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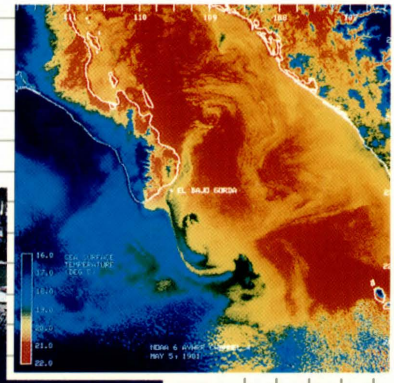
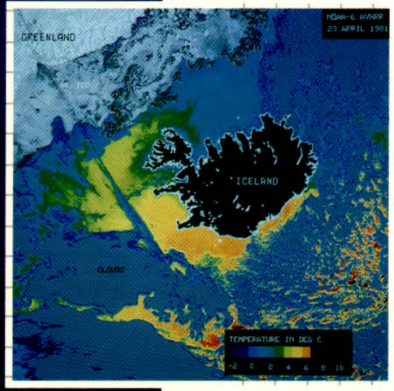
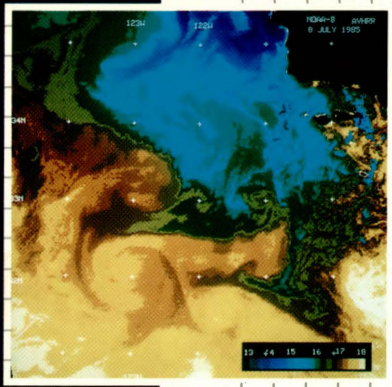
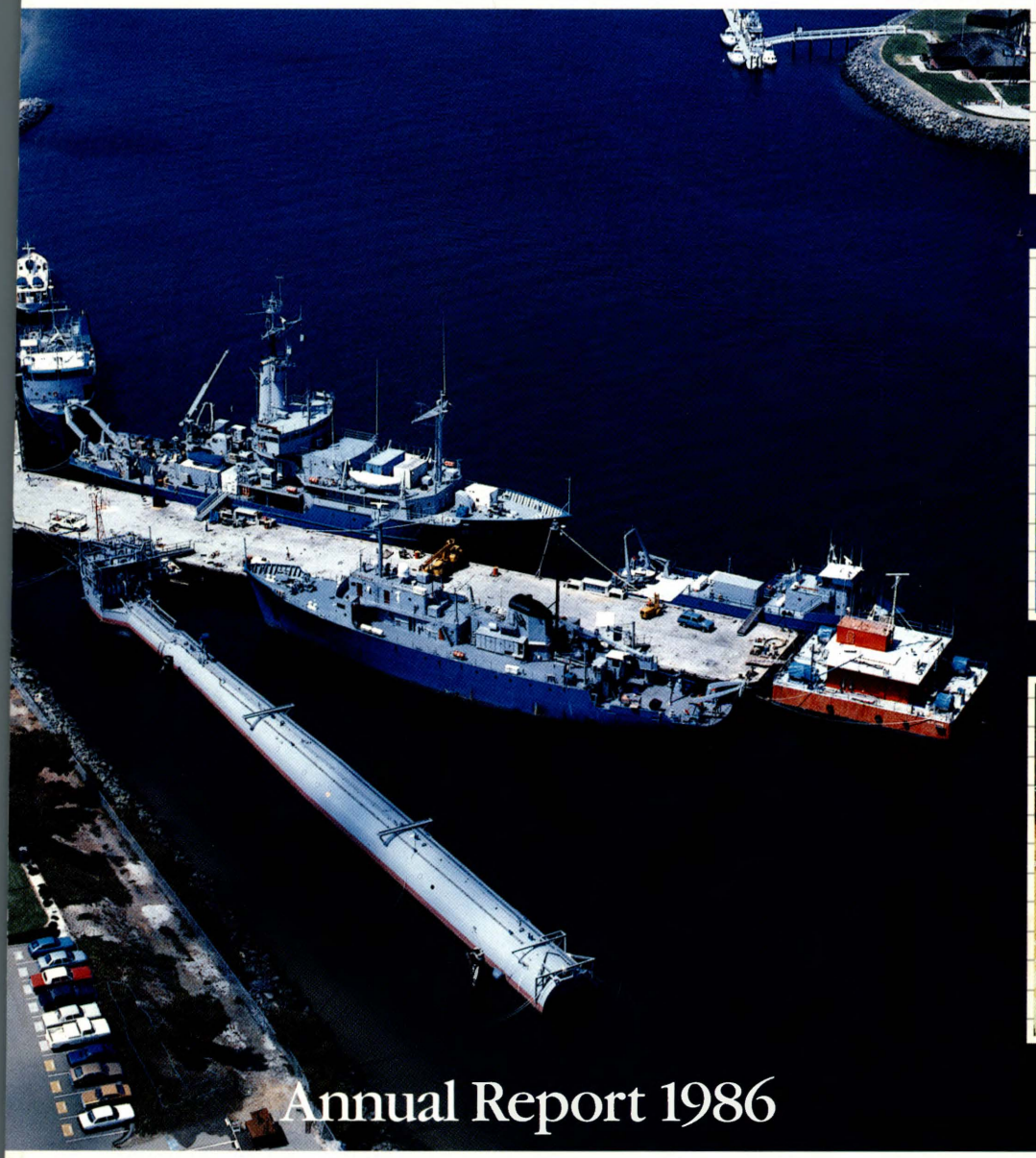
Institution *of* Oceanography









Annual Report 1986

University of California, San Diego

Once described by the *New York Times* as "one of the two or three most articulate spokesmen for science in the Western World," he is a giant in American science, both in stature and in deeds, who has accomplished enough to distinguish several lifetimes.

Roger Randall Dougan Revelle, Scripps director emeritus and UCSD professor of science and public policy, first made his mark in oceanography as a scientist, explorer, and administrator. Today, he is a senior senator of science, giving counsel and guidance in areas ranging from the environment and education to agriculture and world population.

Revelle was a graduate student in geology at UC Berkeley when, in 1931, Scripps director T. Wayland Vaughan dropped by the campus, looking for a research assistant to work on analyzing some deep-sea muds. Revelle took the job, in part because his bride, Ellen, was a native of La Jolla.

By 1936, Scripps had made Revelle into an oceanographer. Then, as a faculty member, and later, as director, Revelle made oceanography into big science. He led the institution into a new age of exploration, during which a series of major expeditions revolutionized knowledge of the seafloor, and he initiated many cooperative international scientific programs. He kept Scripps in the forefront of marine science and recruited faculty from around the world to serve at Scripps and to share in his dream of a UC campus in San Diego. He was the main force in founding UCSD in 1960; Revelle College of UCSD was named for him in 1965.

Revelle left Scripps in 1964 and founded the Center for Population Studies at Harvard University, where he spent more than a decade as its director. His primary interest there was the application of science and technology to world hunger. In the late 1970s, he returned to La Jolla and UCSD.

Throughout his career, Revelle has served on scores of academic, scientific, and government committees and task forces, advising on a wide spectrum of topics. He was science advisor to the Secretary of the Interior and president of the American Association for the Advancement of Science. Over the past three decades, he has guided thinking on one of the most powerful long-term effects of global industrialization—the rising levels of atmospheric carbon dioxide caused by the burning of fossil fuels. In October 1986, he was awarded the internationally renowned Balzan Prize in recognition of his pioneering research in atmospheric carbon dioxide.

A man conspicuous in any gathering because of his 6-foot-4-inch height, Revelle is unassuming in his demeanor. He speaks in a soft voice, choosing words with care and readily crediting the work of colleagues. Once asked by a reporter how he managed to accomplish so much with his life, the 77-year-old Revelle replied, "Well, I've lived a long time."

Scripps

Institution *of* Oceanography

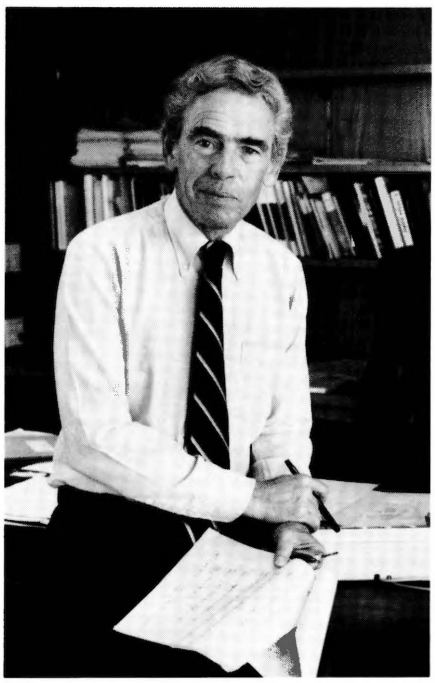
Annual Report 1986

University of California, San Diego

Contents

University of California, San Diego, Volume 20, Number 1, January 1987. A series of administrative publications of the University of California, San Diego, La Jolla, California 92093. Second-class postage paid at La Jolla, California. A major portion of the work reported herein was supported by the National Science Foundation and the Office of Naval Research. Four issues a year: January, March, May, and July. USPS 646-820. ISSN 0194-2816.

Introduction



Bill Call

Although I have served as director of Scripps Institution for just a short time, I have followed the institution's accomplishments for many years and developed a deep respect for the many contributions its people have made both to science and society.

During the 21 years of his tenure as director, my predecessor, William A. Nierenberg, brought the institution to the forefront of modern science by spearheading innovative programs, initiating new technologies for oceanography, and recruiting outstanding faculty and staff. Scripps and the nation are indebted to him for his service, and we wish him well in his new pursuits, which include a major interdisciplinary program with the long-range goal of predicting the movements of ocean current systems.

Scripps developments of note this past year include progress on three construction projects. Several major hurdles in the planning for the new aquarium and ocean science center have been passed, the most important of which is the raising of more than $6.7 million, including $6 million from the Stephen and Mary Birch Foundation. The pier construction, although delayed somewhat, is under way now and will give us a replacement that should last at least as long as the 70 years of the old pier. At the north end of the campus, the SIO conference center is almost finished and will include a screened pavilion entitled *Porch* that will be part of the Stuart Collection at UCSD.

Our staff continues to garner honors and awards, too many to enumerate here, but they are listed in the appendix of this report. I would like to note, however, a day-long symposium that was held in honor of Jerome Namias's seventieth birthday. At this event he received a special certificate from the Department of Commerce and NOAA for pioneering work in long-range weather forecasting. And his keen insight and new ideas in climate prediction continue.

We were saddened by the passing of H. William Menard on February 9, 1986. He was a leader in the great period of ocean-floor exploration that began after World War II, and was greatly admired by his colleagues, students, and many friends. In December 1985, he received the prestigious William Bowie Medal from the American Geophysical Union.

Looking to the future, I see tremendous opportunities for the institution to continue its leadership in many scientific areas that affect the human condition and add to our overall understanding of the planet. New technologies and applications will enable us to expand our pursuits in ways that are yet to be developed. We must be ready to accept the challenges. To help develop a coherent long-range strategy, I have asked faculty, staff, and students to share in two studies. In one they will assess the strengths, weaknesses, problems, and opportunities of the institution as it now stands. The other study will be to plan for the Scripps of the future—where we would like to be in the next decade. Their findings will allow us to embark on a series of new steps. By working together, we can prepare for the era of change the 1980s and 1990s will undoubtedly bring.

Edward A. Frieman, Director
Scripps Institution of Oceanography

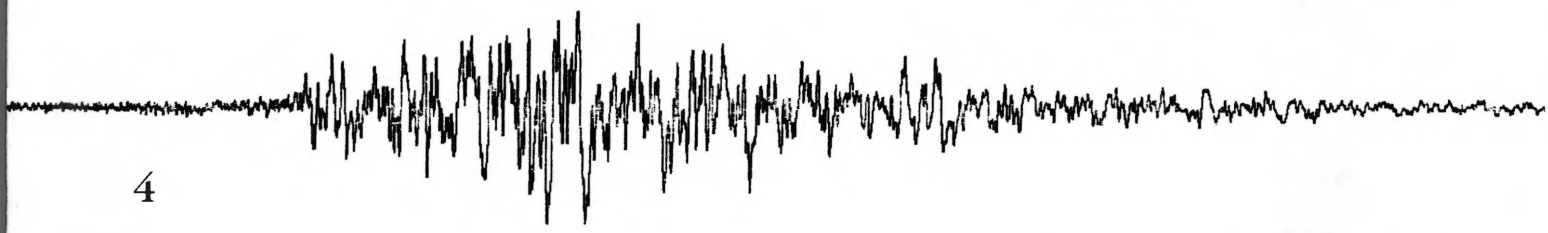
Highlights

Earthquake!

A magnitude 8.1 earthquake on September 19, 1985, caused tragedy in Mexico. Measurements from devices in place before the quake may help avert future tragedies. Records of the strong ground motion during Mexico's earthquake will help engineers develop earthquake-resistant designs for buildings subject to comparable threats throughout the world. These same measurements, gathered in a collaborative effort led by Scripps scientists, provide an exceptional opportunity to study the mechanism of the Mexican earthquake.

Starting in 1984, our research team, headed by Drs. James N. Brune and John G. Anderson, installed a network of 30 strong-motion accelerographs along a part of the Mexican coast, and inland to Mexico City. The instruments, designed to stay on scale during even the strongest shaking, were placed in the area because it was likely to experience a large earthquake. Most of the earthquakes in southern Mexico are discrete events in the thrusting of the Pacific Ocean floor (the Cocos plate) under the Pacific coast of Mexico at a rate averaging about 6 cm/year. The areas most likely to experience the next large earthquakes in this process are the "seismic gaps" between events of the recent past. We put our instruments into gaps along the coast of the Mexican states of Guerrero and Michoacán. Although we considered the Guerrero gap the more likely source for a large earthquake, it was the Michoacán gap that failed in September 1985. One or more earthquakes in Guerrero—possibly similar to large earthquakes in 1899, 1908, 1909, and 1911—will produce additional important strong-motion data in the future, although of course we have no idea when such events may occur.

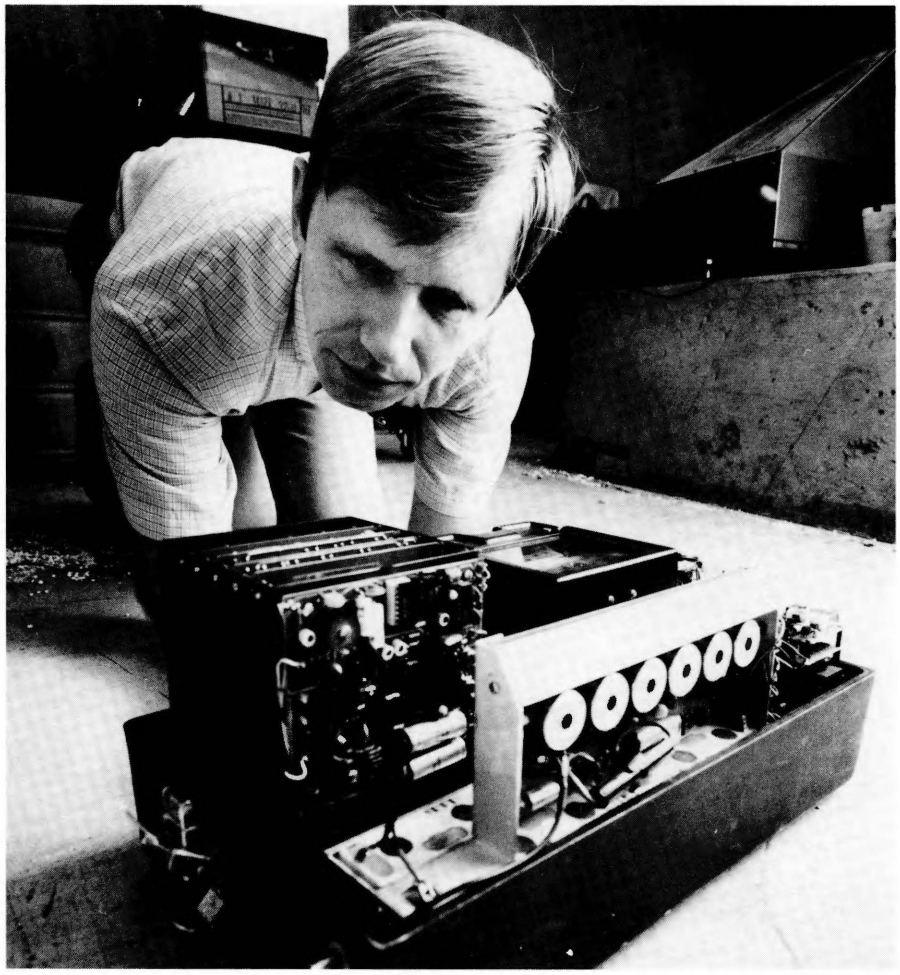
The accelerograms from September 19 are almost the first records from sites directly above the faulting during a magnitude 8 or greater earthquake. They are therefore of great interest to engineers designing seismic-resistant buildings for regions with similar faulting mechanisms. These regions include Alaska, Washington, Oregon, and Puerto Rico in the United States; other threatened nations are Japan, Taiwan, and every Central and South American country bordering the Pacific Ocean.



Damaged building in Mexico City after the September 19, 1985, 8.1 earthquake. Accelerograms are from the earthquake: left, *recorded at Caleta de Campos;* right, *recorded at La Union station.*

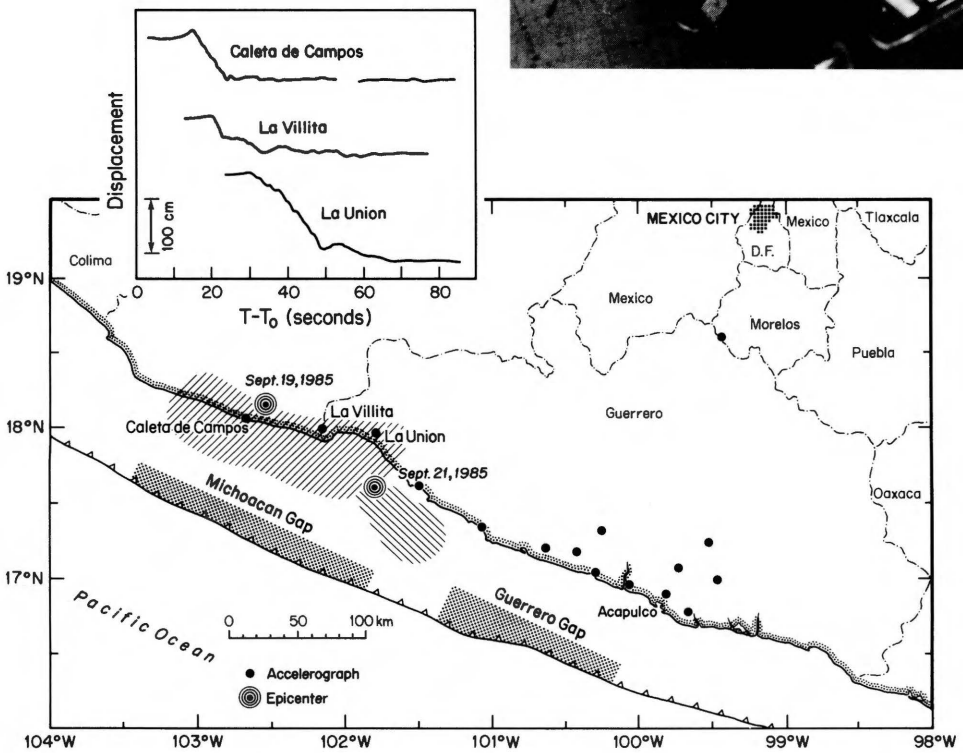
J. G. Anderson

Dr. John G. Anderson checks a strong-motion accelerograph seismometer in the basement of the IGPP building.



