1965. (Photo by Author)

in the 1940s were not successful. It is compelling and necessary that new attempts be made, since human activities that affect seagrasses are increasing.

Before any successful large-scale applications can be made, basic experimental work must be done on seagrass transplantation to discern phenotypic plasticity, biotype formation, and the range of adaptational response of a seagrass species. Seagrass transplantation has two major objectives: 1) to stabilize bottom sediments and to prevent erosion, and 2) to increase productivity in an area that has lost a seagrass cover.

There are two basic transplantation methods presently under investigation. One uses seeds and seedlings. It has achieved success in restoring *Thalassia* growth following its decimation by thermal effluents from the Turkey Point energy plant in Biscayne Bay, Florida. The other method involves the transplantation of vegetative material (Figures 10 to 13). Both methods have certain advantages. Vegetative material results in rapid seagrass growth, especially when planted intact as turfs or plugs in the original sediment, but large quantities of such material can be difficult to transport over long distances. Seeds are much easier to transfer in quantity, but germination rates at ambient salinities are low as is survival in the field. Vegetative material provides for greater survival chances after transplantation, as well as offering the full range of adaptive responses to the environment.

The only large-scale field project using the vegetative method was tried on North American seagrasses growing on dredge spoil banks at Port St. Joe, Florida. The U.S. Army Corps of Engineers sponsored the experiment, which involved transplanting a pioneering species of shoal grass, *Halodule wrightii*, in the sand. After a year, the plugs became fully established, demonstrating that transplantation of seagrasses on dredge spoil is feasible. Within a year, animals (crabs, birds, fish) found in local shoal grass meadows began to invade the new plants.

Thus seagrass restoration projects are possible. They can be used to stabilize spoil bank sediments and to restore seagrass growths that have disappeared, and even to enhance the productivity of meadows that suffer natural or human perturbations.

Figure 12. Eelgrass transplanted as 20-centimeter plugs (plants intact in original sediment) on December 19, 1974. Note flatfish moving over newly transplanted seagrasses. (Photo by Author)

Figure 13. Same site as Figure 12, but on March 4, 1977. The plants from the original plugs have grown enormously and have greatly expanded their coverage over the bottom. (Photo by Author)

Past, Present, and Future Studies

The earliest seagrass studies in the United States were done by William A. Setchell from 1920 to 1935. These represent fundamental phenological and taxonomic studies and underlie most of the later work. From 1935 to about the mid-1950s, seagrass studies in the United States centered around the cataloguing of plant and animal changes resulting from the eelgrass epidemic of the 1930s.

In 1973, with the aid of the National Science Foundation (NSF) and the International Decade of Ocean Exploration (IDOE), C. Peter McRoy of the University of Alaska formed a steering committee that convened an International Seagrass Workshop at Leiden, The Netherlands. This workshop was attended by 38 investigators from 11 countries. The purpose was to assess past studies and to formulate future research needs. Following this workshop, the NSF/IDOE funded a Seagrass Ecosystem Study, utilizing a team approach to seagrass research. This study, currently underway, should prove useful in explaining and predicting patterns of development and activity in seagrass and epiphyte productivity, animal phenology, and the patterns of nutrient cycling in the seagrass ecosystem.

With research conducted thus far, we are able to intelligently advise governmental agencies that have control over our nearshore coastal ecosystems, thus reducing adverse impacting of seagrass ecosystems. In the past, these impacts (such as dredging, thermal and sewage effluent dumping, and oil spills) have damaged these ecosystems, reducing or decimating fish catches, oyster harvests, and clam and shrimp landings.

Future research work should concentrate more intensively on nutrient and heavy metal cycling between seagrasses, the sediments, and water masses. More work also is needed on seagrass productivity and the factors that reduce and increase it; harvesting procedures and nutritional analysis; the use of seeds; temperature tolerances and the daily requirements of plants from different areas; and research on certain vigorous strains that might produce higher yields.

I recently received a letter from a Peace Corps volunteer in Ghana who was interested in using eelgrass as a substitute for bacterial cultivation that could then be used as a nutritional supplement for underfed people. Since the seagrass ecosystem is a detritus-based system and bacterial films on seagrass detritus are the fundamental food items at the base of the food chain, it would be interesting to follow up on the nutritional aspects of seagrass cultivation.

Thus there are many directions for future applied research to take. As I have indicated, it can relate to the use of seagrasses or their seeds for food, or the use of associated bacteria for food. Perhaps the leaves can be used for carbohydrate and/or protein extracts; new meadows can be created by transplantation in coastal ponds, which in turn can be used to generate food animals; and transplantation can also serve to reduce or stop coastal erosion, thus saving millions of dollars. Then, too, when we know enough, we can preserve our natural, existing seagrass meadows. In this way, we would make the highest, most advanced use of our research knowledge in a predictive management program.

Ronald C. Phillips is Professor of Biology at Seattle Pacific University, Seattle, Washington. He has been involved in seagrass research since 1957.

This material is based upon work supported in part by the National Science Foundation under grants OCE76-01307, OCE76-84259, and OCE77-25559.

References

Foster, M., M. Neushul, and R. Zingmark. 1971. The Santa Barbara oil spill. Part 2: Initial effects on intertidal and kelp bed organisms. *Environ. Pollution* 2: 115-34.

Hartog, C. den. 1970. *The seagrasses of the world.* Amsterdam: North-Holland Publ. Co.

Marshall, N. 1970. Food transfer through the lower trophic levels on the benthic environment. In *Marine food chains,* ed. by J.H. Steele, pp. 52-66. Berkeley, Ca.: Univ. California Press.

McRoy, C.P., and C. McMillan. 1977. Production ecology and physiology of seagrasses. In *Seagrass ecosystems: a scientific perspective,* ed. by C.P. McRoy and C. Helfferich, pp. 53-87. New York: Marcel Dekker, Inc.

Neushul, M. 1970. The effects of pollution on populations of intertidal and subtidal organisms in southern California. Santa Barbara Oil Symposium. 16-18 Dec. 1970. Univ. of California, Santa Barbara.

Odum, E.P. 1959. *Fundamentals of ecology.* 2nd Ed. Philadelphia, Pa.: Saunders.

Ogden, J.C. In press. Faunal relationships in Caribbean seagrass beds. In *A handbook of seagrass biology: an ecosystem perspective,* ed. by R.C. Phillips and C.P. McRoy. New York: Garland Publ., Inc.

Petersen, C.G.J. 1918. The sea bottom and its production of fish food. A survey of the work done in connection with valuation of the Danish waters from 1883-1917. Rept. Danish Biol. Sta. 25: 1-82.

Rasmussen, E. 1977. The wasting disease of eelgrass *(Zostera marina)* and its effects on environmental factors and fauna. In *Seagrass ecosystems: a scientific perspective,* ed. by C.P. McRoy and C. Helfferich, pp. 1-51. New York: Marcel Dekker, Inc.

Schubel, J.R. 1973. Some comments on seagrasses and sedimentary processes. Chesapeake Bay Institute, The Johns Hopkins University, Ref. 73-12. Spec. Rept. 33, pp. 1-32.

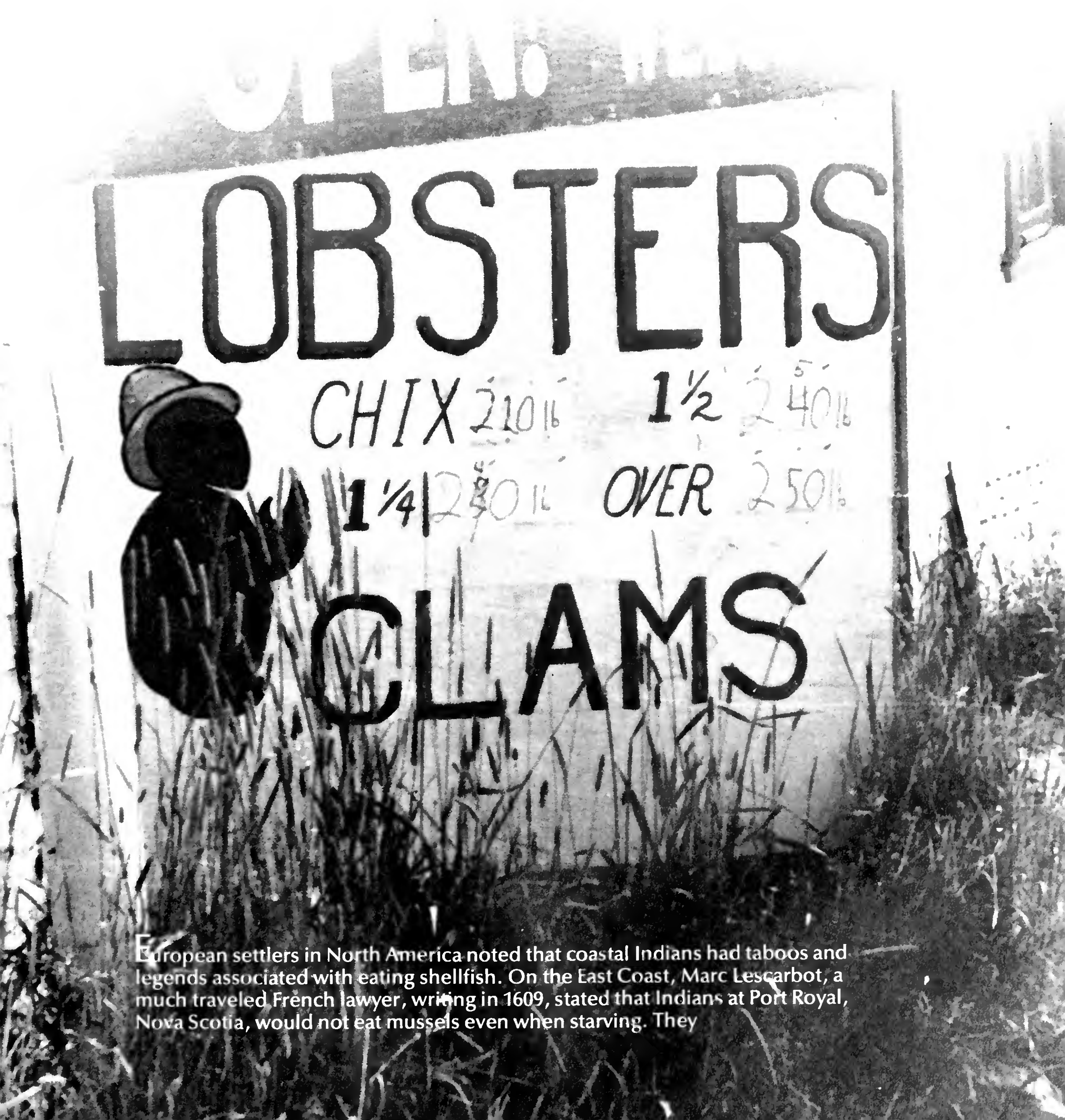
Stauffer, R.C. 1937. Changes in the invertebrate community of a lagoon after disappearance of the eelgrass. *Ecology* 18: 427-31.

Thayer, G.W., D.A. Wolfe, and R.B. Williams. 1975. The impact of man on seagrass systems. *Amer. Sci.* 63(3): 288-96.

Wood, E.J.F., W.E. Odum, and J.C. Zieman. 1969. Influence of seagrass on the productivity of coastal lagoons. Lagunas Costeras. Un Simposio Mem. Simp. Intern. UNAM-UNESCO, Mexico, D.F. Nov. 1967. pp. 495-502.

Red Tide
and Paralytic Shellfish Poisoning

by Barrie Dale and Clarice M. Yentsch



European settlers in North America noted that coastal Indians had taboos and legends associated with eating shellfish. On the East Coast, Marc Lescarbot, a much traveled French lawyer, writing in 1609, stated that Indians at Port Royal, Nova Scotia, would not eat mussels even when starving. They

Figure 1. Boston area newspaper articles, many of which were published after the September 1972 outbreak of PSP.

would eat their dogs and the bark from trees instead. On the West Coast, some Indian tribes maintained a nightly lookout for bioluminescence* in the sea, and they would not eat shellfish when the sea was "glowing." From the Alaskan Coast, there is a legend that Indians disposed of a group of troublesome Russian settlers by inviting them to a feast of shellfish near the islands of Baranov and Chichagof.** The passage between these islands is to this day called Peril Straits, a name that puzzles mariners who can see no obvious navigational hazards. It is probably no mere coincidence that scientists recently discovered extremely toxic shellfish in this vicinity. Examples such as these suggest that the Indians were aware of what scientists today generally call paralytic shellfish poisoning (PSP), and what the lay person calls red tide. These early records establish an important point — that PSP is a natural phenomenon that occurred centuries before the modern industrial world developed.

*Production of light by numerous minute marine and other organisms, for example fireflies, bacteria, and fungi. The light is due to an enzyme-catalyzed chemical reaction, which produces very little heat. In the sea, the phenomenon is most pronounced when the water is disturbed. Many dinoflagellates, some of which produce toxins, are bioluminescent.

**Ironically, when U2 pilot Gary Powers was captured by the Russians in 1960, he carried a suicide vial of saxitoxin.

Why Red Tide?

The term red tide means different things to different people. To the oceanographer, it may mean concentrations (blooms) of planktonic organisms that discolor the sea. In the temperate oceans, blooms of algae occur seasonally and the plankton ecosystem is regulated by their occurrence. On the other hand, the lay person usually associates the term red tide with *adverse effects*. For example, on the coast of Florida, red tide generally signals fish kills, and the spectacle of dead fish on beaches. In northeastern and northwestern North America, the lay person associates red tide with toxic shellfish, and the dangers of paralytic poisoning (Figure 1).

Discolored water — as the term is used here — results from the absorption of light by the pigmentation in planktonic organisms. However, the term red tide is inadequate when used with reference to PSP: red water is often the result of the activities of nontoxic organisms. For example, the larvae of many marine invertebrates swarm, turning the water a rust-red color. Also, there are nontoxic algae that can discolor water. The terminology problem is further complicated by the fact that toxic dinoflagellates may not always be of sufficient abundance to discolor the water,* although they may be numerous enough to toxify shellfish.

*This was not the case in 1972 when the entire Massachusetts, New Hampshire, and Maine coastlines were closed to shellfishing; red patches were in evidence.

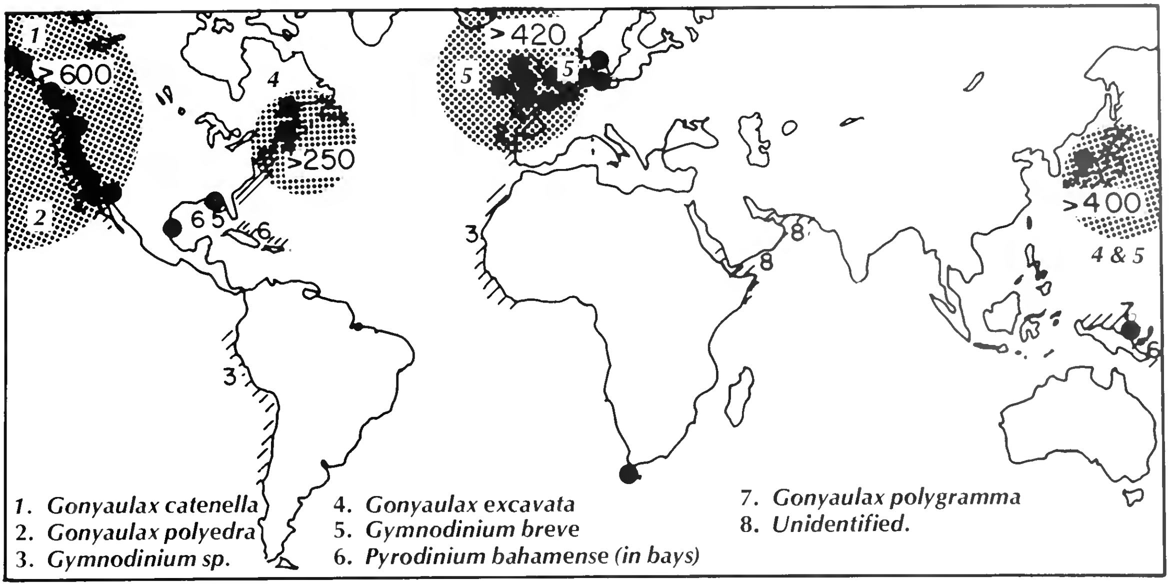


Figure 2. World distribution of PSP incidents. Numerals in hatched areas indicate approximate total numbers of human poisonings in the four major areas affected; dots represent individual outbreaks. (After Prakash, Medcof, and Tennant, 1971; and B. Sweeney, 1976)

Hence, the misnomer "red tide." In fact, there is no accurate general term that applies to dinoflagellate-borne toxicity.

In the last 20 years, research has solved some of the mysteries of PSP, but it also has raised important new questions. Disturbing evidence* that PSP may be increasing in intensity and spreading to new areas has spurred scientific efforts in the last few years. In view of this and the meeting of the Second International Conference on Toxic Dinoflagellate Blooms in Florida October 31 to November 5, 1978, it is appropriate to review what we know and do not know about PSP.

*In 1972, parts of southern Massachusetts having no previous history of PSP were affected, and in 1976 PSP was reported off northern Spain for the first time.

The Nature of PSP

PSP is a food poisoning that occurs when toxins accumulated in shellfish are passed on to humans. It is known to have caused at least 300 fatalities worldwide (Figure 2). The symptoms of the ailment are summarized in Table 1. There is evidence that individuals who habitually eat shellfish containing low levels of toxin can build up a limited immunity. However, it is not only the tourist visiting the coast who succumbs to PSP, but the local person as well (hospital records have even included the name of a coastal warden!). A major difficulty with clinical diagnosis is that the symptoms are often interpreted as those associated with drunkenness (in combination with alcohol, the toxins are known to accentuate these symptoms). In at least one state, Maine, the local medical association has launched a major effort to make physicians and public health

Table 1. Symptoms of PSP.