The accelerograms contained one big surprise for engineers. From California earthquakes with magnitudes from 6.5 to 7, the maximum accelerations observed near the fault have been typically from 0.5 to as much as 1.7 times the acceleration of gravity. Although the geometry of faulting in Mexico is quite different, it was commonly supposed that comparable or greater accelerations would be observed in a magnitude 8 earthquake. In Mexico, however, the maximum acceleration was only about 10 to 15 percent of the acceleration of gravity above the fault. These values were also surprising from the viewpoint of the few available accelerograms from past earthquakes on the Mexico subduction zone, where in one instance a magnitude 6.8 earthquake caused acceleration of 0.7 g. One research challenge is to understand the phenomena that control the levels of ground shaking.

Our observations are also unique from the viewpoint of the physics of the earthquake source. In earth-



Map of coastal Mexico, showing the subduction trench, seismic gaps (in 1985), accelerograph stations, and the aftershock zones of the September 19 earthquake and its main aftershock. Inset, *the north-south component of the ground's displacement during the earthquake at three of the accelerograph sites.*

White band along the shore is caused by dead organisms, killed by a lack of moisture when the land was uplifted.

Paul Bodin

quakes of this type the land can be raised relative to sea level. Indeed, in our accelerograms we observed exactly that process for the first time. The ground heaved upward (by about 1 m) and toward the southwest. We observed this uplift, and the higher-frequency ground motions that accompanied it, progressing from northwest to southeast along the fault.

This uplift caused widespread mortality of intertidal organisms, which were no longer submerged by daily tides. Darwin (*The Voyage of the Beagle*) was the first to observe such intertidal mortality following an 1835 earthquake he witnessed in Chile. Nonetheless, this phenomenon is unusual, and therefore interesting biologically as well as geologically. In collaboration with a graduate student in biological oceanography, we measured the vertical extent of mortality along 250 km of coastline. We found that mortality (hence, uplift) was greatest at sites nearest the epicenter, and decreased to the north and south. These measurements corroborated those given by our accelerographs.

Subduction of the ocean plates around the Pacific Rim, and associated earthquakes and volcanic eruptions are inevitable. Our research will continue to focus on understanding the hazards associated with strong ground shaking.

John G. Anderson

Suggested Reading

Anderson, J. G., P. Bodin, J. N. Brune, J. Prince, S. K. Singh, R. Quaas, and M. Oñate. Strong ground motion from the Michoacan, Mexico, earthquake. *Science,* v.233, 1986. pp. 1043–1049.

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Sardines Spawn Research

When the war came to Monterey and to Cannery Row everybody fought it more or less, in one way or another. . . . The canneries themselves fought the war by getting the limit taken off fish and catching them all. It was done for patriotic reasons, but that didn't bring the fish back. As with the oysters in Alice, *"They'd eaten every one."*

John Steinbeck, Sweet Thursday

During the 1930s, and early 1940s, the California Current supported the largest fishery in the western hemisphere—the sardine fishery. Yet within 20 years sardines had virtually disappeared from the California Current. In 1949, in an attempt to understand the collapse of the sardine industry, the California legislature mandated the California Cooperative Oceanic Fisheries Investigations (CalCOFI) "for research on conservation of marine life of commercial importance to the State." CalCOFI is a cooperative research program involving the California Department of Fish and Game (CDFG), the National Marine Fisheries Service (NMFS), and the Marine Life Research Group (MLRG) of Scripps Institution of Oceanography.

The original CalCOFI was not a harmonious liaison. Participants had different goals: NMFS (then the Bureau of Commercial Fisheries) wanted to promote commercial fisheries; CDFG hoped to restore and preserve state resources. Scientists from NMFS supported the widely held belief that pelagic fish stocks were inexhaustible, and argued that fluctuations of sardine abundance must be due to environmental factors. In contrast, CDFG saw the declining catch-per-unit-effort as clear evidence of excessive fishing pressure. In addition, CDFG represented a large and vociferous sportfishing constituency, which maintained that sardines were more valuable when left in the ocean as forage for sportfish. Academicians from MLRG were less interested in the specifics of the sardine population than in establishing general relationships between marine populations and their environment.

Thus the CalCOFI research program became a compromise. In spite of the disparity of expectations (or perhaps because of it), leaders of the program recognized that no pelagic species can be effectively studied in isolation from its physical, chemical, and biological environment. They adopted an oceanographic approach to the sardine problem "turning on the lights for modern fisheries research" (*National Fisherman,* May 1986) and making CalCOFI a pioneer program in fishery oceanography.

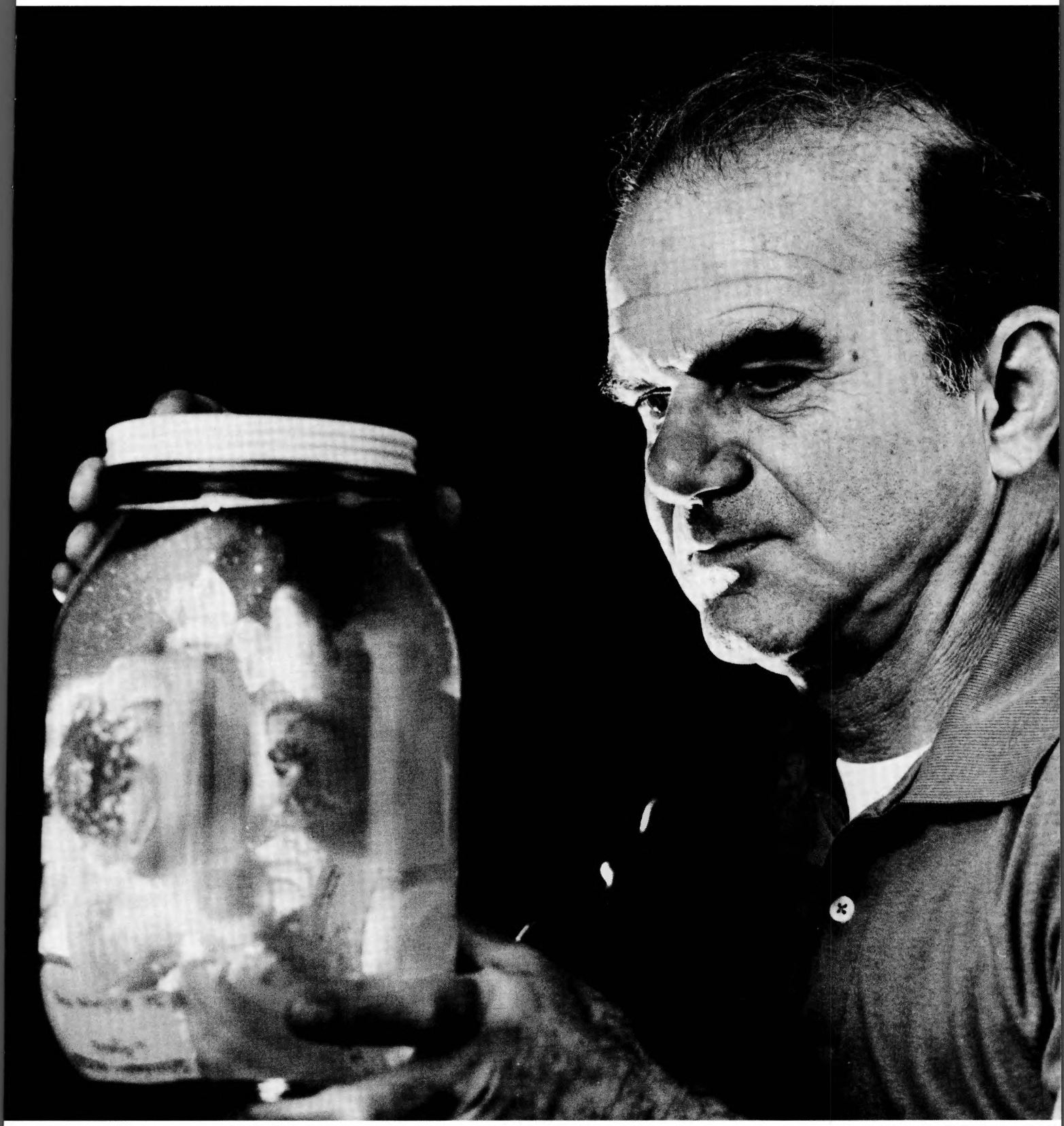
Although CalCOFI supports a large and diverse group of research projects, the backbone of the effort is the CalCOFI surveys. Initially these were monthly, multiship surveys extending from the coast to as far as 1,000 km offshore, from the Columbia River in the north to the southern tip of Baja California. Each ship occupied up to 100 stations. Measurements on each station included temperature, salinity, and oxygen. Net tows were taken for zooplankton and larval fish. More recently, nutrients, chlorophyll, and primary productivity have been added to the suite of measurements.

In the past 37 years many changes have occurred. The participants have resolved their early differences, and CalCOFI goals have been broadened to include "an understanding of the continuity and changes of the nature, environment, ecology and general biology of the pelagic fishes and associated organisms of the Eastern North Pacific" (Roger Revelle, 1958). The routine CalCOFI surveys continue, although the sampling plan has changed in response to increased knowledge and changing needs of the program. At present, cruises occur quarterly and are completed by a single ship, which occupies 62 stations in a two-week period.

One of the major accomplishments of the CalCOFI program has been the accumulation of a 37-year, uninterrupted time series of data and samples. Millions of measurements of hydrographic and biological parameters have been published in the CalCOFI data reports and have been incorporated into hundreds of scientific publications. More than a half-million zooplankton samples are curated at Scripps. These have been lent to institutions from around the world for studies as diverse as global biogeography of copepods, larval development of crabs, and radionucleotide concentrations in marine plankton. For a science as young as oceanography, these samples and environmental data are a unique and invaluable resource whose importance increases with each additional survey.

And what have CalCOFI scientists learned about the sardine and the cause of its demise? We know that the original hypotheses are too simple; most probably, both the intensive fishing pressure and unfavorable oceanographic conditions were involved. Would the sardine population have crashed in the absence of a commer-

H. George Snyder inspects a sample from the CalCOFI zooplankton collection.



B. Call

cial fishery? Perhaps. CalCOFI scientists have been able to estimate the relative sizes of pelagic stocks back to 200 A.D. Even in the absence of commercial fisheries, periods of very low sardine populations have been common. But, the sardine is returning. For reasons as complicated and obscure as those governing its disappearance, recent population estimates have been high enough to justify a small (and carefully monitored) commercial harvest.

Quite apart from the sardine, the sardine experience—the techniques developed and the knowledge gained—is applicable to a wide variety of species and has influenced fishery management around the world.

Elizabeth L. Venrick

There would seem to be only one commandment for living things: Survive! And the forms and species and units and groups are armed for survival, fanged for survival, timed for it, fierce for it, clever for it, poisonous for it, intelligent for it. . . . Life has one final end, to be alive; and all the tricks and mechanisms, all the successes and all the failures, are aimed at that end.

John Steinbeck, **The Log From the Sea of Cortez**

On a CalCOFI expedition Sherry L. Cummings takes a water sample to measure primary productivity.

E. L. Venrick

Suggested Reading

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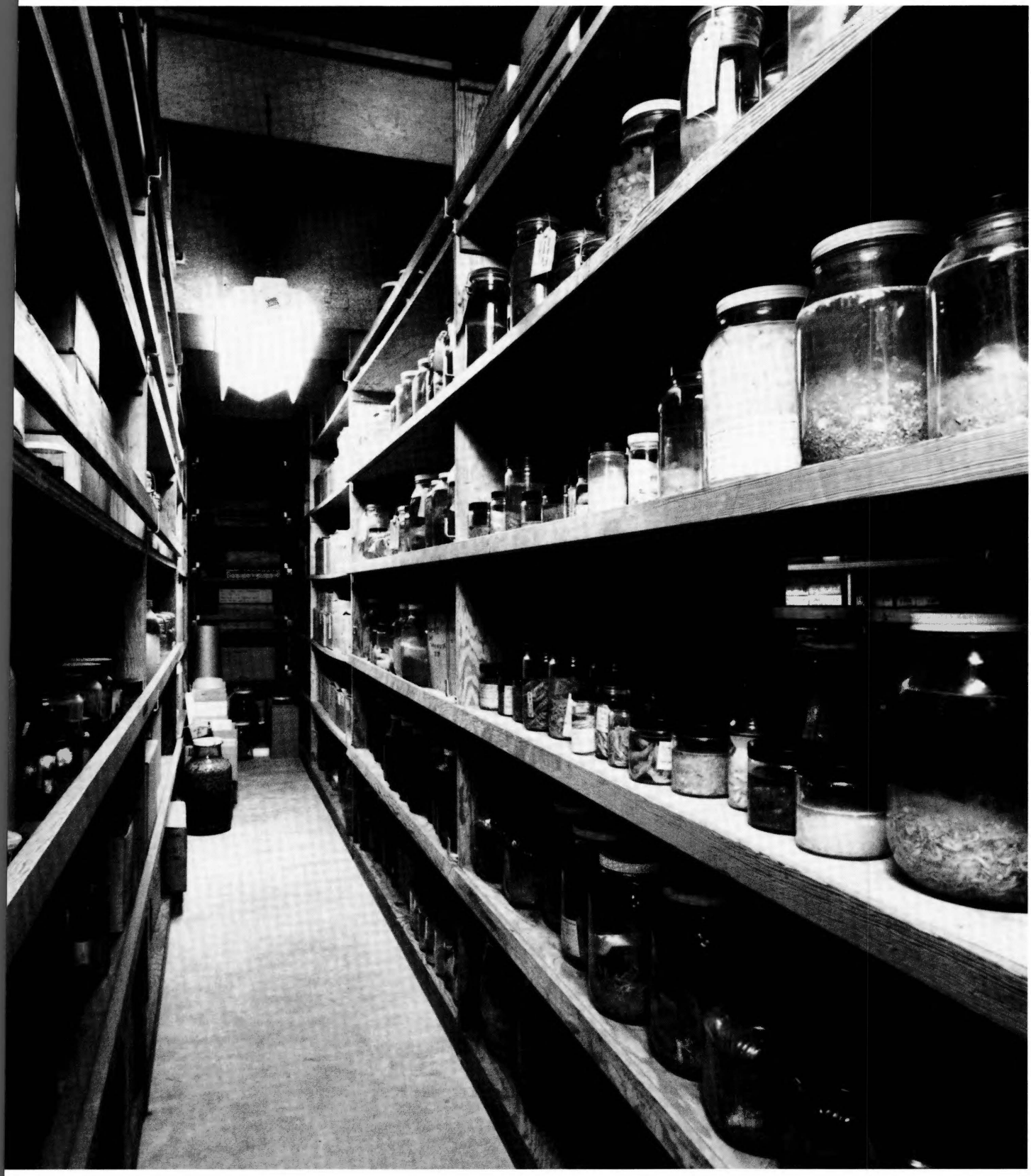
One aisle of CalCOFI samples in the zooplankton collection.



Research Activities

Many of the scientific projects being conducted at Scripps are reviewed briefly in these reports. Some departments have elaborated on a few studies, while other groups give a summary of the many projects. The majority of these studies are being funded by the National Science Foundation, Office of Naval Research, Department of Energy, Department of Commerce, and other governmental agencies.

Scientific papers listed in the Publications section will lead the reader to a more in-depth coverage of the topics discussed in the Research Activities section.

Center for Coastal Studies

The Center for Coastal Studies (CCS) is the organizational focus for coastal dynamics research at Scripps. The center includes the Shore Processes Group, the Sediment Management Group, the Coastal Dynamics Group, the Marine Archaeology Program, and the Hydraulics Laboratory. Analytical and model studies of the complex interactions among waves, winds, currents, and sediments in the coastal ocean, and related field experiments are the topics of CCS research.

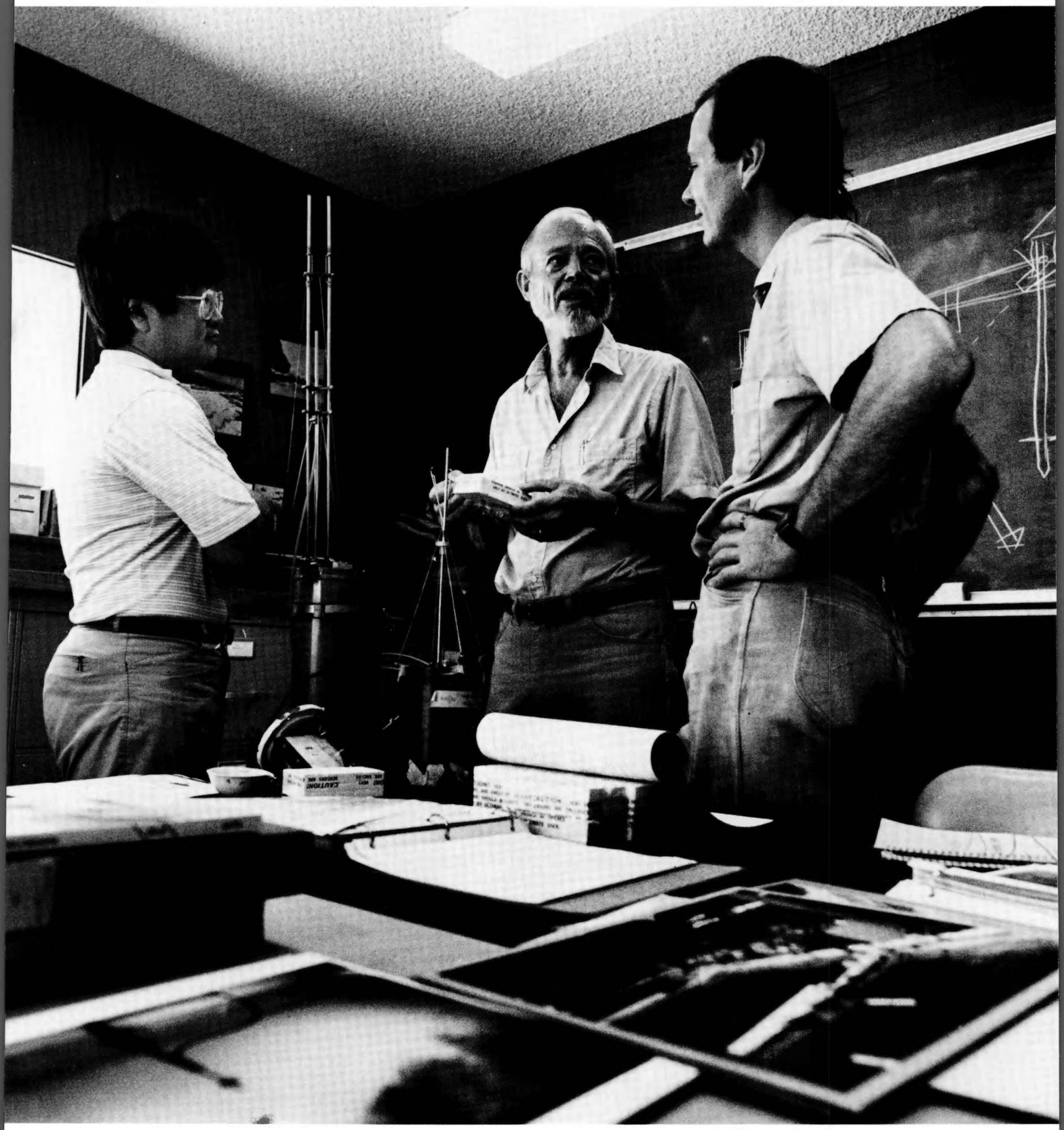
Dr. Douglas L. Inman, CCS director, studies the fluid-sediment interactions that cause sediment transport and the resulting bedforms—ripples, cusps, and the bars and berms that characterize the beach profile. Measurements near the surf zone show that the spatial and temporal scales of near-bed phenomena are controlled by shearwaves that form in the accelerating fluid layer near the bed. The wavelength of the shearwave determines the scale of the "roils" in carpet-flow sand transport, as well as the scale of the ripples that remain when the motion stops. Shearwaves in the roiled fluid-sediment layer may "burst" during decelerating motion, causing plumes of sand and water that scatter the sand into smooth beds. These studies led to a genetic classification of bedforms and to a general theory of bedform response. Coastal areas being studied include the Nile Delta of Egypt, the coast of Israel, and the barrier island chains along the Beaufort Sea coast of Alaska and the Outer Banks of North Carolina. Graduate student Thomas G. White is studying carpet-flow sand transport outside the surf zone.