Symptoms	MILD	SEVERE	EXTREME
Tingling sensation or numbness around lips, gradually spreading to face and neck. Prickly sensation in fingertips and toes. Headache, dizziness, nausea.	MILD	SEVERE	EXTREME
Incoherent speech. Progression of prickly sensation to arms and legs. Stiffness and noncoordination of limbs. General weakness and feeling of lightness. Slight respiratory difficulty. Rapid pulse.		SEVERE	EXTREME
Muscular paralysis. Pronounced respiratory difficulty. Choking sensation.			EXTREME

officials in coastal areas aware of PSP symptoms. One of the most dangerous myths is that cooking denatures the toxins; although cooking slightly reduces the toxins, it is not an adequate precaution. Once determined or suspected toxic, shellfish should be destroyed.

In the body, these toxins act on the nerves. As neurotoxins, they inhibit the sodium/potassium pump that controls the electrical conduction in the nerve. The prevention of nerve impulses to the diaphragm may cause death by respiratory paralysis within 24 hours after ingestion. Efforts to discover an antidote for the toxins have been unsuccessful. A patient suffering severe symptoms has his stomach pumped and is given artificial respiration in an iron lung. Fortunately, once the toxins have worn off, there are no known lasting effects. For this reason, they are referred to as "clean" toxins and are used in some types of neural and coronary therapy.

For public health protection, the PSP problem is costly. Officials face two choices: to monitor shellfish toxicities, or to close the coast to shellfishing altogether (Figure 3). A dramatic example of the latter is the vast coastline of Alaska, which has been closed to harvesting clams and mussels since 1947, following severe outbreaks of PSP. Alaskan shellfish represent an important financial resource, and there is great pressure to reopen the coastline in some areas.

Most shellfishing areas in the United States run toxicity monitoring programs, which regularly test shellfish from representative locations.* The standard mouse test was developed in 1937 and has remained virtually unchanged. A liquid fraction is extracted from macerated shellfish meats and injected intraperitoneally into laboratory mice (Figure 4). The times of death of the mice are related to the toxin level. Typical toxicity levels are shown in Table 2. The "total consumed" level can be the result of eating 12 clams weighing 100 grams at toxin levels of 80 micrograms per 100 grams of tissue, or one clam weighing 100 grams at 1,000 micrograms per 100 grams of tissue.

Toxic Dinoflagellate Ecology

Together with diatoms and coccolithophores, dinoflagellates are major components of marine phytoplankton. They are microscopic, one-celled, and motile (propelled by two flagella). Many dinoflagellates, including those producing shellfish toxins, are bioluminescent, which is probably why the West Coast Indians learned to associate shellfish toxicity with light flashes in the sea. An important feature of dinoflagellates in the context

*Several European countries have or are considering setting up a monitoring program following the 1976 outbreak of PSP off the coast of northern Spain.

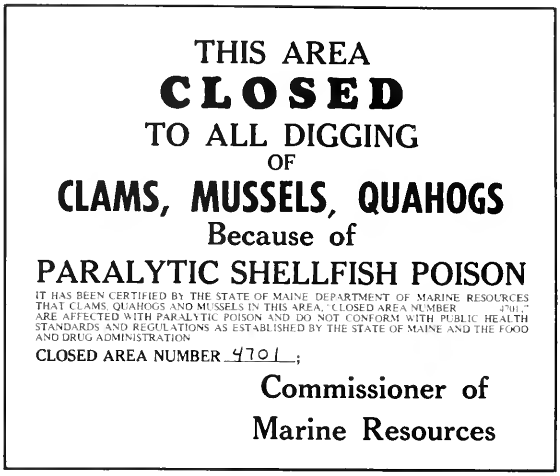


Figure 3. Warning sign for PSP.

Figure 4. The mouse test, the standard method for determining levels of toxin in shellfish. The mouse is injected with liquid from the affected shellfish, and the toxicity level determines the death time.

Table 2. Typical toxicity levels, based on mouse test results.

	Toxin level expressed as micrograms per 100 grams tissue
Limits of mouse test sensitivity.	58
Closure level in United States for shellfish.	80
Moderate symptoms in human adult.	1,000
Lethal level in human adult.	10,000
Highest level in mussels at Monhegan, Maine, in 1975.	22,000

of red tide is their ability to reproduce asexually at a rate from once every five days to twice a day in some cases. This allows a population with relatively few cells to develop quickly into a large concentration (bloom).

It takes concentrations of nearly 1,000,000 cells per liter to discolor seawater. Such concentrations are obtained in two principal ways: 1) accelerated biological growth, which is dependent on specific environmental factors, such as temperature, light, and certain nutrients, and 2) physical (hydrography) mechanisms that concentrate the dinoflagellates. These mechanisms are triggered by meteorological events, such as wind and rain. Most situations are a combination of the two.

Most areas of red tide occurrence are located between the extremes of active upwelling and passive concentrating mechanisms. In some cases, such as off the coasts of Britain, fronts are identified as the zones where red tides are most likely to occur. These frontal zones, or discontinuities between water masses, are formed by tides, winds, and/or the density of seawater.

The majority of the scientific observations of discolored water have been made by chance encounter. Some evidence suggests that red tides are noticed only when the bloom is in its final stages. Thus the initiation and maintenance of the bloom are "history" by the time of observation. This has handicapped studies of bloom formation. An analogy has often been drawn to studies of cancer: once it is observed, it is difficult to reconstruct the historical causes.

Until recently, the process leading to shellfish toxicity was thought to involve a very restricted group of dinoflagellates producing the toxin saxitoxin. These were *Gonyaulax catenella* and/or *G. acatenella* on the west coast of North America, and *G. tamarensis* in northwestern Europe and on the east coast of North America and Japan. Under certain environmental conditions — such as reduced salinity and high organic runoff from land, these species developed large bloom populations. Shellfish were found to toxify as they ingested these motile dinoflagellate cells, particularly under bloom conditions. For many years, scientists have studied the dinoflagellates implicated in PSP, both in laboratory cultures and in nature. The main objectives behind this work have been to identify the species responsible for producing the toxins, to document their growth requirements, and to identify any particular environmental factors contributing to shellfish toxin development. It has been hoped that this might lead to the development of a predictive index, giving public warning of approaching shellfish toxicity. Suggestions for such an early warning system included monitoring motile dinoflagellates in the water and looking for developing blooms.

Taxonomy and Life History Aspects

In recent years, taxonomists have taken a closer look at the small, related group of dinoflagellates producing the toxins responsible for PSP. They have come across a problem common to dinoflagellate studies: how to effectively use minute, morphological details to identify these organisms. Such problems, which were difficult enough using ordinary light microscopy, have become more complicated with the introduction of the scanning electron microscope (SEM). It is now clear that within what used to be called *G. tamarensis* there are several different organisms, based on minute, morphological and physiological details.* As yet, there is no consensus as to whether these should be regarded as different species, strains, forms, or varieties; but work is proceeding on at least recognizing and identifying them (Figure 5). It will be important to establish whether these forms have environmental preferences, and particularly whether they have different inherent toxicities, or whether the toxicity is induced by various environmental factors. Obviously, if they all behave similarly, classification can be treated as a minor academic problem. However, evidence suggests that both in laboratory cultures and in nature at least one form is nontoxic, posing problems for the microscopist trying to monitor toxic dinoflagellates in plankton (see page 19).

A rapidly developing area for research concerns the life histories of these dinoflagellates.

*The New England organism is now referred to as *Gonyaulax tamarensis* by some and *Gonyaulax excavata* by others.

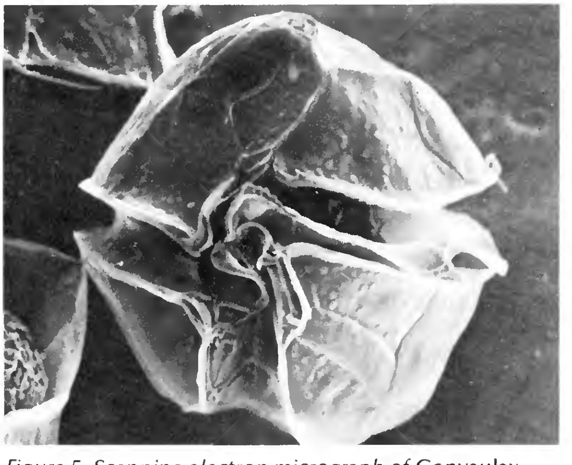


Figure 5. Scanning electron micrograph of Gonyaulax excavata, *which was isolated off Gloucester in the 1972 red tide occurrence. The diameter of the cell is 36 microns. (Courtesy Alfred and Laurel Loeblich, University of Houston, Texas)*