Dr. Robert T. Guza's group continues work on nearshore waves and currents. Dr. Joan Oltman-Shay completed her graduate studies on infragravity edge waves and is using her observations to examine the mechanism of their generation.

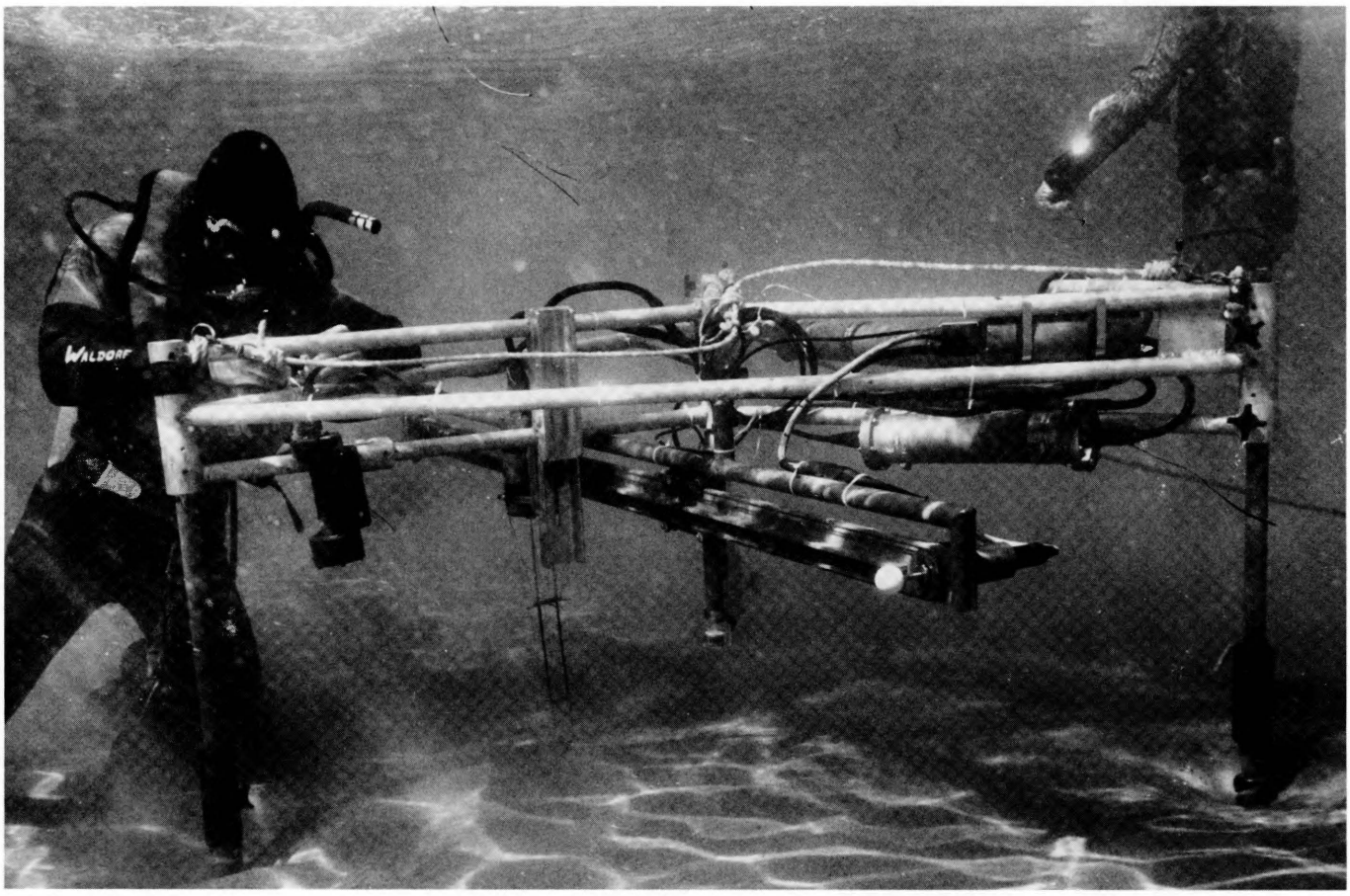
Dr. Reinhard E. Flick (Department of Boating and Waterways) is examining shoreline changes associated with construction activities at the San Onofre Nuclear Generating Station (SONGS). Extensive environmental monitoring for biological impacts of SONGS has been mandated by regulatory agencies, but relatively little attention has been paid to beach changes. The removal of a large construction laydown pad in early 1985 provided the opportunity to study the reintegration of approximately 600,000 cubic yards of sand into the littoral transport system. Dr. Flick also continues his research on surf zone turbulence and—with Daniel R. Cayan—on meteorological forcing of southern California sea level. Dr. Flick and graduate student Thomas C. Y. Fu are compiling and analyzing a local data set of beach profile changes to assess the recovery of San Diego area beaches after the devastating winter storms of 1982-1983.

Dr. Scott A. Jenkins continues work with an array of lifting bodies that prevents siltation under berthed ships and submarines at the Mare Island Naval Shipyard. He is also studying the movement of dredge spoils from the Alcatraz dump site into berths at the Port of San Francisco. The flocculent layer is transported by current motion. A thermodynamic theory for the dependence of this vertical shear stress upon the entropy of the floc layer is being developed.

Dr. Douglas L. Inman and graduate students Hyung Ki Kim (left) *and Daniel C. Conley discuss using hot-film probes to measure oscillatory bursting.*



Walton B. Waldorf positions the surf-spider platform for bursting measurements.



M. Clark

An array of bottom pressure gages was installed in the Strait of Gibraltar by Dr. Clinton D. Winant in collaboration with Dr. Nancy A. Bray and graduate student Julio Candela. The gages are deployed near the sill surface and near the sill bottom on both the Spanish and Moroccan sides of the strait. The researchers hope to deduce—from geostrophy—fluctuations in the Atlantic inflow and Mediterranean outflow. This work is one component of the Gibraltar Experiment, an international cooperative project.

Dr. Bray is measuring the transport of heat and salt between the Atlantic Ocean and the Mediterranean Sea through the Strait of Gibraltar. Her project involves moored sensors (measuring the velocity, temperature, salinity, and pressure) and shipboard surveys of temperature and salinity structure in the strait, the Gulf of Cadiz, and the Alborán Sea. Analysis of data from the study of thermohaline circulation in the Gulf of California continues. Graduate student Cynthia A. Paden is concentrating on observational and theoretical aspects of wave-front generation in sill regions. In addition, Dr. Bray is analyzing the large-scale thermohaline circulation in the Gulf of California, which, unlike most marginal seas, appears to be a three-layer rather than a simple two-layer system.

Food debris in onshore middens and a number of nearshore underwater sites reflect the marine adaptations of the prehistoric peoples inhabiting Southern California Bight coastal regions. Dr. Patricia M. Masters is correlating information on the distribution and location of the underwater sites with faunal analyses of the onshore middens to reconstruct the physiographic environments of southern California's mid-Holocene shoreline. Her findings indicate that an environmental transition occurred approximately 4,000 years ago, when rocky, cobbly beaches turned into the extensive sandy littoral cells observable today. Stable carbon and nitrogen isotope analyses on a prehistoric human skeleton are showing a strong dietary dependence on marine foods. Because the skeleton dates to 8,000 years ago, such marine dependence may provide a remarkable new insight for American archaeology.

The Hydaulics Laboratory provides support for experimental investigations of phenomena that can be scaled in a laboratory. The Hydraulics Laboratory is used extensively by CCS, Scripps, and outside investigators. A complete description appears in the Facilities and Collections section.

Geological Research Division

Interests of scientists in the Geological Research Division (GRD) are wide-ranging, and encompass such diverse topics as earthquake prediction, the petrology of oceanic islands, paleooceanography, and atmospheric trace gases. Here only a few of the many projects in the division are discussed; a more comprehensive accounting can be found in the *Scripps Institution of Oceanography Contributions.*

Progress in molecular biology, particularly abiotic replication of RNA, has provided new insights for geochemical model studies of organic molecules' earliest evolution in the ocean. How simple biomolecules could have been generated before the existence of life was essentially demonstrated through Dr. Stanley L. Miller's work 33 years ago. An unsolved question, now being studied by Dr. Gustaf Arrhenius and collaborators, is how these organic molecular building blocks could have been selectively concentrated from dilute solution of a large number of compounds randomly generated, mainly by plasma processes in the atmosphere and outer space.

A proposal by a British physicist suggested that sorption on clay minerals may have provided the necessary entropy-lowering function. Dr. Arrhenius proposes that marine rust minerals would have been more efficient in this role, particularly manganates and iron oxyhydroxides, which are common in metamorphosed form in the oldest known sedimentary rocks. A discovery made in the course of his work is that iron carbonate, forming the counterpart of limestone in the earliest ocean sediments, when irradiated by sunlight, transforms (by electron transfer and hydrolysis) into iron rust minerals and organic molecules that derive their carbon from the carbonate ion. This process may be regarded as a precursor of life-based photosynthesis.

Dr. Joseph R. Curray continues work in the northeastern Indian Ocean and Southeast Asia. He helped the United Nations Development Program coordinate the completion of SEATAR (Studies in East Asian Tectonics and Resources), a cooperative project among Southeast and East Asian nations. This series of transect investigations, started in 1973, relates onshore and offshore geological and geophysical knowledge to tectonics and resources. The ten transects cut across Burma, Thailand, Laos, Vietnam, Malaysia, Indonesia, the Philippines, Papua New Guinea, Japan, and Korea, with intervening and adjacent marine segments. Scientists from most of these nations, plus many western European and American marine geologists and geophysicists have been involved.

Dr. Curray and graduate student Tissa Munasinghe worked aboard the Lamont-Doherty R/V *Robert Conrad* near Sri Lanka. The Sri Lanka continental margin is anomalous to present concepts of passive continental margin evolution. Sri Lanka formerly lay close to India, and the two contiguous blocks lay against Antarctica in a Jurassic reconstruction. Rifting and crustal extension started during the Jurassic period between India and Sri Lanka and elsewhere along the east Indian continental margin. When the final breakup and seafloor spreading occurred, however, Sri Lanka remained adjacent to India and separated from Antarctica. Thus the eastern and southern margins of Sri Lanka are unusually steep, and show no evidence of rift-stage faulting and extension.

Examination of the subsidence history of the strait between India and Sri Lanka suggests that accelerated subsidence may have started about 30 million years ago. Furthermore, Bengal Fan sediments are deformed at the foot of the steep continental slope off Sri Lanka's SSE margin, suggesting convergence and subduction. Dr. Curray had proposed that Sri Lanka may be separating from India very slowly toward the SSE as a platelet within the overall Indian-Australian plate. The researchers' work at sea off the south and east margins of Sri Lanka showed deformation details of the Bengal Fan sediments, and rock dredging recovered samples of both the Pre-Cambrian rock of Sri Lanka and basalt apparently related to the rifting from Antarctica. Munasinghe will analyze the geophysical data and rocks from the cruise to test this model and elucidate the structure and geological history of this continental margin.

Dr. James W. Hawkins, Jr., continued work on the evolution of island arc-backarc basin systems in the western Pacific. He and a University of Tulsa colleague collaborated with Philippine Bureau of Mines geologists to study the rocks of eastern Mindanao. In the Mindanao mountains and on Nonoc Island the researchers traced a belt of island arc volcanic rocks that has been overthrust by a large peridotite mass. On Nonoc Island they identified remnants of an island arc volcanic series that had not previously been studied. Dr. Hawkins conducted an expedition to the Lau Basin aboard R/V *Thomas Washington* to map seafloor morphology and structures with Sea

Beam, and to do rock dredging for chemical analysis. During this expedition fragments of polymetallic sulfides from a backarc basin were recovered. The fragments—formed of zinc, iron, and copper sulfides, as well as amorphous silica and barite—appear to be parts of a chimney from a black-smoker-type hydrothermal vent. Although such fragments were previously found on the East Pacific Rise and the Mid-Atlantic Ridge, this was the first time they were found in the western Pacific.

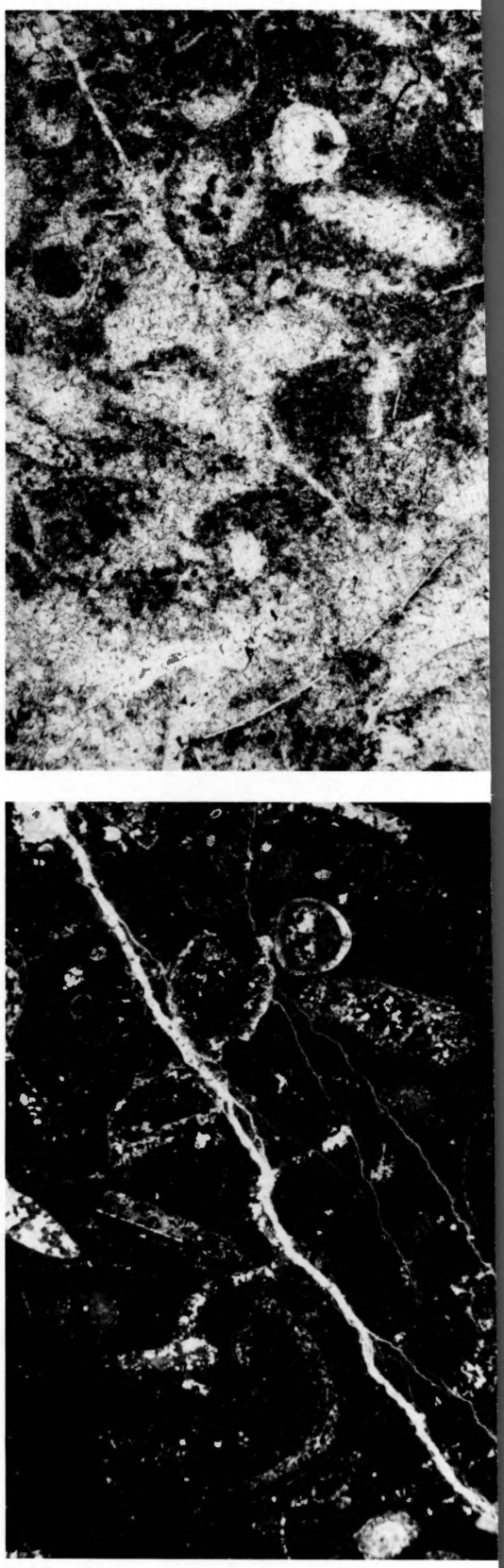
Most of what is known about the deep ocean environment comes from water samples and sediment cores recovered from abyssal depths. When brought to the surface, these samples suffer sudden decompression, warming, and other related insults that make it impossible to determine fundamentals such as the sediments' oxygen demand, or rates of calcium carbonate dissolution. Dr. Clare E. Reimers developed a deep-ocean vehicle, providing seafloor data that give significant insight into these subjects. Mounted to the vehicle is a self-contained profiling and recording instrument that lowers an array of microelectrode sensors across the sediment-water interface. Results from oxygen microelectrodes have a vertical resolution of 1 mm and show surprising heterogeneity in oxygen profiles only a few centimeters apart. Chemical heterogeneity on the seafloor is thought to be related to factors such as biological mixing of particulate organic matter, sediment microtopography, and bottom-flow dynamics.

Dr. Hubert Staudigel and Patricia S. Doyle showed that the $^{143}Nd/^{144}Nd$ of ancient seawater can be determined by analyzing fossil fish teeth. Isotopic analyses of fish teeth up to 50 million years old suggest that seawater masses from the Atlantic and Pacific oceans have a distinct $^{143}Nd/^{144}Nd$ fingerprint throughout this time. The establishment of $^{143}Nd/^{144}Nd$ as an isotopic tracer for fossil seawater is invaluable to paleooceanography, as it allows scientists to date the opening and closing of ocean straits, and helps quantify the chemical transport between oceans through geological time. The residence time of Nd and nutrients is very similar, and thus $^{143}Nd/^{144}Nd$ is useful for studying the exchange of nutrients between oceans.

Dr. William R. Riedel, Dr. Linda Tway, and students developed computer-optics procedures for measuring selected aspects of the shapes of oceanic microfossils. The surface topography of microscopic fish teeth has been captured with a series of parallel light and dark bars. The researchers project these bars onto the fossil from an oblique angle, then use the distortion of the originally straight bars to deduce the elevations of surface points that permit drawing a detailed contour map. In a related project, the pore pattern in radiolarian skeletons is being described in terms of the distance and direction of each pore from its neighbors. With this information, the scientists hope to gain quantitative data on difficult-to-measure shapes and patterns. Drs. Tway and Riedel are developing a system to aid in biostratigraphic (and eventually taxonomic and paleoenvironmental) interpretations. This system, written in the artificial intelligence language OPS5, helps interpret ages in microfossil assemblages.

Annika Sanfilippo is working out the relationships of the genera within the radiolarian family Pterocorythidae. These siliceous microfossils occur in open-ocean sediments deposited throughout the Cenozoic era, and provide clues to conditions in the water columns that they inhabited. The patterns of change contribute to the continuing discussion of the tempo and mode of evolution of simple oceanic organisms.

Dr. Edward L. Winterer continued research on the early history of the equatorial Tethys seaway, which opened when the supercontinent of Pangea began to split in the Jurassic period. Dr. Winterer has studied the earliest history of continental stretch-



GRD

Fossiliferous limestone formed on a deep bank in the Tethys seaway during rifting, before formation of new ocean. Top, *transmitted light from a 3-mm sample.* Bottom, *cathodoluminescence reveals details of the same sample.*

Drs. Edward L. Winterer and Christopher V. Metzler prepare to take core samples from a slab of breccia with a dentist's drill. The breccia, from the Alps, was formed when a dolomite formation shattered during submarine sliding along the margin of a rift basin created during the stretching and break-up of the ancient supercontinent of Pangea, about 180 million years ago. White calcite then precipitated from seawater into the open spaces between the dark dolomite blocks.

Drilling the breccia for samples for analysis of stable isotopes of oxygen and carbon. The samples of isotopic compositions provide clues to the environment in which the breccia was formed.

ing and rifting, and the creation of new oceanic crust in both the Central and North Atlantic. These investigations involved the drill ships *Glomar Challenger* and *Joides Resolution,* as well as field work with his students in the Alpine mountain chains of southern Europe. The Atlantic segment of Tethys remains undeformed and continues to widen, while the Alps result from closure and deformation of parts of the early Tethys ocean and its margins.

Dr. Winterer also investigated the age, abundance, and geographic distribution of lithified radiolarian ooze. Studies of this ooze (originally deposited in deep water beneath regions of high biological fertility, in the narrow basins created by rifting and the earliest stages of ocean-floor spreading) suggest a gradient in Jurassic oceanographic conditions. The cherts reflect high fertility in Greece, near the eastern entrance to the long seaway, and progressively lower fertility westward through Italy, Spain, the Central Atlantic, and the Gulf of Mexico. The basins were at first poorly ventilated, with near-anoxic conditions close to the bottom, but freshened as the bordering continents drifted farther apart and oceanic connections widened. Dr. Winterer and a University of Lausanne colleague are developing a model for the evolving geography and oceanic circulation patterns in this ancient, narrow, equatorial ocean.

Several investigations are under way in the Isotope Laboratory. Drs. Harmon Craig, Devendra Lal, and colleagues are determining the degree of stability of noble gases like He and Ne trapped in diamonds at the time of their formation, as well as possible in situ nuclear sources of isotopes of these gases, ^{3}He in particular. These experiments may demonstrate whether diamonds can serve as recorders of primordial composition of noble gases. The researchers found that the cross-section for the formation of ^{3}H (which decays to ^{3}He) in thermal neutron capture by ^{10}Be is about 1 barn—about 20 times larger than the value reported in the literature. This implies existence of an important mechanism for the production of ^{3}He in underground mineral samples containing boron, because of capture of radiogenic neutrons. Diamonds often contain appreciable amounts of boron.

Drs. Lal and Yu-Chia Chung are developing a nuclear method for studying the dynamics of phosphorus in the upper ocean. The method is based on the naturally occurring radioisotopes ^{32}p (half-life = 14.3 days) and ^{33}p (half-life = 25 days), which are produced by nuclear interactions of cosmic-ray particles in the atmosphere. Their concentrations in the dissolved phosphorus, organic particulate phosphorus, and other particulate phases depend on the recycling time of phosphorus through these phases. Several surface-seawater and suspended particulate samples were analyzed and found to contain ^{32}p and ^{33}p in the approximate amounts expected from cosmic-ray production and "hold-up" in the soluble/particulate phases. These experiments clearly demonstrate the feasibility of using the radioisotopes ^{32}p and ^{33}p as tracers for studying phosphorus dynamics.

Marine Biology Research Division

Marine Biology Research Division (MBRD) scientists continue investigating the biochemical, physiological, cellular, and ecological characteristics of marine plants, animals, and bacteria. They study such phenomena as interactions between marine animals and their algal and bacterial symbionts, navigation and predation by sharks, the changes occurring in sperm at the moment of egg contact, the taxonomy of deep-sea animals, and the metabolism of sulfur compounds.

Early in 1985, Dr. Robert R. Hessler had the opportunity to return to the Rose Garden hydrothermal vent site at the Galápagos Spreading Center after six years' absence. He found remarkable changes in the fauna. Conditions at the Rose Garden—unlike those in most deep-sea environments—have changed a good deal. Nearly all the giant tube worms have disappeared, and the vast adjacent filter-feeding subcommunity is markedly diminished; huge piles of mussels remain. In documenting these changes, Dr. Hessler is producing the first detailed map of a hydrothermal vent community.

Scientists in Dr. George N. Somero's laboratory studied the biochemical adaptations of marine organisms, including species from the deep-sea vents. Work with graduate student Mark. A. Powell revealed mechanisms that allow vent animals to survive in the presence of the toxic molecule hydrogen sulfide, which occurs at high concentrations in vent waters. Powell and Dr. Somero also studied how animals from sulfide-rich habitats exploit the energy in the sulfide molecule. In some species like the large vent tube worm *Riftia pachyptila,* symbiotic bacteria oxidize sulfide directly. Other species themselves perform the initial steps in sulfide oxidation and may thereby gain energy in the form of adenosine triphosphate (ATP). ATP-generating oxidation of sulfide was observed in mitochrondria of the gutless clam *Solemya reidi,* which is found in sewage outfall areas. These studies offer the first evidence that animals can exploit inorganic energy sources.

Other research in Dr. Somero's laboratory focused on environmental influences on protein metabolism and function. Graduate students Mary Sue Lowery and Sandor E. Kaupp continued their studies of how diet and exercise affect protein and nucleic acid metabolism in marine fishes. Lowery showed that during starvation marine fishes rapidly shut off the synthesis of some proteins. The changes in nucleic acid metabolism underlying these shifts in protein turnover are also under investigation. Kaupp showed that several marine fishes have marked changes in protein accumulation patterns during ontogeny. Susan J. Roberts continued her studies of protein-protein interactions in marine fishes. Graduate student Allen G. Gibbs is studying how temperature and pressure affect the membrane-bound transport enzyme sodium-potassium adenosine triphosphatase. Inhibition by high pressure is offset by elevated temperatures, an interaction that may be important for animals in deep-sea hot springs, and during vertical migration.

The metabolism of sulfur compounds is the focus of Dr. Russell D. Vetter's research. Dr. Vetter demonstrated that marine crustaceans, including hydrothermal vent species, detoxify hydrogen sulfide in the hepatopancreas. This process converts highly toxic sulfide to less toxic molecules like thiosulfate, and may allow marine invertebrates to invade sulfide-rich habitats and exploit the food resources there. Dr. Vetter also studies the sulfide metabolism pathways in animals from deep-sea vents and other high-sulfide environments to discover how these animals help cycle and exploit sulfur compounds in diverse marine habitats.

Dr. Mark E. Huntley and graduate students Victor H. Marin and Paul F. Sykes study the feeding behavior of the copepod *Calanus pacificus.* They find that this copepod rejects a number of commonly occurring dinoflagellates as food. The rejection is mediated by a variety of chemical compounds that cause physiological abnormalities in copepods, from regurgitation to elevated heart rate and loss of motor control. Recent field work focused on the feeding behavior and distribution of the Antarctic salp *Salpa thompsoni,* which dominated the zooplankton in the Scotia Sea and Antarctic Peninsula region in early 1984. These physiological studies are the first to be performed on salps outside the tropics and subtropics.

New information was obtained in Dr. Francis T. Haxo's laboratory about the photosynthetic capabilities of unusual pigments of algal chloroplasts. These capabilities may influence species adaptation to, and distribution in natural light fields. Although in chloromonads an appreciable fraction of the light absorbed by diadinoxanthin seems available for photosynthesis in cryptmonads, the transfer efficiency from alloxanthin appears to be very low, as shown in a joint study with Dr. Maria Vernet and graduate student Amir Neori. Thus the presence of an acetylenic group in a carotenoid molecule does not ensure efficient sensitization of chlorophyll *a.*

Dr. George D. F. Wilson sketches a limb of a deep-sea isopod.

In a separate study, spectrally distinct phycoerythrins were found in the marine algae *Trichodesmium* spp. of different origins in conformity with their characteristic action spectra.

Dr. A. Peter Klimley is studying the correlation of spatial distribution between white sharks and pinnepeds. To conduct his 18-month experiment, Dr. Klimley placed pingers on two *Carcharodon carcharias* at southeastern Farallon Island. Work continued on development of multisensor, ultrasonic, telemetry transmitters and a microprocessor-based decoder to study orientation and navigation in pelagic fishes. Graduate student Steve B. Butler and Dr. Klimley used satellite imagery to correlate the appearance of an oceanic fish community at a seamount at the mouth of the Gulf of California with the incursion of a warm, oceanic water mass. Such an incursion may underlie the spring movement of many tropical fish species into this area.

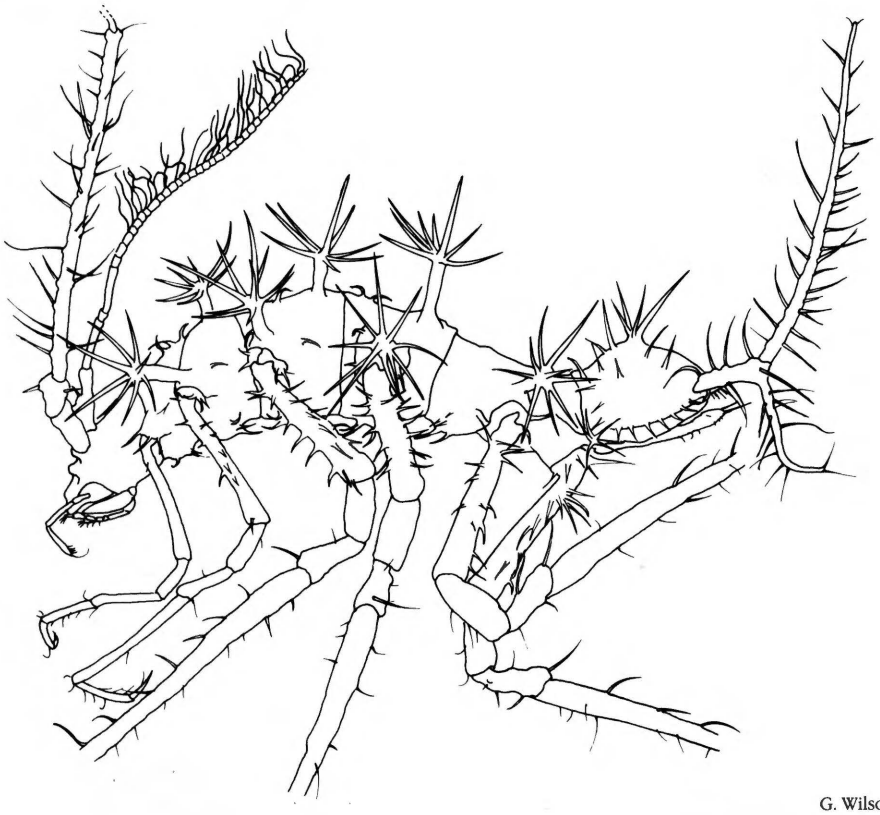
Hundreds of cultures of algae isolated from the picopleuston are stored in light- and temperature-controlled culture chambers in Dr. Ralph A. Lewin's laboratories. These microscopic algae, with cells in the range of 1-3 micrometers (including some of the smallest eukaryotic cells known), float at the surface of the ocean and may play important roles in the formation of so-called slicks. Many of the algae have high lipid contents, which contribute to the cells' buoyancy. Samples from as far afield as the Caribbean, Tahiti, the Seychelles, Singapore, and the Mediterranean have yielded many of the same range of species, in about six genera. Pure cultures have been isolated, and Dr. Lewin and Dr. Lanna Cheng are characterizing them physiologically and biochemically, in preparation for ecological and field observations.

In addition to research on truly marine insects, Dr. Cheng is studying problems of aerial insect drift over the oceans. Insects are sometimes carried by wind currents for long distances over land and sea. Some insect pests may survive journeys of hundreds of kilometers to infest plants or animals in new locations. Oxford University data from a late 1930s survey of insect drift over the North Sea are being compiled by Dr. Cheng. Her study has implications for the transoceanic spread of agricultural pests.

Ecological energetics of deep-sea communities are studied in the laboratory of Dr. Kenneth L. Smith. Investigations on active and passive transport of particulate organic matter in the deep midwater at stations in the central and eastern North Pacific are under way. Scientists are using the recently developed free-vehicle acoustical array to assess active transport by midwater animals. Faunal ground-truth for acoustic targets is provided from large opening/closing net samples. Dr. Smith and a colleague used ingestible acoustic tags to trace species involved in vertical transport (e.g., grenadier fish) to depths of 5,800 m. To study the behavior of grenadiers, Dr. Raymond R. Wilson is using free-vehicle, baited, video cameras. Graduate student W. Waldo Wakefield is analyzing the importance of planktotrophic development of slope-dwelling demersal species in the transport of organic matter through the water column. Graduate student Ronald S. Kaufmann is studying the sensory systems of scavenging demersal amphipods from coastal and oceanic communities.

Dr. Frederick I. Tsuji discovered a new bioluminescence reaction in the Japanese firefly squid, *Watasenia scintallans,* which comes inshore by

This deep-sea isopod of the genus Dendromunna *has no eyes, and its terminal body appendages are similar to the antennae on its head* (to the left) . *The legs and the second antenna are long (not completely illustrated). This specimen is found 2,802 m deep in the northwestern Atlantic Ocean.*



G. Wilson

the billions to breed in spring. The reaction depends on the energy-storage compound, ATP. This is a second example in addition to the widely known reaction in the firefly, which depends on ATP for producing light.

Scientists in the laboratory of Dr. Victor D. Vacquier study the physiology of the sea urchin sperm cell membrane. Of special interest are the proteins of this membrane that mediate the activations of the sperm at fertilization. One protein is the enzyme guanylate cyclase, which is phosphorylated before the sperm meets the egg; however, the instant contact is made the protein dephosphorylates, decreasing its activity. The phosphorylation of the sperm histone Hl occurs when the sperm contacts the egg. The researchers identified a sperm membrane protein of 210,000 daltons that regulates ion fluxes in and out of the cell.

Dr. George D. F. Wilson's studies involve the crustacean component of deep-sea faunas. In his work on the deep-sea Isopoda, he seeks to clarify the evolutionary relationships among the variety of taxa in the suborder Asellota, and to translate that knowledge into useful classifications. He revised the classification of the swimming family Munnopsidae based on computer-generated estimated phylogenies. In addition, a comparative approach to evolutionary morphology of the sex organs revealed novel relationships between shallow- and deep-water isopods. Dr. Wilson and graduate student Timothy J. Ragen are studying the crustacean fauna of the equatorial Pacific manganese nodule province at a 5,100-m-deep site south of Hawaii. They hope to describe the fauna's composition and indicate its importance to the benthic community structure. The main components of crustacean fauna are the peracarid orders Isopoda and Tanaidacea. This latter study is part of a larger, multi-investigator program to plan a controlled impact experiment to estimate the effects of manganese nodule mining in the deep Pacific Ocean. Dr. Wilson, with Drs. Fred N. Spiess and Robert R. Hessler, is involved in a related project at a 4,500-m-deep site disturbed in 1978 by a nodule mining device. Material collected with transponder-navigated box corers is being studied to clarify mining's impact on the benthic community structure. As in previous deep-sea studies, an amazing species richness has been found, thereby complicating the understanding of anthropogenic impacts on this community.

Dr. Benjamin E. Volcani's group continued their studies on silicon's regulation of gene expression and DNA replication in the diatoms. Dr. J. Richard Ludwig constructed a hybrid plasmid of the diatom *Cylindrotheca fusiformis* plasmid (pCf-2) and the bacterial plasmid YRp 7. This would provide large amounts of pCf-2 for use in hybridization studies with a sample bacterial plasmid preparation procedure, and determine the ability of pCf-2 to promote autonomous replication in other eukaryotes (e.g., yeast and *Chlamydomonas*) as well as in the diatom. UCSD student Donna K. Corey explored the presence of plasmids in 23 diatom species representing a broad sampling of species and genera of differing morphology, physiology, and habitats. Only five species and two genera contained plasmids, which differed in number and size in different diatoms.

Intertidal algal assemblages in San Diego County, differing markedly from vegetation studied elsewhere, are the subject of Dr. Joan G. Stewart's field studies. Spatial and temporal shifts in distributional patterns reflect the processes that regulate individual species abundances. Data are presently being analyzed and evaluated to assess the importance of physical factors and biotic interactions.

Marine Life Research Group

Scientists in the Marine Life Research Group (MLRG) study the physical, chemical, and biological characteristics of the eastern North Pacific. These characteristics affect populations of fishes that are economically and socially important to California. MLRG scientists track long-term trends and episodes in the California Current and its surrounding waters, maintain a comprehensive data base on those events, form hypotheses from that data base, and test the hypotheses at sea and ashore. MLRG researchers often work with personnel from the California Department of Fish and Game and the Southwest Fisheries Center of the National Marine Fisheries Service, through the California Cooperative Oceanic Fisheries Investigations (CalCOFI). MLRG provides a framework around which investigators carry out diverse research beyond the California Current.

This year MLRG researchers participated in the collection of time-series data from about 320 samples of California's coastal waters. These data advance understanding of the return to "normalcy" following a massive perturbation, like the El Niño event of 1982-1984. These data also led researchers to investigate other phenomena that were observed on survey cruises. Large regions of very clear water—clearer than oligotrophic central Pacific water—were seen repeatedly during 1985 and examined in detail in the spring of 1986 by Dr. Thomas L. Hayward. He discovered that the depth of the nutricline was related to water transparency patterns. He is now assessing the significance of these observations.

Drs. Mark R. Abbott, Hayward, and P. Peter Niiler used satellite imagery of sea-surface temperature (SST) and near-surface phytoplankton pigment concentrations to study biological processes in the California Current system. The researchers focused on the characteristics of large filaments that apparently originate near shore and transport large volumes of coastal water offshore. The dynamics and importance of these filaments are not well understood, and they will be the subject of future research.

Dr. Mark D. Ohman and two New Zealand oceanographers are studying how stored lipids in the subantarctic copepod *Neocalanus tonsus* affect recruitment. This species produces two generations per year. The first generation is spawned and hatched at a depth of 500-1,000 m in winter, and wax esters stored in the adult females' bodies provide the energy source for egg production. The second generation is spawned and hatched in the spring in surface waters, and egg production depends upon phytoplankton ingested by the adult females, rather than upon stored lipids. This unusual life history implies that instantaneous "snapshots" of phytoplankton production cannot always accurately predict herbivore recruitment. Dr. Ohman's analysis of the lipid composition of four species of California Current zooplankton indicates that copepodid stage V contains primarily depot lipids, and stage VI adults contain primarily phospholipids, reflecting stage-specific differences in allocation to storage and growth.