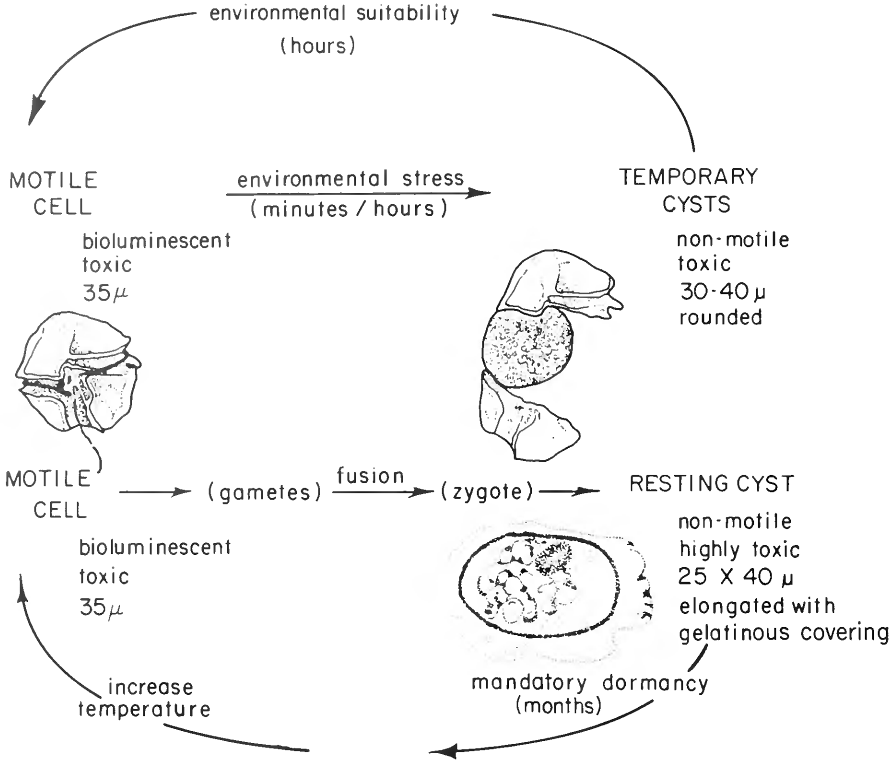


Figure 6. Probable life history cycle of Gonyaulax excavata.

It has been shown that in addition to the familiar motile stage, present in New England waters from mid-April to mid-October, *G. excavata* produces at least two other nonmotile stages (Figure 6). One is called a temporary cyst, since it is easily induced in cultures of motile cells subjected to unfavorable conditions, and since it quickly (within hours) reestablishes a motile population on return to favorable conditions. So far, temporary cysts have been seen only in laboratory cultures. We think that their role in nature might be to provide a method for overcoming temporary environmental setbacks.

A second type of nonmotile cyst — the resting cyst (Figure 7) — is probably a zygote produced in sexual reproduction. These cysts, equipped with food storage products, sink to the bottom of the water column and accumulate in the flocculant layer at the sediment/water interface. There they overwinter. They appear to require at least a four-month resting period. We recently measured toxicity levels in cysts several months at rest, and found them to be at least 10 times higher than in motile stages. There is a suggestion that toxicity decreases with time after formation, such that resting cysts when first formed may be as much as 1,000 times more toxic than the motile cell.

Cysts behave as fine silt particles within the sedimentary regime; some areas act as "sinks" for collecting them, while other areas remain relatively cyst-free. We are discovering large concentrations of toxic resting cysts in bottom sediments along the Maine coast, and they have been reported as far south as Woods Hole, Massachusetts. This calls for a new approach to the shellfish toxicity problem. Resting cysts probably account for shellfish toxicity where there is no obvious link with motile dinoflagellates (for example, in deeper waters, or in winter), and they probably contribute significantly to toxicity following blooms. If so, then the monitoring of plankton for shellfish toxicity will have to be broadened to include benthic resting cysts and the sedimentary process.

Recent Work with Trace Metals

Considerable evidence has accumulated to implicate organic materials and trace metals in the regulation of growth and distribution of phytoplankton. Early experiments showed that growth was enhanced, particularly in dinoflagellate cultures, by adding soil or seaweed extracts, or other organic chelating* compounds to seawater and growth media. In the 1960s, the correlations were good enough that some investigators proposed a river runoff index for the Bay of Fundy, and an iron runoff index for the Peace River in the Gulf of Mexico. These have not stood up completely, probably because of an oversimplified approach. Recently, more sophisticated experiments by D. Anderson and F.M.M. Morel at the Massachusetts Institute of Technology have shown that when the metals in the growth medium are carefully manipulated, *G. tamarensis* will grow well only when the concentrations of cupric ion are at exceedingly low levels. In other words, *G. tamarensis* appears to be several orders of magnitude more sensitive to trace metals (for

*A combining of large molecules with ions.

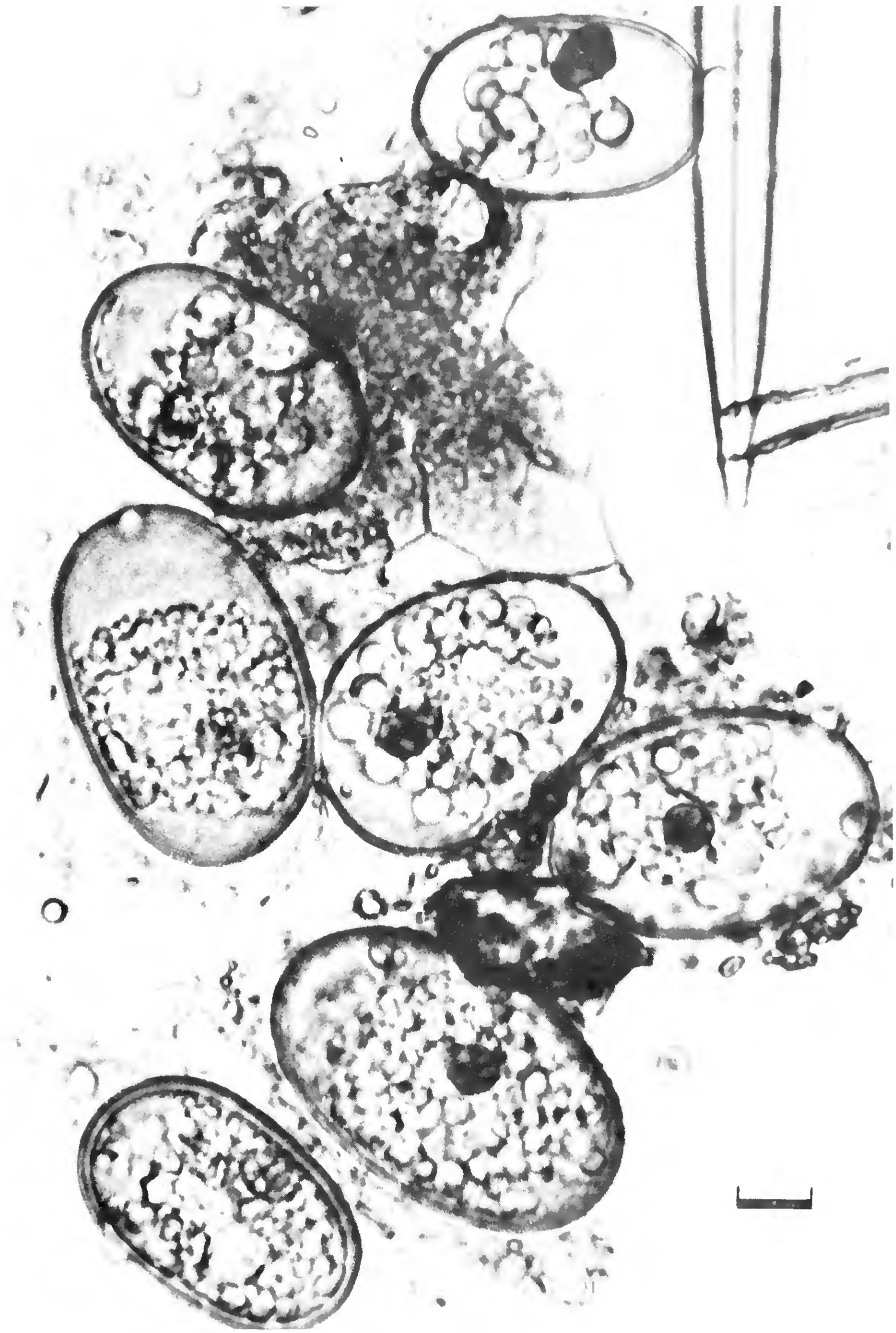


Figure 7. Resting cysts collected in January 1977 at 100 meters depth off Monhegan Island, Maine. Bar equals 10 microns. (Photo by Barrie Dale)

example, cupric ion) than are other members of the summer phytoplankton community.

How might this work in the real world? Based on their culture data, the MIT authors suggest that the normal ambient levels of cupric ion along the coast of New England would be sufficient to suppress the rapid division and growth of *G. tamarensis*, while permitting other phytoplankton to flourish. However, after a heavy rain and flushing of organic material from intertidal seaweeds as well as estuaries, or a mixing of organic materials from the shallow bottom, the copper would be reduced to nontoxic levels and then *G. tamarensis* could divide and bloom. Another aspect of this hypothesis is that with increased organic material, there is greater availability of iron compounds, which dinoflagellates require in larger quantities than the amount needed by other members of the phytoplankton community. Accordingly, increased chelation would improve both the copper and iron status for *G. tamarensis* and other dinoflagellates.