Dr. Abraham Fleminger used present-day species patterns to hypothesize that, during Pleistocene glacial periods, coastal upwelling combined with an intensified western boundary current west of New Guinea to create a cold temperature barrier to stenothermal, epipelagic organisms. This hypothetical cold barrier would also account for a terrestrial biogeographic limit called Wallace's Line. Dr. Fleminger's work with an Ecuadorian colleague revealed that the distributions of herbivorous copepods in the eastern equatorial Pacific are closely related to surface-water circulation in the region. Work on an isolated population of the copepod *Calanus belgolandicus* s.l. in the Black Sea provided new insights into how geographical isolation and directional selection influence cladogenesis (derivation of new evolutionary lineages) in a planktonic copepod.

Dr. Edward Brinton has been following changes in distributions and population structures of euphausiid species in the California Current during the decline of the 1982-1984 El Niño. Warm-water plankton species persisted in the Southern California Bight region into mid-1984, well past the collapse of El Niño, while populations off central California more readily reverted to their cool-temperate character. These observations have interesting implications concerning the ability of the Southern California Bight to serve as a trap for planktonic populations.

Margaret Knight has differentiated all eleven species of the genus *Euphausia* (krill) in the California Current as early as the third phase of development, the metanauplius, and onward to the calyptopis phase. At the later, furcilia, phase, she has distinguished nine of the eleven from each other and from the remaining two, but has yet to devise a method for differentiating two from each other. When her work is completed and phase-specific keys are made available, ecologists and population

biologists will have the tools to refine their models of biological interaction in the sea.

Tetsuo Matsui has discovered autumn and winter sexual segregation in the bottom-dwelling fishes, rattail (*Coryphaenides acrolepis*), sablefish (*Anaplopoma fimbria*), Dover sole (*Microstomus pacificus*), and slickhead (*Alepocephalus tenebrosus*). Work on another group of fishes, the tube shoulders (*Sagamichthys abei*) and *Holtbyrnia latifrons*, has revealed that the yolk-rich larvae of this group do not migrate upward into the rich euphotic zone during development, but rather remain at mid-depths. But the discovery of emaciated, underdeveloped larvae with nearly exhausted yolk sacs suggests that tube shoulder larvae may need to feed before the yolk is absorbed. These observations raise further questions about energy use and feeding strategies in these larvae.

Drs. Loren R. Haury, Niiler, John A. McGowan, and Elizabeth L. Venrick joined the FRONTS I and FRONTS II cruises aboard R/V *New Horizon* in July 1985. They investigated the physical, chemical, and biological properties of a persistent, complex system of fronts and eddies southwest of San Diego, where cooler waters of the California Current abut the warmer oligotrophic waters to the south. These cruises were carried out with a Mexican colleague and with the cooperation of the Mexican government. Analyses of the data show marked changes in primary productivity in the upper 100 m, and changes in the distribution of plankton species and biomass to depths of 1,000 m across a relatively weak frontal structure that was physically identifiable in only the upper 400 m.

Dr. James J. Simpson analyzed data taken in cooperation with NOAA scientists during cruises of the Sardine-Anchovy Recruitment Program. He discovered that mesoscale eddies in the California Current system have a strong steering influence on the main core of the California Current and that these eddies provide a mechanism for mixing inshore and offshore waters of different physicochemical and biological characteristics. These observations may have important implications for understanding the fertility of the California Current and its ability to support important fisheries.

Dr. James J. Simpson and UCSD student Lance Al-Rawi test their new, real-time data-acquisition system.

Dr. Venrick is investigating the structure and dynamics of phytoplankton in the central North Pacific. Analysis of samples collected during April-May 1985 on an east-west transect of the Pacific at 24°N demonstrates an extraordinarily large and stable ecosystem: over 13,000 km of virtually invariant phytoplankton biomass and productivity. The most conspicuous feature of this area is the "hole" in the chlorophyll maximum layer between 170° and 176°W, just west of the Hawaiian seamount chain. Work is under way to investigate possible coupling between bottom topography and the biomass and productivity of phytoplankton.

The amount of water carried by the various currents of the South Pacific Ocean at all depths has been estimated by Joseph L. Reid. A pattern of total transport can be calculated by summing these from top to bottom. Though the flow may be in different directions at different depths, the summed transport reveals a fairly simple pattern. A strong Antarctic Circumpolar Current flows eastward into the Pacific from the Indian Ocean south of Australia. Its exchange with the northern area is guided by the set of ocean ridges. It loops into the Tasman Sea, shows a large gyre in the central basin between the ridge extending north from New Zealand and the East Pacific Rise near 110° W, and loops around the basin that lies east of the rise.

Visiting scholar Dr. Shiro Imawaki worked with Dr. Niiler to deploy satellite-tracked drifting buoys in the equatorial Pacific Ocean. These buoys, equipped with thermistor chains, measured the daily cycle of heating and cooling as well as longer-term temperature trends. The data will be compared with and augmented by satellite SST data in order to understand the frequently observed swift currents leaving the equator, both to the north and south.

Dr. Dean H. Roemmich and colleagues completed a transpacific section of hydrographic stations from San Diego to Nagasaki, Japan. The researchers are analyzing the data to estimate the transport of heat, salt, nutrients, and deep-water masses into the northern North Pacific. Because the 216 stations spanned the ocean from the California Current in the east to the Kuroshio Current in the East China Sea, and from the ocean surface to the bottom, all water masses flowing into or out of the North Pacific were sampled. They hope to quantify the inflow of cold water near the ocean bottom from sources as remote as the far northern Atlantic into the deep basins of the North Pacific. They also hope to determine the import and export of warmer layers. Together with recent sections in the Atlantic, the transpacific survey will yield a global estimate of the oceans' role in transporting heat poleward to maintain the earth's climate.

Marine Physical Laboratory

Scientists at the Marine Physical Laboratory (MPL), under the direction of Dr. Kenneth M. Watson, are investigating underwater acoustics, marine physics and geophysics, signal processing, and ocean technology.

Ocean Environmental Acoustics and Signal Processing

Dr. Fred H. Fisher is studying the vertical directionality of ambient noise in the 100-300 Hz frequency region. His work involves the deployment of a vertical line hydrophone array from R/P FLIP in water over 3,500 m deep. Both the 48-element Navy array and the MPL 32-element, rapidly deployable array were used at the sound channel axis 700 m deep. The Navy array was used while FLIP was moored at 32°N, 124°W; the MPL array was used at a series of drifting stations 124°W, 136°W, and 150°W at constant latitude 32°N. Data analysis by Dr. William S. Hodgkiss showed a rapid structural change in the ambient noise's vertical directionality in the region centered about the horizontal axis.

Dr. Hodgkiss, in collaboration with Dr. Victor C. Anderson's research group, improved the system control and quick look/calibration analysis software for a high-speed data recording system (HSRS). The HSRS was designed and fabricated by MPL.

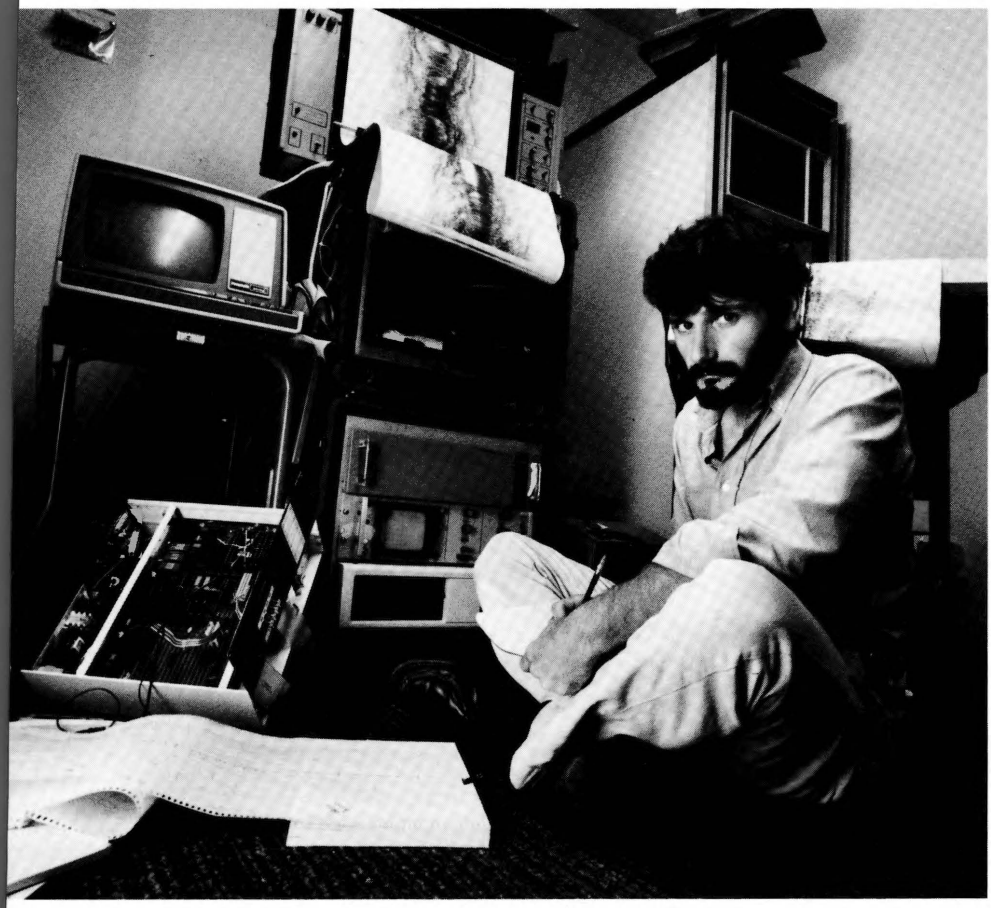
With Dr. Anderson's research group, Dr. Hodgkiss continued developing a freely drifting array of Swallow floats for measuring infrasonic ambient ocean noise in the 1-20 Hz frequency region. Although the sensors are freely drifting, each float pings periodically, providing a localization signal that is received by the other sensors. Knowing each element's location enables researchers to coherently process the array element outputs (beamforming) to measure the directionality of the ambient noise field. Sea tests were performed with five of these floats. Graduate students are developing software for buoy localization and data analysis, as well as a model of very-low-frequency acoustic propagation in the water column and sediment.

Ocean Technology

Dr. Fred N. Spiess's group used seagoing equipment to locate and recover six different sets of moored instruments whose anchor releases had failed on earlier projects. Of the six units recovered from 2,000-5,000 m, three belonged to Scripps, one to NOAA, one to Oregon State University, and one to the University of Hawaii. The MPL Deep Tow system was used for a fine-scale, side-looking sonar and bottom photography expedition in an abyssal hill area about 800 km south of San Diego.

As part of an undersea geodesy program, Dr. Spiess was involved in an effort to design and construct an acoustic instrument with an accuracy of better than one part in 10^5 for measuring the speed of sound on the seafloor. Devices were designed and built to lower and release ocean-bottom seismographs at precise positions on the seafloor. Dr. Spiess also designed and constructed a thruster-powered instrument package that can be operated at the end of an electromechanical cable close to the

Dr. Christian de Moustier compares Sea Beam swath map (bottom left) *with computer data* (upper center) *generated by a Sea Beam imagery system under development.*



seafloor for sampling, photography, and recovery of lost objects.

Dr. John A. Hildebrand and F. Vince Pavlicek are constructing a horizontally moored acoustic hydrophone array. The array, 1.5 km long, contains 200 individual hydrophones, and is operated from the R/P FLIP. The array will be used in deep ocean basins to study 10-100-Hz acoustic noise generated by shipping, storms, and organisms. The long, horizontal, hydrophone array allows the azimuthal distribution of noise source to be examined with approximately 1° of resolution.

Dr. Christian de Moustier's group is measuring acoustic backscatter from deep seafloors with the multibeam echo-sounder Sea Beam. The researchers designed and built a system to digitize and record, on magnetic tape, complex acoustic data from Sea Beam's 16 preformed beams. This system was tested aboard R/V *Thomas Washington* during leg 3 of the Papa-Tua Expedition. The system was also used aboard the French R/V *Jean Charcot* as part of a collaborative venture to acquire and process Sea Beam acoustic data. Working with the complex recorded data, Dr. Dimitri Alexandrou applied adaptive noise canceling techniques to suppress the sidelobe interference inherent in multibeam sonars. With this processing, it is possible to use the backscattered acoustic returns received by Sea Beam, with a 2.66° angular resolution, to infer seafloor geology.

Dr. Daniel E. Andrews, Jr., and a graduate student are examining the internal electroacoustic characteristics of a very-low-frequency underwater transducer that employs a gas-filled resonant bubble as the wet radiating surface. This type of source, which is only a small fraction of a wavelength across, is of special interest in the VLF band because it permits large mechanical displacements at the surface of the bubble-containing bladder. An experimental transducer has been constructed and tested with resonances in the vicinity of 20 Hz; most observations are in the 15-to-80-Hz band.

Marine and Arctic Physics/Geophysics

The Upper Ocean Physics Group, directed by Dr. Robert Pinkel, studies the dynamics of small-scale motions in the top kilometer of the ocean, analyzing existing data, and developing and field testing new instrumentation.

Graduate student Jeffrey T. Sherman developed and tested a coherent Doppler sonar system. A single beam successfully measured shear profiles out to 25 m, with a resolution of 1 m in range and 1 sec in time. The existing incoherent system has a total range of nearly 2 km, but a resolution of 20 m and 3 min.

Dr. Jerome A. Smith has been analyzing the MILDEX data set and relating near-surface velocities from two Doppler sonars to the velocities sensed by fixed and profiling current meters. Surface convergences associated with Langmuir circulation appear intermittently at all resolvable scales up to about three times the mixed layer depth. Comparisons of the Doppler sonar data with the current meters continues. Graduate student Albert J. Plueddemann is working on the time-space characterization of the internal wavefield, using information from the four down-looking Doppler sonars.

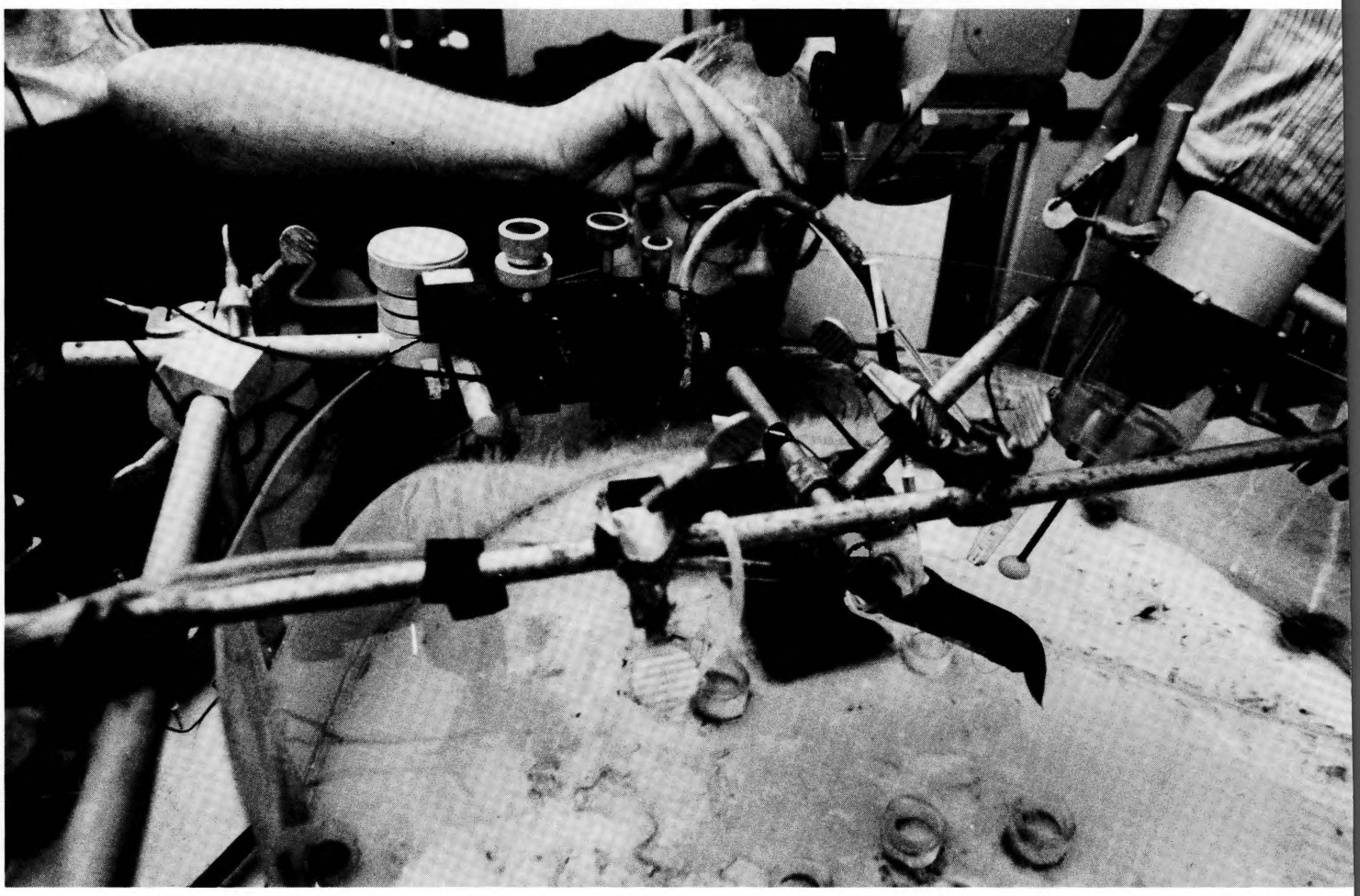
A series of flow measurements in the upper Arctic Ocean is now being analyzed. The velocities, measured by two commercial Doppler sonar systems, revealed low overall energy in the Arctic internal wavefield. Wave propagation is evident, and significant interactions between the waves and the background shear field are seen. An isolated Arctic eddy, which passed through the test site, was measured by the sonar and found to have peak velocities of 30 cm/sec.

Neurobiology Unit

Scientists in the Neurobiology Unit, associated with Marine Biology and the Marine Biomedical Program, study the sensory and neural mechanisms of natural behavior.

Dr. Theodore H. Bullock found that electrical recordings of the brain show, within a few hours, the acoustic frequencies a fish can hear. The results from these recordings are in agreement with results from much more laborious, traditional methods requiring training. Young (1 kg) yellowfin tuna, for example, hear only between 300 and 600 cycles per second, a narrower range than most fish. Dr. Bullock and colleagues used computer-averaged brain waves to reveal the brain correlates of cognitive events in a dolphin's brain. Drs. Bullock and Erol Basar employed

Dr. Horst Bleckmann records from primary lateral-line afferents of the prickleback Xiphister atropurpureus. *The goal of Bleckmann's research is to compare the function of the mechanosensitive lateral-line system in "specialized" and "nonspecialized" teleost and nonteleost fishes.*



computer processing of brain waves to measure parameters, such as coherence, as function of separation of recording loci. They also used frequency spectrum of amplitude modulation, both as function of brain wave frequency, to study the evolution of brains in advanced invertebrates and a range of vertebrates. As part of the evolutionary study Drs. Jose M. Gaztelu and Elio Garcia-Austt compared brain waves in the hippocampus and cortex of turtles.

Dr. Jeff Schweitzer completed a study of brain areas responsive to electrosensory stimuli up through the midbrain and into the diencephalon in an elasmobranch, recording compound potentials and single units and marking the areas anatomically.

Dr. Bullock and two colleagues mapped the brain areas responsive to lateral-line (water-movement) stimuli and characterized their dynamic properties in rays. The best frequencies and sensitivity appear to be higher in the brain than in the sensory nerve fibers. Dr. Horst Bleckmann, in a theoretical study of wave analysis by surface-feeding fish and arthropods, showed that they may compute the distance of a source of disturbance by the ray-tracing method familiar to physical oceanographers.

Dr. Leo Demski and others described the anatomy of the nervous terminalis in elasmobranchs and cetaceans. The nervous terminalis is a little-studied cranial nerve found in most vertebrates; it may function as a social chemoreceptor.

Dr. Janet L. Leonard has worked out the ethology of several opisthobranchs; one study reconciled conflicting reports on gill withdrawal movements in *Aplysia,* much studied in simple models of learning. She also used the alternation of male and female roles in the simultaneous hermaphrodite *Navanax* to test theoretical models of the evolution of reproductive behavior.

Dr. William L. R. Cruce studied the problem of neural pathways from forebrain to spinal cord in sharks, using new fluorescent tracers.

Ocean Research Division

Scientists in the Ocean Research Division (ORD) work in many disciplines; in this discussion, we have chosen programs in marine biology, marine chemistry, marine physics, and physical oceanography to represent the whole. ORD also serves as the home of the Physical and Chemical Oceanographic Data Facility and the Scripps Satellite Research Facility. Both of these are described in the Facilities and Collections section of this report.

Internal Hydraulics of Gibraltar Strait and Ocean Mixing Processes

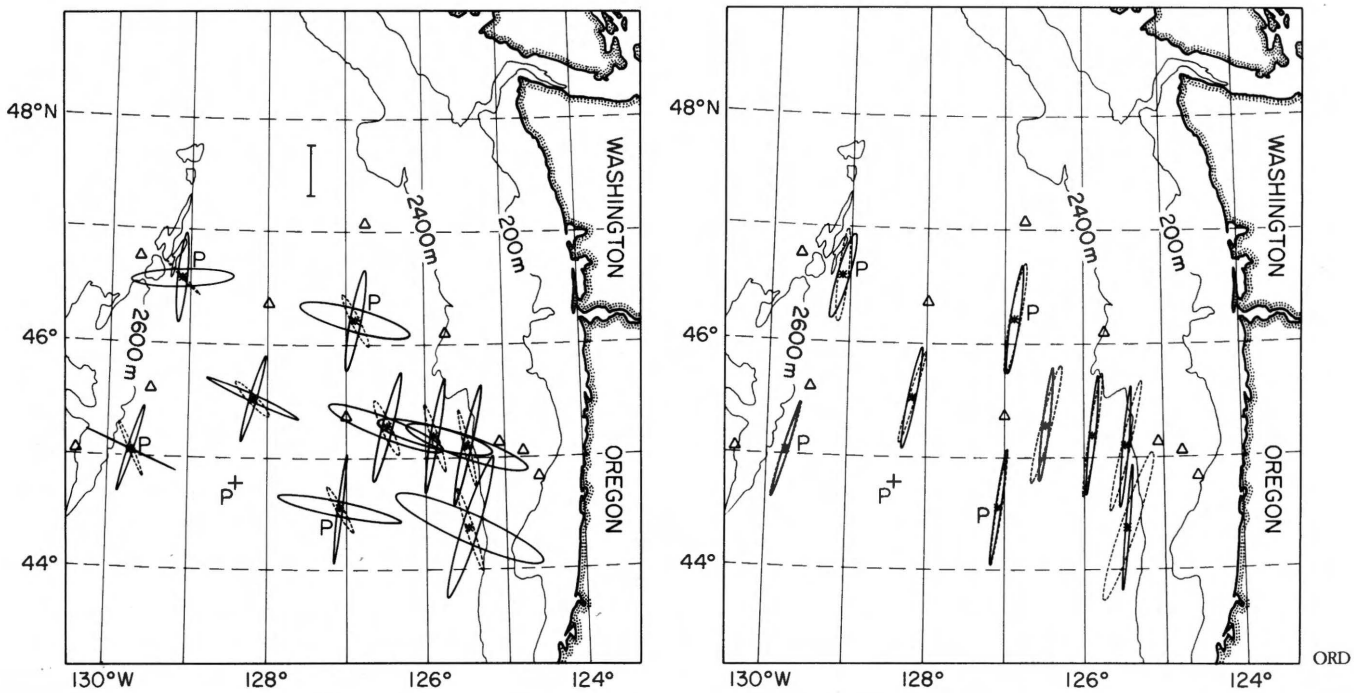
Dr. Laurence Armi is studying the internal hydraulics of the Gibraltar Strait. His objective is to resolve the essential features of time-dependent internal hydraulic control in the strait and how this control influences two-layer exchange between the Mediterranean and Atlantic. This project has five aspects: (1) the time-dependent structure of flow near the first sill (Camarinal), including the hypothesized supercritical flow west of the sill crest—the internal hydraulic jump connecting the subcritical conditions in Tangier Basin; (2) the submaximal conditions (such as flow reversal of deep layer) over the sill during inflow that are required to specify the exchange throughout the tidal cycle; (3) the internal hydraulic transition between subcritical flow just east of the sill and supercritical flow in the eastern part of the strait, together with the adjustment back to subcritical flow at the entrance to the Alborán Sea and the response of these features to traveling bores generated near the sill; (4) the behavior of fronts in the narrow section of the sill; and (5) interpreting the above processes in terms of internal hydraulic theory and determining their influence on the exchange of water between the Mediterranean and Atlantic.

Time series measurements were made in April 1986 at specific locations (Camarinal Sill, Tarifa Narrows, and the eastern end of the strait), and a sequence of traverses along the axis of the strait and across the strait recorded density, velocity, and acoustic backscatter profiles. These measurements will describe the spatial and temporal structure of the hydraulics, and are aimed at resolving the exchange problems. Moored thermistor chains and current meters will be deployed to acquire sufficient temporal resolution to describe the time-dependent hydraulic response.

Ocean mixing processes are also studied in Dr. Armi's laboratory. The structure of fronts and associated intrusions, and other small-scale structure embedded in large-scale eddies and jets off the California coast are being studied. These large-scale coherent flow features show distinctive signatures in satellite infrared scanner images; these images were used for in situ sampling strategy. For simplicity, the researchers focused on the California coast; however, they believe that a limited number of coherent structures exist in the oceans, and that this study will apply to other areas.

EMSLAB seafloor array between the coast of northwest America and Juan de Fuca Ridge (2,600-m bathymetry feature to the west). The east-west-trending ellipses represent the horizontal electric field that corresponds to the semidiurnal lunar constituent M2 at stations where both electric and magnetic fields were recorded. The dashed ellipses represent the magnetic field for M2. The north-south-trending ellipses combine both electric and magnetic information for estimating tidal barotropic velocity for the M2 tide. The scale segment, upper center, *corresponds to* 10^{-6} V m^{-1} *(electric field),* 5×10^{-9} T *(magnetic field), and 2.5 cm* s^{-1} *(velocity).*

Right, *the continuous ellipses represent independent estimates of barotropic tidal flow for M2 derived from seafloor pressure data from stations P (and a few others off map). The dashed ellipses represent the electromagnetically estimated barotropic M2 flow (shown in adjacent figure).*



Volunteer Ship Program

The volunteer observing ship (VOS) program, under the direction of Drs. David L. Cutchin and Warren B. White, operates in the tropical Pacific area. Commercial ships voluntarily collect biological and chemical data for Scripps and international researchers, and are equipped to deploy XBT (expendable bathythermograph) probes. Several of the ships carry satellite communications equipment. Hardware and software for receiving and processing data were developed to view the data in near-real time. Previously it might have taken six months to view the thermal structure of the tropical Pacific; it now can take as little as a few hours. This enables researchers to keep abreast of late-breaking oceanographic news, such as the development of El Niño events.

VOS XBT data has recently been used by Drs. White and Stephen E. Pazan and others to describe climatic variability of the subsurface thermal structure over the entire Pacific Ocean. Drs. White and Pazan compare the real ocean against a wind-driven model ocean to develop a hindcast/forecast procedure for El Niño events, and to investigate the balance between wind-driven and geostrophic currents in the tropical Pacific Ocean. Drs. White and Pazan are now managing thermal data for the Tropical Ocean/Global Atmosphere (TOGA) Project, in which the VOS XBT data will play a predominant role.

This year, Drs. Dean H. Roemmich and Bruce D. Cornuelle used a VOS network vessel, *Southland Star,* to make precise XBT sections across the South Pacific subtropical gyre in the area between Fiji and New Zealand.

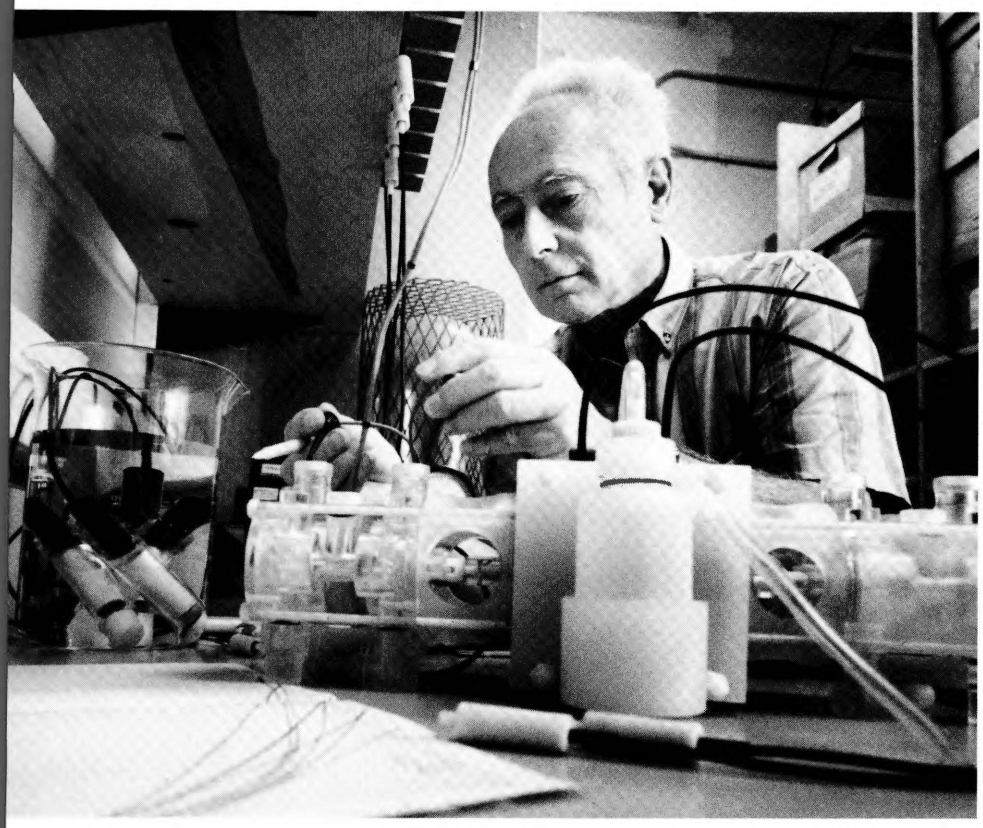
In cooperation with EXXON and the U.S. Minerals Management Service, *EXXON Jamestown* was diverted from its course to cut directly across a detached loop current eddy. This is the first time that a VOS has changed course at scientist's request to sample a more interesting part of the ocean.

New Chemicals from Marine Organisms

Dr. D. John Faulkner's group isolates and identifies new chemicals from marine organisms. Many of the natural products isolated in his laboratory have potentially important pharmacologic properties, including antimicrobial, anti-inflammatory, and antimitotic (anticancer) effects. The research has focused on understanding in what ways these unusual metabolites are important to the organisms that produce them.

Identifying chemical signals that influence the settlement and metamorphosis of invertebrate larvae has highlighted recent work. *Phragmatopoma californica,* a polychaete worm that forms reefs from aggregated tubes of sand, produces planktonic larvae that metamorphose in response to compounds isolated from the sand tubes of adult worms. Such compounds might be used to control worm-reef formation so as to prevent the erosion of shorelines and beaches.

Dr. Jean H. Filloux tests an electrode-switching device (salt-bridge chopper) prior to an expedition. Below, *aboard the Royal Australian Navy research vessel* HMS Cook *a marine technician secures an electric field recorder after its return from a four-month operation on the Tasman Sea floor.*



Kym Degener

Also potentially useful are novel metabolites isolated from unfouled colonial invertebrates (sponges, corals, and tunicates). These animals use their chemicals to prevent the larval settlement of organisms that might otherwise consume or smother them. Particularly effective compounds may help prevent the settlement and growth of invertebrate foulers on ships' hulls, buoys, and other maritime structures.

Electromagnetics Beneath the Juan de Fuca Plate

Dr. Jean H. Filloux's work has centered on the international project EMSLAB (Electro Magnetic Study of Lithosphere and Asthenosphere Beneath Juan de Fuca Plate). EMSLAB is the study of a spreading plate from accretion along Juan de Fuca Ridge to and beyond subduction under the North American continent. Dr. Filloux's group observed the seafloor with an array of 29 recorders—all recovered—including 14 electrometers, 9 magnetometers, and 6 pressure recorders. Data coverage, simultaneous with land operations, lasted 65 days.

Natural electromagnetic fluctuations observable on the seafloor are generated by ionospheric-magnetospheric processes and the interaction of oceanic motions with the earth's main field. In both cases electric-to-magnetic relationships are controlled by the structure of electrical conductivity of the submarine basement to great depth; in the second case these relationships are also affected by the geometry of oceanic velocity fields. Separation of ionospheric and oceanic contributions should greatly enhance the resolution of electromagnetic exploration of the solid earth, while providing an alternative to investigations of large-scale oceanic motions. An example from the extensive seafloor data coverage from EMSLAB follows.

The horizontal electric field at 9 stations, correlated with gravitational driving, is shown in an accompanying figure for semidiurnal lunar tide con-

stituent M2. Divided by the earth's vertical main magnetic field, it should correspond to the barotropic flow except for the effect of electric currents driven in ocean and seafloor by oceanic fields. A first-order correction can be made from the magnetic signature of these electric currents, as recorded by EMSLAB magnetometers. An appropriate combination of electric and magnetic data closely provides the barotropic flow.

Tidal elevations derived from seafloor pressure records at five sites have been used to simulate the semidiurnal tide over the area in terms of Kelvin and Poincaré wave modes, in turn leading to alternate barotropic flow estimates. A single, closely defined two-mode Kelvin-Poincaré mix allows a remarkably close fit with electromagnetic estimates.

Sensory Biophysics

Behavior depends mainly on how an animal perceives the world in which it lives. Thus knowledge of the ocean's physical features and the information they offer to animals is essential for the study of sensory detection. The need for a physics-oriented approach is obvious when sensory systems unfamiliar to humans are involved, for example, the electric sense of sharks, skates, and rays. However, the objectivity of the scientific method is equally important in studying the more familiar senses. In hearing, for instance, marine animals need not detect or perceive acoustic fields the same way we do.

Research conducted by Dr. Adrianus J. Kalmijn has revealed that aquatic animals produce steady bioelectric fields in their immediate vicinity, incidental to the normal physiological processes taking place at the body-seawater boundary. Within less than half a meter from the source, the common bioelectric fields are usually too weak to be detected by instruments. Nevertheless, these fields routinely guide marine sharks, skates, and rays to their prey, even in the night or when the prey is hiding under sand on the bottom.

The versatility of the elasmobranchs' keen electric sense became apparent when Dr. Kalmijn demonstrated that sharks, skates, and rays are also capable of orienting to the motional-electric fields of ocean currents, and may even use the electric sense to determine their magnetic compass headings. The physical principles of these orientation mechanisms date back to Faraday's 1832 paper on electromagnetic induction. All Dr. Kalmijn's orientation studies are first conducted in land-based facilities and subsequently verified at sea.

Elasmobranch fishes are most readily attracted to acoustic sources at frequencies well below 100 Hz. Only fishes that use the swim bladder as a hearing aid detect considerably higher frequencies, up to several thousand hertz. The basic hearing function would, according to Dr. Kalmijn, detect the low-frequency hydrodynamic flow fields produced by moving objects such as predator or prey. Notably, the sharks, skates, and rays lack a swim bladder, and even many of the fishes with swim bladders do not seem to use them in hearing.

More precise information from the water perturbations in the vicinity of predator and prey is acquired by the lateral-line system, which is developmentally related to the inner ear, but has its receptors arranged in linear arrays on the head and along the length of the body. Behavioral studies have recently shown that at night teleost predators cautiously approach their prey, probably aided by their inner-ear sense, and fully rely on the lateral line to initiate their fast and well-aimed attacks from striking distance.

Dr. Kalmijn's theories about the origin of vertebrate hearing are not only based on the well-known physics of hydrodynamic and acoustic fields, but also on the biophysical properties of the fishes' lateral-line and inner-ear sense organs. A reevaluation of the various sensory structures has recently clarified the detection of underwater sound and resolved long-standing inconsistencies.

Oceanic Cloud-Radiation Feedback Processes

Dr. Richard C. J. Somerville and graduate students Beth Chertock and Sam F. Iacobellis used remote sensing and modeling to study oceanic cloud-radiation feedback processes. They employed a multiyear time series of earth radiation budget (ERB) parameters, which recently became available from the Nimbus-7 satellite. These data permit an assessment of the natural variability of the measured parameters, including earth albedo, longwave terrestrial flux, and net radiation. The researchers' goal is to clarify the clouds' role in modifying the greenhouse effect. This effect is likely to raise the earth's surface temperature in the next few decades, as the atmosphere absorbs increased concentrations of carbon dioxide, methane, and other trace gases.

The satellite ERB data provide a promising means of validating several proposed cloud-radiation feedback mechanisms. One such mechanism is caused by the possible dependence of cloud optical thickness on temperature, as proposed recently by Dr. Somerville. Other mechanisms involve the possible systematic dependence of cloud height and cloud amount on variables such as temperature and relative humidity.

Clouds respond rapidly to their environment, so an analysis of how they change as sea-surface temperature (SST) undergoes an annual cycle may provide clues as to how they will respond to a long-term SST change like that caused by increases in the concentration of atmospheric CO_2 and other "greenhouse" trace gases. Statistical effects of SST variability may be sought in time and space averages of satellite ERB data. These effects vary with geographical region, synoptic regime, and other factors. It would be naive to regard seasonal and interannual variability as a simple surrogate for longer-time climate variability. Nevertheless, physical processes that are important in oceanic cloud-radiation feedback may occur on a wide range of time scales, including those accessible through the Nimbus-7 data.