This work needs field testing. Unfortunately, the methodologies that can be used in seawater to detect the speciation of these trace metals have limitations. However, some data and circumstantial information support the hypothesis. There was an apparent correlation of iron levels with a bloom of dinoflagellates at Monhegan Island off the Maine

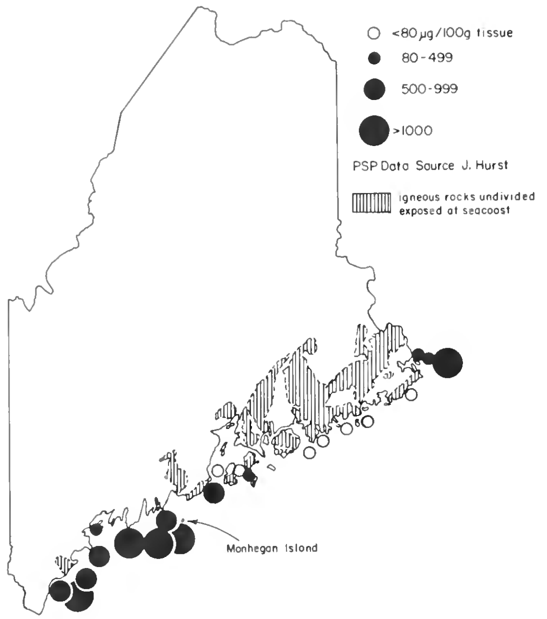


Figure 8. Peak shellfish toxin levels, off the Maine coast, for 1975.

coast in 1976. Field measurements for the 1977 season indicated that the copper levels were too high and the iron levels too low to support growth of *G. tamarensis*. Blooms of the organism were not observed during the summer of 1977. In contrast, field data of the upwelling system off Peru showed extremely low levels of cupric ion. Correlated with this were immense blooms of the dinoflagellate *Gymnodinium splendens* and a ciliate with a dinoflagellate-like symbiont, *Mesodinium rubrum*.

Consistent too with this hypothesis is the presence and absence pattern of shellfish toxin along the Maine coast (Figure 8). The area where no toxin has been detected is composed of igneous rocks, including those from abandoned copper mines. Analysis of seaweeds that are known to accumulate metals reveals that they are twice as high in copper levels in this area as seaweeds from other areas of the Maine coastline. Preliminary data also suggest that there may be fewer benthic resting cysts of *G. tamarensis* in this area.

The Chemistry of the Toxins

For several years, the causative toxin was considered to be pure saxitoxin in species of *Gonyaulax* found along the coasts of North America. Accordingly, the mouse test was, and still is, standardized with saxitoxin. More elaborate recent testing has revealed that there are at least seven toxins associated with saxitoxin in *Gonyaulax tamarensis*. The associated toxins are structurally similar to saxitoxin (Figure 9) and have been named Gonyautoxins by Y. Shimizu and coworkers at the University of Rhode Island. Their potency is similar to saxitoxin, one of the most potent toxins known. In crystalline form, toxin the size of an aspirin tablet (350 milligrams), if split and consumed by 35 persons, would theoretically be a lethal dosage for all; or if subdivided among 350 persons, would result in moderate poisoning of all.

A unique aspect of the toxins is that they are very high in nitrogen. Some researchers are investigating the possibility that the toxins may serve as a nitrogen pool for the organism in the motile stage as well as the encysted stage.

Future Work

Important objectives in future shellfish toxin research include: how to insure safety for public health; how to better utilize the shellfisheries; and how to investigate the apparent spread of shellfish toxin, along with the possibility that it may be aggravated by human activities.

A new replacement test for measuring toxicity would help with the first two objectives. The mouse injection is too cumbersome to be used by Alaskan fishermen on board ship, when considering whether to harvest a particular bed of clams, or by the local shellfish warden who must send samples to a central processing laboratory. It is hoped that new chemical work on the toxins will eventually lead to a test suitable for use as a preliminary guide in the field.

It will be useful to develop a new predictive index for the monitoring of PSP. This index will have to take into account several of the factors that we have mentioned in this article. The original concept of monitoring dinoflagellates in the plankton is unsatisfactory in view of the knowledge that there are blooms of nontoxic dinoflagellates that are indistinguishable from the toxic forms under the conventional light microscope. Added to this is the fact that highly toxic cysts in sediments may cause

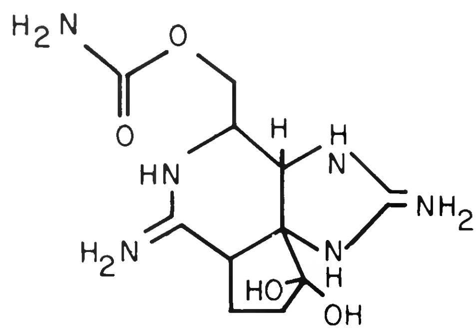


Figure 9. Chemical structure of saxitoxin. (From Schantz, et al., 1975, in First International Conference Proceedings)

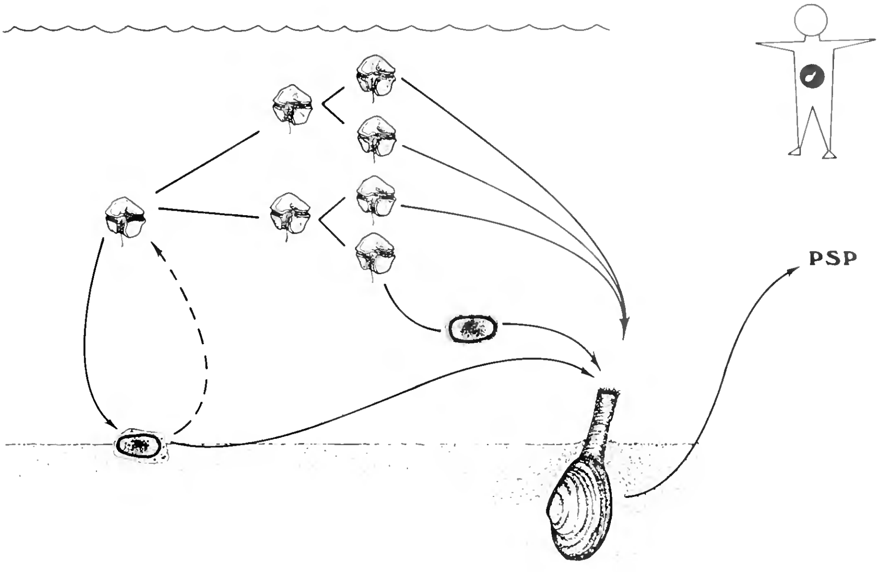


Figure 10. Motile cells developing into cysts, and their role in perpetuating shellfish toxin, leading to PSP in humans.

shellfish toxicity without any accompanying build-up of a plankton bloom.

To address the possible role of spreading, we need to understand more about the bloom phenomenon. We know that some dinoflagellates, including those implicated by PSP, appear to be present every year in small numbers, although they only bloom in particular years when they reach enormous concentrations, whereas other species occur every year, without ever blooming. Trace metals and chelation appear to be likely factors causing some species to bloom, but we do not know yet the natural incidence rate of these blooms. Caution therefore is needed in presuming that shellfish toxicity is spreading to new areas. In such areas as southern Massachusetts and northern Spain, where there have been recent outbreaks of PSP, a probable explanation is that the toxic dinoflagellates were there many years before, but apparently never bloomed. The important question then becomes: are these recent blooms natural, long-term events whose scale falls outside our records, or is this in some way due to man's activities?

One area of immediate concern arises from the discovery of large concentrations of highly toxic cysts in bottom sediments. Those engaged in projects such as artificial seeding of shellfish beds, shellfish culturing, and marine dredging operations should be alerted to possible dangers that might arise from such activities. Dredged sediment could well contain toxic cysts that could be carried far from the source after dumping at sea, likely settling at or near the sediment/water interface. Caution also should be used when transferring shellfish from one area to another; microscopic cysts could easily be carried with them. It should be emphasized that once introduced into a new area, cysts may directly contaminate shellfish. They also may establish a more permanent local toxic dinoflagellate population by acting as "seed beds" (Figure 10).

One fact is evident: we need to improve our data collecting, especially on a worldwide scale. The establishment of an international rapid communication network for red tides and toxic dinoflagellate blooms will be addressed at the Second International Conference on Toxic Dinoflagellate Blooms.

Barrie Dale is a Visiting Investigator at the Institute for Marine Biology and Limnology, University of Oslo, Norway. Clarice M. Yentsch is a Research Scientist at the Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine.

Suggested Readings

Anderson, D.M., and F.M.M. Morel. 1978. Copper sensitivity of *Gonyaulax tamarensis*. *Limnol. and Oceanogr.* 23: 283-95.

Dale, B., C.M. Yentsch, and J.W. Hurst. 1978. Toxicity in resting cysts of the red tide dinoflagellate *Gonyaulax excavata* from deeper water sediments off the Maine coast. *Science*, In Press.