Dr. Somerville's group carried out preliminary analyses in several test regions and will document the regional and temporal variability of ERB parameters. Both the planetary albedo and SST in the test regions show substantial interannual and seasonal variability. Furthermore, the SST and albedo time series sometimes display similar features. For example, the envelopes that bound the variability of the two curves may have similar structures. These albedo changes over the oceans are presumably caused by cloud variability. The researchers found that under some circumstances cloud parameters, and hence cloud effects on earth radiation budget components, may vary systematically with sea-surface temperature.

Dr. Somerville and his students have also used a hierarchy of models to interpret the satellite data and to use them to assess and improve the method of applying cloud-radiation interactions in large-scale numerical weather prediction and climate simulation. The nature of cloud feedback is recognized as one of the major uncertainties in present-day climate models. Cloud effects may amplify climate changes such as those expected from increasing atmospheric CO_2, or the clouds may act as a global thermostat, stabilizing our climate.

North Pacific General Circulation and Mesocale Studies

Dr. Lynne D. Talley has been studying North Pacific general circulation and mesoscale. In her circulation study she uses maps of the potential vorticity field on a large number of surfaces of constant density to infer aspects of the general circulation. Heuristically, potential vorticity is a quantity related to angular momentum; in the absence of forcing and friction it is conserved following the flow. It is a fundamental dynamical quantity in theories of large-scale ocean circulation. Maps of this quantity are interesting because potential vorticity is a property, like salinity or a nutrient, that can add information to the basic velocity shear calculated from temperature and salinity.

Potential vorticity can be compared easily with circulation theories used to interpret the potential vorticity distributions. Vorticity maps reveal the presence of mode waters in the subpolar gyre, and circulation of low-potential-vorticity water around the eastern part of the subtropical gyre, analogous to features found in the North Atlantic, and hitherto thought caused by deep winter convection. In the North Pacific, winter convection is not important because the mixed layer depth is constrained by a strong, shallow halocline. The presence of mode water indicates that there are processes that are common to all oceans and do not require deep winter convection—although such convection greatly enhances the mode waters of the North Atlantic.

Another aspect of the general circulation that reveals the potential vorticity field, assuming that theories of wind-driven circulation are approximately correct, is the depth and shape of the wind-driven gyres. Thus it is possible to separate the three-dimensional regions where flow is driven by the wind and thermocline forcing from those where the forcing is entirely thermohaline. In the North Pacific, the maximum depth of the wind-driven circulation is hypothesized to be about 2,500 m.

Dr. Talley has also been involved with seagoing hydrographic data collection; a trans-Pacific section at 47°N in the subpolar gyre was made in August 1985. Data from this cruise have already revealed a northward-flowing deep western boundary current; a strong separation of eastern and western regions in the upper 1,000 m, the possible effect of abyssal geothermal heating slightly changing the abyssal temperatures (so we surmise that the abyssal waters are older to the east); and a strong northward undercurrent in the upper water near the shelf just west of Seattle.

Drs. White and Talley have been looking at the mesoscale eddy field of the mid-latitude North Pacific using the eight-year TRANSPAC XBT data set. The data were collected to study large-scale phenomena (in excess of 1,000 km) rather than mesoscale phenomena (100-to-1,000-km scales), but the richness of the data set in providing space and time information led the researchers to try quantifying space and time scales. They found that length scales are shorter in the Kuroshio Extension than elsewhere in the mid-latitudes, that dominant phase propagation is westward everywhere in the North Pacific, and that there was an eight-year cooling trend in the eastern North Pacific.

Dr. Talley and a colleague used a quasi-geostrophic numerical model to study the instabilities of a barotropic jet, particularly the differences between instabilities that are strongly trapped to the jet, and those that can radiate to the far field. Linear, analytic theory predicts that an eastward jet will not radiate and that a westward jet will, via Rossby waves of the far field. The numerical calculations extend the linear theory to the nonlinear "turbulent" regimes. The researchers found that linear growth is followed by nonlinear vacillation, followed by growth of the entire spectrum; radiation is indeed important in determining the final shape and energy level of the mean flow.

Physiological Research Laboratory

Scientists in the Physiological Research Laboratory concentrate on the physiological and biochemical adaptations of aquatic and terrestrial animals. In this report two of the several projects in the laboratory are highlighted.

Diving Biology of Sea Snakes

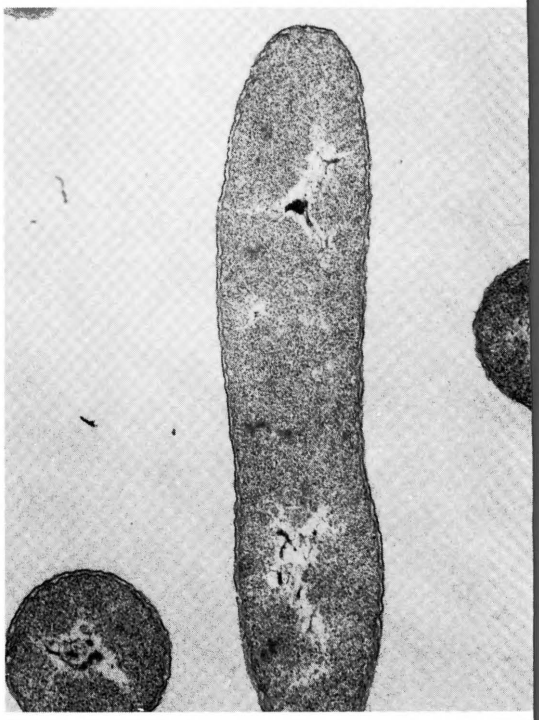
The diving biology of the yellow-bellied sea snake, *Pelamis platurus,* is a continuing subject of research for Dr. Jeffrey B. Graham and his colleagues at the Smithsonian Tropical Research Institute in Panama and at the University of Manitoba, Canada. Acoustic tracking studies of free-swimming *Pelamis* in the Gulf of Panama, and deep-tank experiments at Scripps, have yielded several new discoveries about the behavior and physiology of this highly venomous and widely distributed sea serpent.

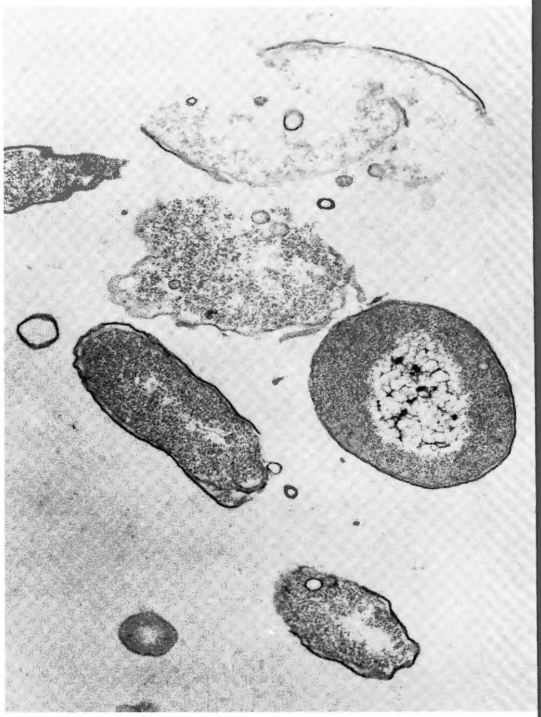
Tracking showed that *Pelamis* makes long repetitive dives to depths of at least 50 m and that—despite previous perceptions that this snake occurs mainly at the surface—it spends an average of 87 percent of its time submerged. The longest dive measured so far is 213 minutes. Normally drifting in oceanic surface currents, *Pelamis* occurs throughout the tropical Pacific and Indian oceans, and ranges from eastern Africa to Central America. Track data show that diving snakes drift more slowly than those on the surface, and in some cases they can move against the prevailing surface drift. Diving seems to provide *Pelamis* with a means of relocating itself in the surface drift for purposes ranging from feeding to encountering mates.

Comparative studies show that the swimming efficiency of *Pelamis* is much greater than that of the freshwater snake (*Nerodia*) and is similar to that of eels. However, *Pelamis* must swim both at the surface and at depth. Dr. Graham and colleagues observed *Pelamis* in Scripps's 10-m deep tank and discovered that before diving, *Pelamis* hyperinflates its lung with enough air to compensate for increased pressure at depth and achieves neutral buoyancy while diving. Neutral buoyancy enables the snake to minimize its subsurface energy expenditure for swimming and thus further reduce oxygen requirements. Several years ago Dr. Graham discovered that *Pelamis* can breathe through its skin. Unique properties of the snake's blood circulation favor skin gas exchange and minimize the loss of lung gas and thus buoyancy during long dives. Analysis of time-depth diving records of tracked snakes indicates that they compensate for loss of gas and lift from the lung by gradually ascending, allowing the lung to expand, and thus maintaining buoyancy during the course of a long dive.

Bringing the Deep Sea to the Laboratory

Physical factors in the sea influence both the distribution of oceanic life and its evolution. The importance of salinity and temperature for oceanic life has long been recognized. The importance of pressure, however, has not been as widely appreciated nor as well studied. Several Scripps scientists are investigating the physiological, biochemical, and molecular bases

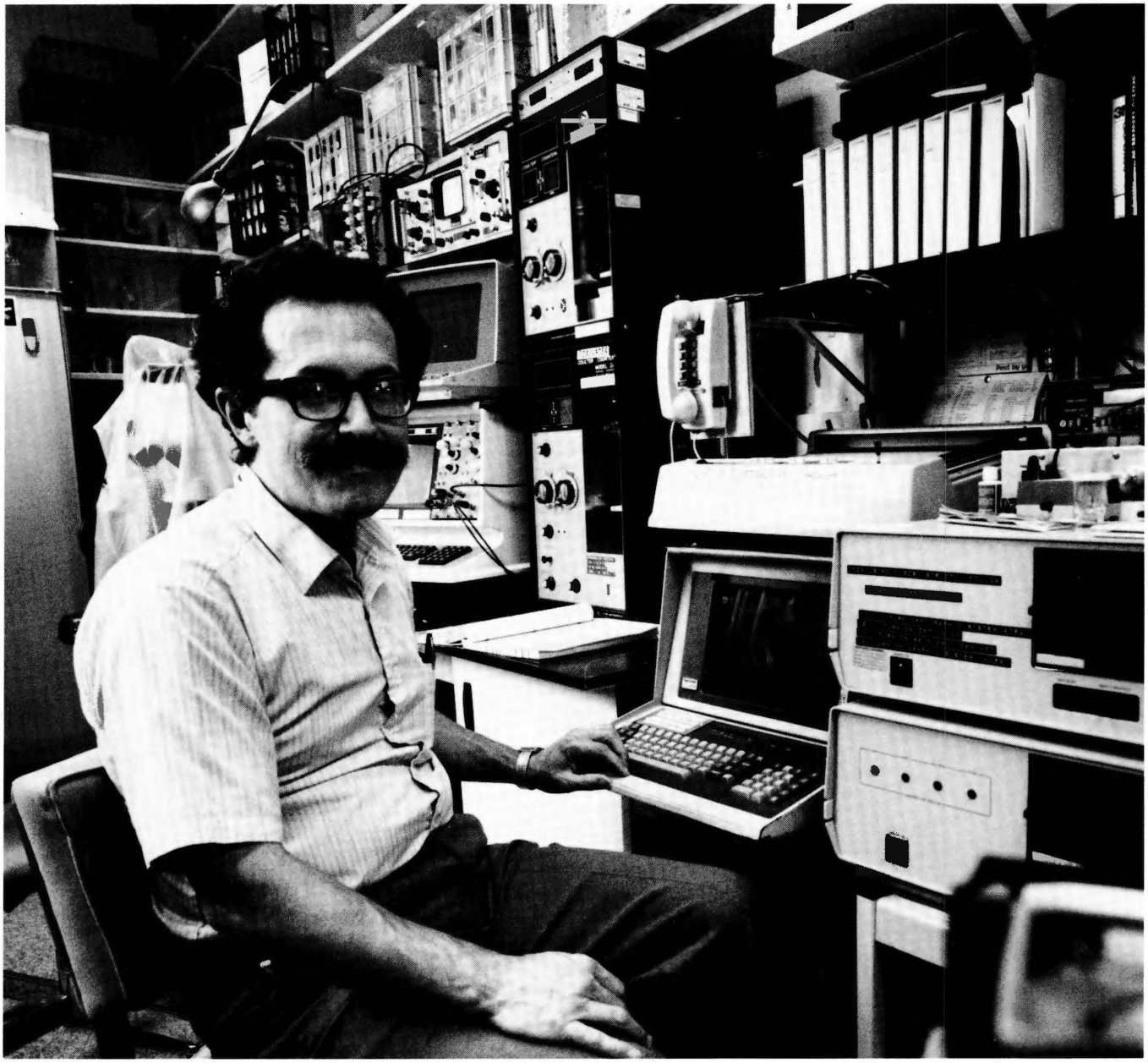




R. A. Chastain

Electron micrograph (top) *of a deep-sea bacterium preserved immediately after decompression from its habitat pressure of 1,000 atm to 1 atm. Although the cells die at atmospheric pressure, the thin sections of these cells show normal bacterial morphology, implying that the effects of decompression are not immediate. The second electron micrograph* (bottom) *shows cells fixed 48 h after decompression and exhibiting severe morphological change. The experiments were done at 0°C.*

Dr. A. Aristides Yayanos works on the computer analysis of bacterial growth-rate data to help determine the role of pressure as a parameter affecting the vertical distribution of oceanic life.



allowing mammals, birds, fish, crustacea, and even bacteria to live with the pressure variability that they encounter in the ocean.

Researchers in the laboratory of Dr. A. Aristides Yayanos are studying the physiology of deep-sea bacteria grown under simulated deep-ocean pressures and temperatures. Because temperature and pressure together influence biological structures and biochemical reactions, bacteria have been isolated from habitats differing in temperature and pressure. Most of the deep ocean has a temperature near 2°C. Notable exceptions to this are the waters near hydrothermal vents (2°C-350°C), the Mediterranean Sea (13.5°C), the Sulu Sea (9.8°C), the Halmahera Basin (7°C), the Celebes Sea (3.9°C), and the deep waters near Antarctica (− 0.5°C). Dr. Yayanos and his colleagues have been on expeditions to various parts of the North Pacific Ocean to collect bacteria that live at high pressures (up to 1,100 atm) and at 2°C.

In the fall of 1985 the researchers went to the eastern Mediterranean Sea aboard the French R/V *Le Noroit.* The sites visited—south of the Island of Rhodes, south of Crete, and west of Peloponnesus—have depths to 5,000 m and a temperature at this depth of 13.5°C. Bacteria were isolated from water and sediment samples and from

parts of trapped animals. Studies completed with two pure cultures of deep Mediterranean Sea bacteria show that they are barophilic but cannot grow at 2°C at any pressure. Thus the physical conditions of temperature and pressure together make it impossible for the same organism to inhabit deep, cold ocean niches and deep Mediterranean Sea niches.

In the spring of 1986 Dr. Yayanos and colleagues joined R/V *Thomas Washington* for Leg 8 of Papa-Tua Expedition for a 4,700-nautical-mile trip in the western Pacific. Microbiological sampling was done in the Halmahera, Celebes, and Sulu seas and in two trenches. Studies of bacteria from these samples and from those of the Mediterranean Sea should elucidate how temperature and pressure together influence the distribution and evolution of oceanic life.

Graduate students Linda H. Lutz and Edward F. DeLong discovered some surprising aspects of deep-sea bacteria. Lutz found that some deep-sea bacteria can repair their DNA damaged by exposure to ultraviolet light by a photoreactivation mechanism. Deep-sea bacteria presumably are never exposed to visible light, so it is paradoxical that they should possess the photoreactivation mechanism. Lutz's studies may explain both the nature of photoreactivation and the evolution of deep-sea bacteria. She has also found that excision repair and photoreactivated repair of DNA are pressure-adapted processes in deep-sea bacteria.

DeLong has discovered that many deep-sea bacteria make polyunsaturated fatty acids as part of their membrane phospholipids. Although he is studying primarily the importance of these acids to membrane function in a high-pressure environment, he has noted that they are essential nutrients for deep-sea animals, and they are too refractory to be supplied only from primary production in shallow parts of the ocean. He has thereby established at least one critical role for deep-sea bacteria in the deep-sea food web.

In his search for animal-associated bacteria in the deep sea, Dr. Yayanos has used two types of animal traps: those that retain both the temperature and the pressure found at the capture depth, and those that retain only the temperature. Although bacteria that can survive brief decompressions can be obtained from all ocean depths, animals that can survive brief decompression have so far been caught only in depths less than 3,600 m. One type of insulated trap is a Niskin sampling bottle rigged with bait inside, with timed closing and ballast-releasing mechanisms. One of two giant isopods caught with this device at 2,500 m in the Sulu Sea is *Bathynomus giganteus.* The isopods survived the transit from the western Pacific to the United States and were maintained for an additional five weeks in the laboratory at atmospheric pressure. Observations of the isopods suggested that decompression had adversely affected their nervous systems. It is likely that recompression of these animals in a high-pressure aquarium would have allowed longer laboratory survival. When such aquaria become available, scientists will be able to study rare and seldom captured deep-sea animals like these isopods.

Visibility Laboratory

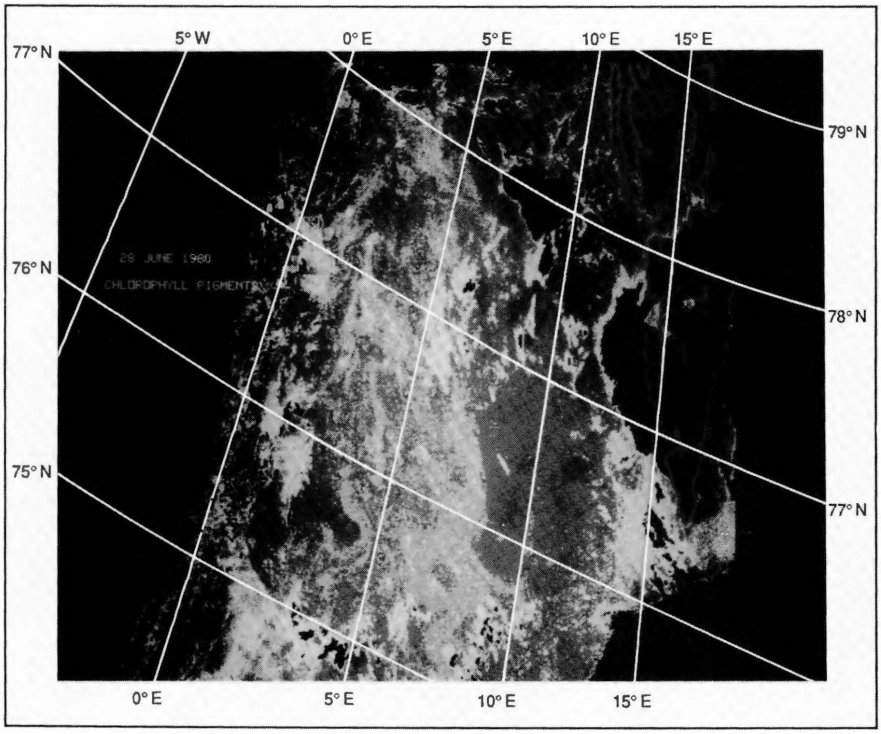
Scientists in the Visibility Laboratory focus on environmental optics, optical remote sensing, and digital image processing. They study the oceanic and atmospheric distribution of optical properties and are developing improved measurement methods. They investigate distribution of attenuation properties and phytoplanktonic pigments in the oceans using new remote sensing methods.