LoCicero, V., ed. 1975. Proceedings of the First International Conference on Toxic Dinoflagellate Blooms. Wakefield, Mass.: Massachusetts Science and Technology Foundation.

Oshima, Y., L. J. Buckley, N. Alam, and Y. Shimizu. 1977. Heterogeneity of paralytic shellfish poisons. Three new toxins from cultured *Gonyaulax tamarensis* cells, *Mya arenaria* and *Saxidomus giganteux*. *Comp. Biochem. and Physiol.* 57: 31-34.

Prakash, A., J.C. Medcof, and A.D. Tennant. 1971. Paralytic shellfish poisoning in eastern Canada. Bulletin 177, Fisheries Research Board of Canada.

Pingree, R.D., P.R. Pugh, P.M. Holligan, and G.R. Forster. 1975. Summer phytoplankton blooms and red tides along tidal fronts in the approaches to the English Channel. *Nature* 258: 672-77.

Tyler, M.A., and H.H. Seliger. 1978. Annual subsurface transport of a red tide dinoflagellate to its bloom area: water circulation patterns and organism distributions in the Chesapeake Bay. *Limnol. and Oceanogr.* 23: 227-46.

The Green Sea Turtle

by James L. Considine
and John J. Winberry

Over-exploitation of ocean resources is not a new phenomenon, but with the world population and the demand for calories and protein increasing, the sea is a potentially important food source. The annual worldwide catch of all species as of 1976 was 72 million tons, and some of these are now threatened with extinction. Unless current methods of exploitation are modified, the number of species

of the Cayman Islands

threatened will continue to increase. Such is the case with the green sea turtle, *Chelonia mydas mydas* — also called the Atlantic Green Turtle. It has been called the world's most economically valuable reptile because of the many products derived from it. These include meat; the white calipee (the unossified undershell) and calipash (the cartilaginous greenish gelatin that lines the shell), used for soup; and eggs. Nonfood articles include oil, skins, and shells. Since the 17th century, the green sea turtle has been intensively hunted by man, and the result has been the near annihilation of the species in American and Asian waters.

Since the middle of this century we have seen the application of plant genetics to increase the productivity of wheat and rice and to improve the nutritiveness of sorghum — advances that have quelled, at least for the present, the food/population threat. Of equal importance is research applied to the productivity of the sea. If species can be domesticated and their reproduction controlled, exploitation of the oceans will change from a hunting/gathering process to sophisticated husbandry. Not only would production be more efficient, but major inroads could be made in the protein shortages of the tropical world.

The green sea turtle has been the subject of such research since 1968, much of it carried out on the Caribbean island of Grand Cayman (Figure 1). Turtle fishing — long a major part of the island's economy — was made illegal in 1970, after a process of over-exploitation and virtual extinction.

History of Turtle Hunting

Apparently there was no permanent pre-Columbian Indian settlement in the Cayman Islands, but bands of Arawaks or Caribs probably visited the islands occasionally. Archaeological and ethnographic evidence in the Caribbean indicates that turtles were hunted for food, but whether this was the reason for such stays in the Caymans is not known.

On May 10, 1503, Christopher Columbus, returning from his fourth voyage, passed the Lesser Cayman Islands and named them "Las Tortugas," but the discovery of Grand Cayman is unrecorded. All three islands appear on 16th-century charts, and Europe-bound Spanish vessels probably stopped there for supplies, specifically turtles and water. By 1562, English ships also were anchoring in the Caymans, and through the 16th and early 17th centuries, the islands were frequented by French and Dutch vessels as well. In 1655, England

Figure 1. Green sea turtle range in the Caribbean. (Photo Russ Kinne, PR)

conquered Jamaica and brought the Caymans within her Caribbean sphere. As a result, the frequency of English visits to the Caymans increased as well as the representation of these islands in colonial documents. In the early 1660s, Jamaicans settled the Lesser Caymans for the purpose of hunting turtles.*

At first, hunting was a haphazard, unplanned affair. A vessel would stop at an island in hopes of discovering a fleet of turtles on the beach. If nesting turtles were found, large numbers were easily captured. Though graceful in the water, the green sea turtle is slow and awkward on land — easily being turned on its back. Unable to right itself, the turtle was killed and salted or taken on board alive to provide fresh meat during the voyage. By the 1600s, turtle fishing in the Cayman Islands had undergone changes. Instead of depending on random encounters, hunters began searching systematically for nesting herds. In addition to setting up shore camps during nesting season, they also netted swimming turtles, finding that the ones mating offshore were easy prey. These practices, though rudimentary, were devastating. As early as the 18th century these hunting methods, which focused on killing the females and collecting their eggs, threatened the green sea turtle population.

In 1734, a small English colony was established on Grand Cayman. Initially, it relied on agriculture and privateering, but turtling grew in importance. By the late 18th century, Georgetown had become the capital of Grand Cayman and, with the rise of turtle fishing, served as a major market for turtle products. In the 1790s, six small turtling vessels operated out of Grand Cayman; the meat was sold to merchant ships returning to Europe and to buyers from Jamaica. Methods for capturing turtles changed little over a span of 150 years, but the systematic and indiscriminate hunting eventually caused the virtual disappearance of the turtle population in Cayman waters.

Cayman turtle hunters then sought new fishing areas, securing permission from Spain in the early 1800s to fish off Cuba's southern coast. The Cuban sea turtle population was quickly decimated through the use of nets set over feeding grounds and coral reefs. By 1850, fishing shifted to the waters off Honduras and Nicaragua, especially the Miskito Cays. During the latter half of the 19th century, the turtle catch of the Cayman fleet — now numbering 12 vessels — was sold to passing ships or at markets in Jamaica. By 1900, the market for green sea turtles included Europe and the United States. The turtling fleet grew to 25 vessels, but the industry's success held the seeds of its decline. By 1940, the fleet fishing Nicaraguan waters was down to 15 vessels, and by 1950 only 10 were active. The number of turtles caught, however, remained constant, though generally they were smaller and of poorer quality.

The 1960s were difficult years for Cayman turtle hunters. The population of turtles in Central American waters had declined to near extinction, and the remaining reptiles were protected by an international agreement. The era of Cayman turtle

Behavioral Aspects

The green sea turtle (Chelonia mydas), *which gets its name from the greenish color of its body fat, has been known to migrate long distances – in some cases 1,000 miles or more.*

They are strong swimmers, having been observed cruising at a speed of 0.88 to 1.4 miles per hour. Physiological studies (Berkson 1966, 1967) indicate that the green sea turtle in prolonged dives can survive up to 5 hours with no measurable oxygen in the trachea or in the blood of the carotid artery and that as long as 9 minutes may elapse between heartbeats.

In the past, wild green turtles have been weighed in at more than 1,000 pounds. Today the largest are about 4-foot long and weigh in the vicinity of 500 pounds. Most are under 100 pounds. The adults feed largely on seagrasses in shallow water, although they have also been known to feed on algae, mollusks, jellyfish, and small crustaceans.

Mating occurs off the nesting beaches, usually close to shore. Several males may simultaneously court and attempt to mate with a single female. Males have been known to fight with one another during the breeding season. During copulation, which occurs usually at the surface, the male's claws have been observed cutting into the female's carapace, leaving deep, bleeding wounds. Nesting occurs on the beach at night.

The nearly spherical, soft, white eggs are 35 to 58 millimeters in diameter and weigh 44 to 65 grams. The average number of eggs per clutch or nest is in the vicinity of 110. The incubation period is anywhere from 30 to 72 days. Hatching rates vary widely.

---

*The Grand Cayman turtle fishery is distinct from that of the Lesser Cayman Islands. The Lesser Caymans, or Cayman Brac, though semi-permanently settled as early as the 1660s, had long been deserted and were recolonized from Grand Cayman only in 1833. The inhabitants of Cayman Brac developed their own turtle fishery, relying on the hawksbill turtle, *Eretmochelys imbricata*. Although the hawksbill was valued primarily for its shell, the people of Cayman Brac developed a taste for what had been hitherto thought of as unpalatable meat. Interestingly, when the turtle industry of Cayman Brac declined, the former turtlers became involved with tourism and turned to making handicrafts. They abandoned their traditional economy in order not to infringe on Grand Cayman's fishery.

Farm worker amid approximately 800 turtles in a Mariculture holding tank. (Photo James Considine)

fishing ended in 1970. No legally registered schooners left for Nicaraguan waters that year, although some Cayman vessels continued to hunt turtles illegally or bought them from poachers.

Domestication of the Sea Turtle

Since turtling grounds were closed due to conservation regulations, an artificial method of dealing with the green sea turtle was implemented. Prior to 1945, there had been several attempts to establish turtle ranches in the Caymans, but limited knowledge of the reptile's habits doomed them. In the 1950s, a ranch for 500 green sea turtles was attempted, but it also failed. In the late 1960s, a program aimed at domesticating the green sea turtle was proposed by a company called Mariculture, Ltd., to the Grand Cayman government. The program had two general purposes: to produce turtle meat and products and to relieve pressure on wild species. Commercially, the turtle has a high market potential (virtually every part is salable). Its food to meat conversion ratio is approximately 2:1— half that of chicken or hog and less than an eighth of cattle. This is because the turtle is a cold-blooded animal and uses no food energy to maintain body heat. At that time, however, little was known about the turtle's biology and behavior, especially about its ability to breed in captivity.

Farm worker holding an 8-month-old turtle. (Photo James Considine)

In August, 1968, Mariculture began operations. Initial experiments sought to answer questions about feeding, growth rates, behavior, and stock survival. Eggs were collected on Costa Rican beaches, hatched, and the turtles reared under controlled conditions for about a year. They were then released into a natural water body to feed on seagrasses. Despite expectations that young turtles would not migrate after a year in captivity, they still wandered. The idea of an open range had to be abandoned. At this juncture, it was decided to raise the turtles in enclosed pens. This required a more complex operation than the few holding pens used for hatchlings prior to their controlled release.

In 1971, Mariculture moved to a new location and constructed large permanent pens for the turtles that were in effect artificial environments. The new site was closer to clear ocean water needed

Artificial breeding pond and nesting beach. (Photo James Considine)

for filling the pens and for expelling effluent. The company at this point also shifted its emphasis from gathering research data on the turtles to applying the knowledge gained toward production for profit.

The new complex is located at Goat Rock in the northeastern corner of Grand Cayman Island, and includes concrete pens, tanks, and a breeding and stock pond. It can accommodate more than 100,000 sea turtles, which are grouped into the various holding pens according to size and weight. An artificial beach that can hold about 80 nesting turtles has been constructed adjacent to the breeding pond.

The ultimate goal of Mariculture is to establish a complete turtle breeding cycle on the farm. At present, however, the company purchases eggs collected from nesting beaches in the Caribbean and Atlantic. It agrees to return approximately 1 percent of the hatched turtles to the natal beaches when they are a year old. Because only one or two tenths of 1 percent of the hatched turtles reach adulthood, this more than compensates for a reduction of population due to egg collection. The eggs are gathered several times annually, and are flown to Grand Cayman. After nine egg collections, the company averaged an 80 percent hatching rate. Of these, 85 percent reached one year of age. As the turtles grow, they are shifted to larger tanks, and a weight/volume formula determines the optimum number per tank. After three years, each turtle weighs approximately 100 pounds and is ready for processing.

Though much of the reproduction cycle has been realized under artificial conditions, it has not been perfected. Successful mating and subsequent egg laying on the artificial beach at Goat Rock are crucial to the venture because without both, domestication of the species and the industry's self-sufficiency are impossible. Various husbandry experiments have been performed in an effort to establish a breeding cycle. Sporadic nestings by fertilized females from the wild and numerous copulations in the breeding pond have occurred. Mating in 1973 at the farm resulted in some 12,000 eggs; in 1974, the figure was 10,000. Once captive breeding is established and better understood, genetic and growth experiments can be attempted. Then, the venture will become an aquaculture one, and not a ranch, relying on turtles in the wild to replenish the stock.

Future of Mariculture

If a successful aquaculture venture can be established, it will revive the market for turtle steaks, stew meat, soup stock, lower-grade meat, flippers, leather, oil, and shell. The company has marketed meat in Georgetown since 1972, also selling it in the United States, Canada, Australia, and Western Europe. But there are still basic problems to overcome. The turtle's complete biological cycle has yet to be established. As well, certain problems with disease must be addressed.* Furthermore, the problem of turtle conservation has not been solved. Though this had been a highly desired by-product of the venture, the fact that Mariculture has not increased production substantially means that natural populations are still threatened.

Based on present results of the experiment, production of the sea turtle could potentially increase some 650-fold over natural conditions. Such a result would be an extremely important development for man if it could be extended to

*Parasitism has been minimal. The most frequently observed pathology thus far has been infections resulting from bite lesions, which are treated with gentian violet. The crowding of turtles in pens and tanks, however, poses the possibility of severe bacterial or viral epidemics. Any microbial agents of serious disease that might be endemic should be identified.

other sea creatures. Areas of protein deficiency in the Third World could benefit from expanded turtle husbandry.

Once there is a breakthrough in domestication of the green sea turtle, cultivation would not entail large-scale equipment or high capital investment.* Many coastal communities could establish small-scale farms for domestic meat production. The development in the tropics of larger farms could also be undertaken.

The potential of turtle farming is great, but it requires additional research and development for ultimate success. When the major goal of domesticating the green sea turtle has been fully realized, perhaps the creature will regain its position as the world's most economically valuable reptile, pointing the way to further advances in aquaculture.

James L. Considine is Assistant Planning Director of the Adams County Board of Commissioners, Brighton, Colorado. John J. Winberry is Associate Professor of Geography at the University of South Carolina.

---

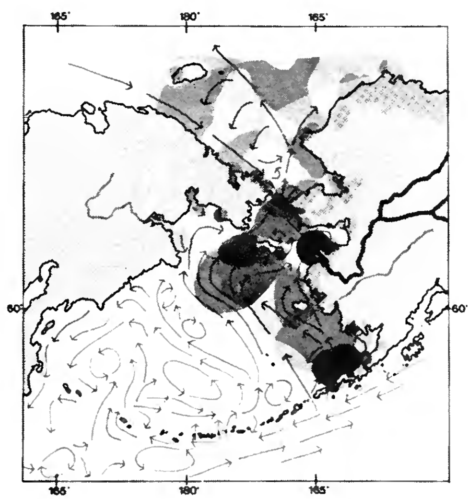
*This has been questioned in a general study of aquaculture practices by Weatherly and Cogger, 1977. Although the green sea turtle feeds naturally on various seagrasses that could be readily and cheaply harvested, current feeding practices at Mariculture emphasize animal-protein feed pellet supplements that are imported from the United States.

Selected Readings

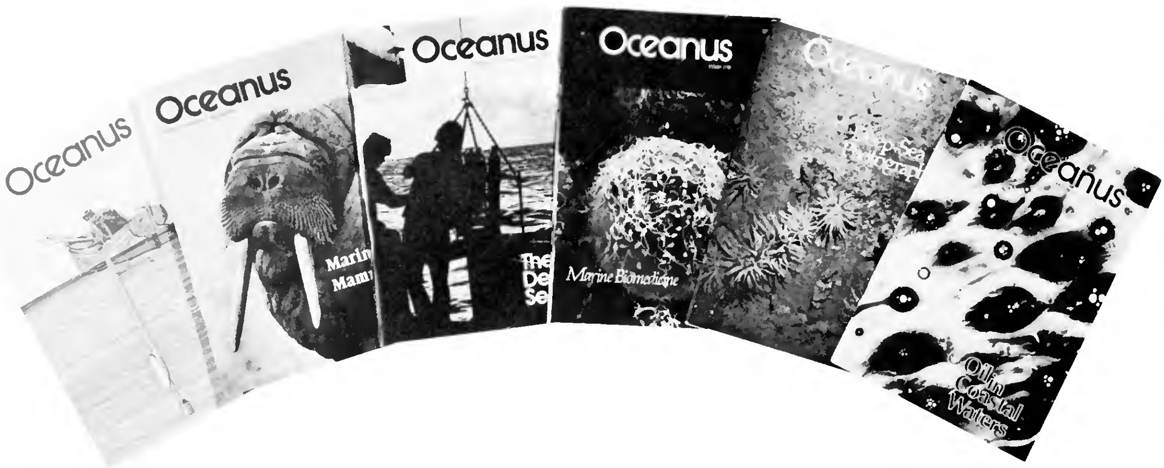
Brown, L.R., and G.W. Finsterbusch. 1972. *Man and his environment: food.* N.Y.: Harper and Row.
Bustard, H.R. 1972. Turtle farmers of Torres Strait. *Hemisphere* 16: 24-28.
Carr, A. 1967. *So excellent a fishe: A natural history of sea turtles.* Garden City, N.Y.: The Natural History Press.
———. 1969a. Sea turtle resources of the Caribbean and Gulf of Mexico. *IUCN Bulletin,* New Series 2(10): 74-75, 83.
———. 1969b. Survival outlook of the west Caribbean green turtle colony. *IUCN Publications,* Suppl. Paper No. 20: 13-16.
———. 1970. Green sea turtles in peril. *National Parks Conservation Magazine* 44: 19-24.
Ehrenfeld, D.W. 1974. Conserving the edible sea turtle: can mariculture help? *Am. Sci.* 62: 23-31.
Emery, K.O., and C. O'D. Iselin. 1967. Human food from ocean and land. *Science* 157: 1279-81.
Hendrickson, J.R. 1974. Marine turtle culture — an overview. In *Proceedings of the Fifth Annual Meeting of the World Mariculture Society.* Baton Rouge: Louisiana State University Press.
Lewis, C.B. 1940. The Cayman Islands and marine turtle. In *The herpetology of the Cayman Islands,* ed. by C. Grant. Kingston, Jamaica: Inst. of Jamaica.
Parsons, J.J. 1962. *The green turtle and man.* Gainesville, Fla.: Univ. of Florida Press.
Reiger, G. 1975. Aquaculture: has it been oversold? *International Wildlife* 5: 21-24.
Ryther, J.H. 1975. Mariculture: how much protein and for whom? In *The oceans and man,* ed. by J.B. Ray, pp. 29-45. Dubuque: Kendall/Hunt.
Thompson, E.F. 1945. The fisheries of the Cayman Islands. *Development and Welfare in the West Indies,* Bull. No. 22, Advocate Bridgetown.
Weatherly, A.H., and B.M.G. Cogger. 1975. Fish culture: problems and prospects. *Science* 197: 427-30.

Two Atlantic green turtles engaged in mating behavior. (Photo Gordon S. Smith from National Audubon Society, PR)

Correction



In the article "Strategies for Protecting Marine Mammal Habitats" by G. Carleton Ray, James A. Dobbin, and Rodney V. Salm that appeared in the Spring issue (Vol. 21, Number 2, 1978), the wrong map appeared in Figure 2 at the top of page 61. The correct map appears above.



Oceanus Back Issues

Limited quantities of back issues are available at prices indicated; a 25 percent discount is offered on orders of five or more. PLEASE select alternatives for those in *very limited supply*. We accept only prepaid orders. Checks should be made payable to Woods Hole Oceanographic Institution; checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. Address orders to: Oceanus Back Issues, 1172 Commonwealth Ave., Boston, MA 02134.

SEA-FLOOR SPREADING, Vol. 17:3, Winter 1974 — Plate tectonics is turning out to be one of the most important theories in modern science, and nowhere is its testing and development more intensive than at sea. Eight articles by marine scientists explore continental drift and the energy that drives it, the changes it brings about in ocean basins and currents, and its role in the generation of earthquakes and of minerals useful to man. *Very limited supply.* **$3.00**

ENERGY AND THE SEA, Vol. 17:5, Summer 1974 — One of our most popular issues. There is extractable energy in the tides, currents, and temperature differences; in the winds that blow over them; in the very waters themselves. Eight articles discuss these topics as well as the likelihood of finding oil under the deep ocean floor and of locating nuclear plants offshore. **$4.00**

MARINE POLLUTION, Vol. 18:1, Fall 1974 — Popular controversies, such as the one over whether or not the seas are "dying," tend to obscure responsible scientific effort to determine what substances we flush into the ocean, in what amounts, and with what effects. Some progress is being made in the investigation of radioactive wastes, DDT and PCB, heavy metals, plastics and petroleum. Eleven authors discuss this work as well as economic and regulatory aspects of marine pollution. **$4.00**

FOOD FROM THE SEA, Vol. 18:2, Winter 1975 — Fisheries biologists and managers are dealing with the hard realities of dwindling stocks and increasing international competition for what is left. Seven articles deal with these problems and point to ways in which harvests can be increased through mariculture, utilization of unconventional species, and other approaches. **$4.00**

DEEP-SEA PHOTOGRAPHY, Vol. 18:3, Spring 1975 — A good deal has been written about the use of hand-held cameras along reefs and in shallow seas. Here eight professionals look at what the camera has done and can do in the abyssal depths. Topics include the early history of underwater photography, present equipment and techniques, biological applications, TV in deep-ocean surveys, the role of photography aboard the submersible *Alvin* along the Mid-Atlantic Ridge, and future developments in deep-sea imaging. **$4.00**

MARINE BIOMEDICINE, Vol. 19:2, Winter 1976 — Marine organisms offer exciting advantages as models for the study of how cells and tissues work under both normal and pathological conditions — study leading to better understanding of disease processes. Vision research is being aided by the skate; neural investigation, by the squid; work on gout, by the dogfish. Eight articles discuss these developments, as well as experimentation involving egg-sperm interactions, bioluminescence, microtubules, and diving mammals. **$3.00**

ESTUARIES, Vol. 19:5, Fall 1976 — Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life — and the constitutional issues posed by estuarine management. **$4.00**

SOUND IN THE SEA, Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines. **$3.00**

Oceanus

The Illustrated Magazine of Marine Science Published by Woods Hole Oceanographic Institution

SUBSCRIPTION ORDER FORM

Please make checks payable to Woods Hole Oceanographic Institution. Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. (Outside U.S., Possessions, and Canada add $2 per year to domestic rates.)

Please enter my subscription to OCEANUS for

☐ one year at $10.00
☐ two years at $18.00

☐ payment enclosed. (we request prepayment)
☐ bill me

Please send MY Subscription to:

Name (please print)

Street address

City State Zip

Please send a GIFT Subscription to:

Name (please print)

Street address

City State Zip

Donor's Name

Address

2

Oceanus

The Illustrated Magazine of Marine Science Published by Woods Hole Oceanographic Institution

SUBSCRIPTION ORDER FORM

Please make checks payable to Woods Hole Oceanographic Institution. Checks accompanying foreign orders must be payable in U.S. currency and drawn on a U.S. bank. (Outside U.S., Possessions, and Canada add $2 per year to domestic rates.)

Please enter my subscription to OCEANUS for

☐ one year at $10.00
☐ two years at $18.00

☐ payment enclosed. (we request prepayment)
☐ bill me

Please send MY Subscription to:

Name (please print)

Street address

City State Zip

Please send a GIFT Subscription to:

Name (please print)

Street address

City State Zip

Donor's Name

Address

2

Marine Pollution

Food from the Sea

PLACE
STAMP
HERE

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

PLACE
STAMP
HERE

Oceanus
Woods Hole Oceanographic Institution
Woods Hole, Mass. 02543

as experimentation involving egg-sperm interactions, bioluminescence, microtubules, and diving mammals. **$3.00**

ESTUARIES, Vol. 19:5, Fall 1976 — Of great societal importance, estuaries are complex environments increasingly subject to stress. The issue deals with their hydrodynamics, nutrient flows, and pollution patterns, as well as plant and animal life — and the constitutional issues posed by estuarine management. **$4.00**

SOUND IN THE SEA, Vol. 20:2, Spring 1977 — Beginning with a chronicle of man's use of ocean acoustics, this issue covers the use of acoustics in navigation, probing the ocean, penetrating the bottom, studying the behavior of whales, and in marine fisheries. In addition, there is an article on the military uses of acoustics in the era of nuclear submarines. **$3.00**

GENERAL ISSUE, Vol. 20:3, Summer 1977—The controversial 200-mile limit constitutes a mini-theme in this issue, including its effect on U.S. fisheries, management plans within regional councils, and the complex boundary disputes between the U.S. and Canada. Other articles deal with the electric and magnetic sense of sharks, the effects of tritium on ocean dynamics, nitrogen fixation in salt marshes, and the discovery during a recent Galápagos Rift expedition of marine animal colonies existing on what was thought to be a barren ocean floor. **$3.00**

OIL IN COASTAL WATERS, Vol. 20:4, Fall 1977 — From a standing start a decade or two ago, scientists have made good progress in investigating how petroleum gets into coastal waters, where it goes, and what effects it has along the way. Articles discuss long-term studies of two spills plus work on effects of oil on fish eggs, fish, and lobsters. **$3.00**

THE DEEP SEA, Vol. 21:1, Winter 1978 — Over the last decade, scientists have become increasingly interested in the deep waters and sediments of the abyss. Articles in this issue discuss manganese nodules, the rain of particles from surface waters, sediment transport, population dynamics, mixing of sediments by organisms, deep-sea microbiology — and the possible threat to freedom of this kind of research posed by international negotiations. **$3.00**

MARINE MAMMALS, Vol. 21:2, Spring 1978 — Attitudes toward marine mammals are changing worldwide. This phenomenon is appraised in the issue along with articles on the bowhead whale, the sea otter's interaction with man, behavioral aspects of the tuna/porpoise problem, strandings, a radio tag for big whales, and strategies for protecting habitats. **$3.00**

OUT OF PRINT

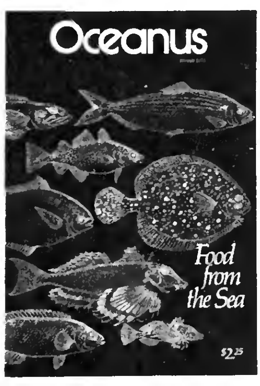
AIR-SEA INTERACTION, Vol. 17:4, Spring 1974
THE SOUTHERN OCEAN, Vol. 18:4, Summer 1975
SEAWARD EXPANSION, Vol. 19:1, Fall 1975
OCEAN EDDIES, Vol. 19:3, Spring 1976
GENERAL ISSUE, Vol. 19:4, Summer 1976
HIGH-LEVEL NUCLEAR WASTES IN THE SEABED? Vol. 20:1 Winter 1977

REISSUES

Last fall, we asked readers to pick the back issues they would most like to see reprinted. After reviewing responses, we have chosen the four shown below. The reissue price is $4.00 per copy.

Energy and the Sea

Marine Pollution



Food from the Sea

Estuaries

Oceanus
WOODS HOLE
OCEANOGRAPHIC
INSTITUTION
Woods Hole, MA 02543
Postmaster: Please Send
Form 3579 to Above Address

ND-CLASS
TAGE PAID
OUTH, MASS.,
DDITIONAL
NG POINTS