Gerald D. Edwards supervised two major field operations during the year. Vertical profiles of oceanic optical properties were made during a cruise from Seattle, through the Gulf of Alaska, and into the Bering Sea. An intensive six-month series of measurements was initiated off the Florida coast to document the optical attenuation and reflectance properties of the water as a function of time.

Under the direction of Richard W. Johnson, electro-optical (E/O) camera systems were devised to exploit the atmospheric scattering model developed by Wayne S. Hering. Automated techniques using these E/O cameras for assessing sky radiance distributions, horizontal visibility, cloud type, and fractional cloud cover characteristics are being studied.

Roswell W. Austin, Janet E. Shields, and Hering prepared data for an atlas that will show the distribution of water attenuation properties for Northern Hemisphere oceans using Coastal Zone Color Scanner (CZCS) images of spectral radiance. Remote sensing is a practical method for developing global-scale information.

Dr. Nancy G. Maynard enhances Coastal Zone Color Scanner (CZCS) satellite image of chlorophyll pigments in waters around Iceland. Map (below) *shows CZCS-derived pigment distribution from the Greenland Sea west of Spitsbergen. Eddy and ring formation can be seen on either side of this north-south-oriented band of high pigments that reflect the interaction between the north-flowing West Spitsbergen Current and the southward-flowing Arctic waters. Land and cloud areas are shown as black. Pigment concentrations are represented as shades of gray, increasing from dark to light.*



N. Maynard

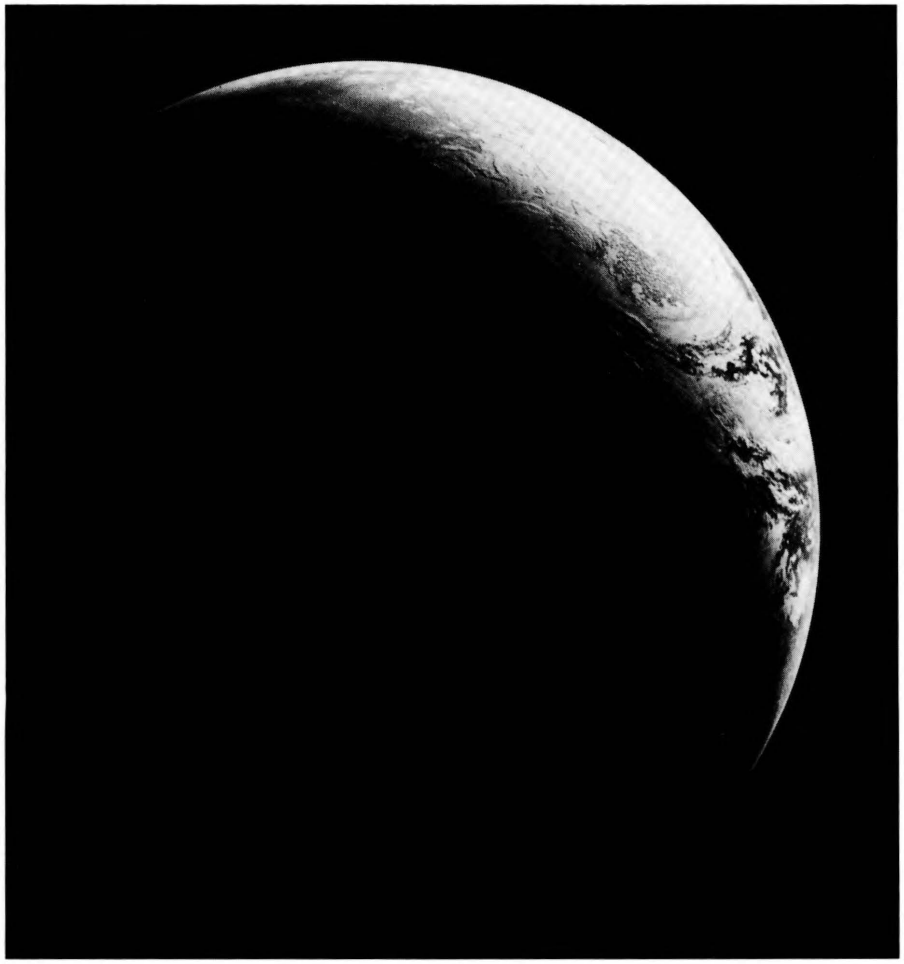
Dr. Nancy G. Maynard directed CZCS use in polar regions to understand the advance and retreat of the marginal ice zone and the biological productivity associated with the ice edge. She and a NOAA colleague demonstrated that it is possible to obtain imagery comparable to that produced at mid and low latitudes. This imagery clearly indicates gradual changes in phytoplankton distribution, and also provides synoptic mesoscale information about physical processes like eddy and ring formation, water-mass distribution, and current dynamics. CZCS imagery was processed in high-latitude locations including the Greenland Sea, Norwegian Sea, Barents Sea, Bering Sea, and the Chukchi Sea. Two pigment-distribution studies from the vicinity of Iceland and the Bering Sea have yielded more information about the regions' seasonal productivity patterns and interdependence upon hydrography, climatology, and ice distribution. In a joint program with the Institute of Marine Research, Reykjavik, Iceland, Dr. Maynard will compare CZCS imagery with data from circum-Iceland cruises carried out by the Icelanders. The researchers hope to better understand relationships among the physical oceanography, ice distribution, primary productivity, and fisheries in Icelandic waters.

Dr. Kenneth J. Voss's research emphasizes the link between inherent and apparent optical properties. An underwater Electro-Optic Radiance Distribution Camera system will instantaneously measure the complete distribution of radiance surrounding the camera capsule, thereby permitting many apparent and inherent properties to be determined. These measurements, when combined with those of light scattering and light absorption, will enhance investigation of the classical radiative transfer equation.

California Space Institute

The California Space Institute (Cal Space), a multicampus research unit of the University of California, supports and participates in space-related research. Cal Space, under the direction of Dr. James R. Arnold, is headquartered at Scripps.

Crescent earth from space.



NASA

One of the major multicampus activities of Cal Space is a minigrant program that provides seed money for UC researchers in astrophysics and planetary sciences, remote sensing, climate, and materials processing in space. Each year a number of Scripps investigators receive small grants from this program.

Dr. Catherine H. Gautier leads part of Cal Space's research in remote sensing and climate. The Cal Space group has joined with Dr. Richard C. J. Somerville and others in an informal unit called Climate and Remote Sensing (CARS).

The remainder of Cal Space research focuses on access to space. Scientists are concerned with making space facilities easier to build and use, for scientific as well as other human purposes. This goal is particularly urgent in the post-Challenger era. One area of Cal Space interest is the rapidly developing field of automation and robotics. Following last year's NASA-sponsored study, a consortium of universities and industrial companies formed C-SAR (Consortium for Space Automation and Robotics). Dr. David R. Criswell is acting director of C-SAR, and the program is temporarily housed at Scripps. Cal Space scientists think there are strong similarities between space and undersea environments for robotic operations, and hope for fruitful interactions with groups studying undersea applications.

A new study for NASA on advanced space propulsion methods, particularly those that do not use traditional chemical rocket systems, began this year. Cal Space scientists think a new generation of simpler, lower cost, more reliable propulsion systems for movement in space, and even for direct launch from earth, may be possible. They seek to compare such yet-untried methods with the "base case" of existing rocket systems for transport between low earth orbit and the lunar surface. They also hope to identify the most promising areas for future research.

Institute of Geophysics and Planetary Physics

The San Diego branch of the University of California systemwide Institute of Geophysics and Planetary Physics (IGPP) is located at Scripps Institution, and is strongly linked to Scripps through joint faculty appointments, research interests, and shared facilities. Other IGPP branches are located at the Los Angeles and Riverside campuses and at the Los Alamos and Lawrence Livermore national laboratories.

Dr. Duncan C. Agnew studied crustal deformation, analyzing tide-gage measurements, and showing that apparent changes in mean sea level may result from slight gage clogging. Reviewing methods for measuring continuous strain and tilt, he concluded that borehole and long-base techniques offer the best avenues for future development. Dr. Agnew and graduate student Nancy E. King used the Global Positioning System satellites to make geodetic measurements on San Clemente Island for determining strain accumulation off southern California.

Frank K. Wyatt III and Dr. Agnew direct work at the Cecil and Ida Green Piñon Flat Observatory, a field station in the Santa Rosa Mountains for developing and testing geophysical instruments. Recent work focused on installations of borehole tiltmeters by groups from several institutions, and comparisons between them and existing long-base instruments.

Dr. Agnew directs the Project IDA global network of 18 very-long-period seismometers. Network data are sent to several institutions; of special note was data from the Mexican earthquake of September 19, 1985. This data made it possible to rapidly determine the source mechanism.

Dr. Jonathan Berger, with Frank L. Vernon and graduate student Jennifer S. Scott, operated the Anza Seismic Array, a set of telemetered, high-frequency seismic stations deployed along the San Jacinto fault near Anza, California. Scientists analyzing data from this array concentrate on the high-frequency properties of the area's earthquake sources and on how propagation and attenuation affect the waveforms. With Dr. William E. Farrell and graduate student William H. Nugent, Dr. Berger developed a new seismograph system employing digital feedback. Initial theoretical studies have engendered a prototype, wideband seismograph with dynamic range and precision not available in standard analog units. A testing and modification program is under way. Dr. Berger and colleagues developed new instrumentation for the IDA network to extend its bandwidth and dynamic range and observe three components of earth motion. Deployment of the prototype station at Piñon Flat Observatory will be followed by installation in a new seismic vault being built on Easter Island.

Drs. James N. Brune and John G. Anderson and colleague Michael S. Reichle of the California Division of Mines and Geology worked together with groups in Mexico to study seismic hazard, earthquake strong motion, earthquake mechanism, and earth structure.

Drs. Brune and Anderson are also studying high-frequency (30 Hz) seismic wave excitation of earthquakes to aid in distinguishing nuclear explosions from earthquakes.

Dr. Anderson and graduate student Susan E. Hough study the attenuation of seismic waves at high frequencies. They found that there is a zone of very low attenuation in California coincident with the depths at which earthquakes occur.

Drs. Brune and Ralph H. Lovberg constructed 3-D, foam rubber topographic models to study site effect and seismic engineering problems important to understanding earthquake hazards. Physical modeling of these problems is used in conjunction with computer modeling to cross-check results. Study of physical models can also lead to insights that would not be evident from computer modeling or theoretical calculations.

Drs. Allen H. Olson, Anderson, and Brune are studying recordings of ground motion near large earthquakes to learn about the earthquake rupture process. They use linear inverse theory for data resolution analysis and to obtain dynamic models of fault slip. Dr. Olson has developed a Chebyshev-iterative technique for solving large least-squares problems. In addition to the faulting problem, he applied the Chebyshev method on three-dimensional elastic scattering calculations with Dr. John A. Orcutt, and on global seismic tomography with Dr. Orcutt and graduate student Kenneth M. Toy.

Dr. Orcutt directs a marine seismology group that collected an enormous quantity of multichannel seismic data along the crest of the East Pacific Rise. Analysis of these data has revealed a very continuous body of magma underlying the volcanic East Pacific Rise. This body of molten rock is the source of the bulk of the earth's crust; the continuity has been something of a surprise to geochemists and petrologists, many of whom have proposed that the chamber must be discontinuous. Evaluation of the propagation of high-frequency seismic phases called P_n and S_n has provided an accurate estimate of the rigid tectonic

lithosphere's thickness in the old North Pacific. The estimated thickness, 200 km, is substantially greater than earlier estimates.

Drs. T. Guy Masters and J. Freeman Gilbert have constructed a new data set of free oscillation degenerate frequencies. This data set has been used to constrain models of spherically averaged earth structure. The researchers found that previous measurements of toroidal mode frequencies were seriously in error and that coupling effects, which bias the data, are clearly apparent. Drs. Masters and Gilbert and graduate student Michael H. Ritzwoller showed that large-scale aspherical structure must be postulated in or on the boundaries of the earth's core. This will explain the anomalous splitting of free oscillations that are sensitive to the properties of this region.

Drs. Masters, Brune, and Joan S. Gomberg and a University of Nevada, Reno, colleague completed a study of the crust and upper mantle structure of Mexico. Waveform modeling of surface waves shows that lateral variation in structure exists, though most of the data can be modeled by low crust and lid velocities in the trans-Mexican volcanic belt.

Dr. Masters and a visiting scholar study underwater acoustic wave propagation. They use a modal representation to test if approximate theoretical treatments can be used to explain tomographic data. They found WKBJ synthetic sonograms and modal sonograms in agreement for propagation in a structure characteristic of the ocean at temperate latitudes. They also found that the modal representation is more compact and reliable for structures typical of high latitudes (for example, the Greenland Sea).

Dr. Mark A. Zumberge and graduate student Glenn S. Sasagawa periodically measure the earth's gravity at a number of California sites. Deformations in the earth's crust associated with earthquake processes should be accompanied by slight changes in gravity. The researchers hope these minute changes can be detected with an absolute gravity meter, which was built at IGPP.

Dr. Zumberge and Wyatt are developing an instrument that uses fiber-optic sensors to measure strains in the earth's crust. They plan to install an optical fiber, similar to the ones used in modern communication systems, in a deep borehole and monitor small changes in its length with laser light.

Dr. George E. Backus developed the mathematics necessary to represent satellite measurements of the geomagnetic field B taken at altitudes where electric currents vitiate the standard Gauss representation of B as a harmonic potential field (the gradient of a harmonic scalar field). As a by-product, he found a perturbation expansion that represents all force-free fields near any given harmonic potential field. He also estimated the crustal contribution B at satellite altitudes and at the core-mantle boundary by combining the accepted crustal power spectrum with vector and tensor analogues of the scalar addition theorem for spherical harmonics.

Dr. Alan D. Chave investigated the nature and applications of electromagnetic fields in the ocean. Drs. Jean H. Filloux, Douglas S. Luther, and Chave are preparing to investigate the wind-forced barotropic variability in the North Pacific using electromagnetic methods. A joint study with AT&T Bell Laboratories on robust, time-series-analysis methods has been completed. In other collaborative investigations the use of transient electromagnetic methods for seafloor explorations continues.

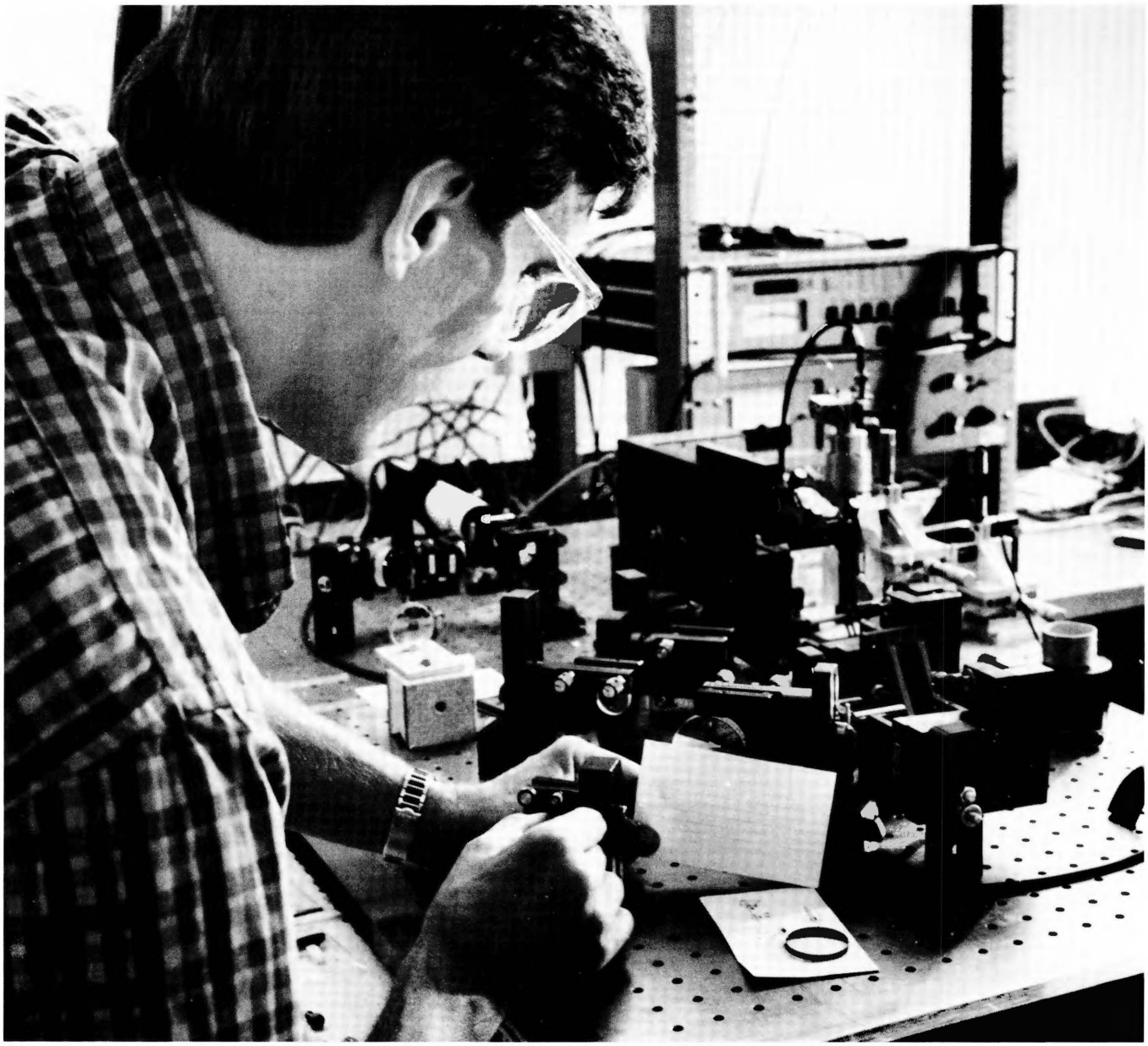
Dr. Robert L. Parker, in his theoretical work on seamount magnetism, has developed a new method for computing the magnetic pole position at the time of body formation. By introducing a model for the nonuniform component of the magnetization as a stationary random process, he has been able to provide new, tight limits on the uncertainty in the pole's location. Drs. Parker, Masters, and Orcutt, working with graduate student Philip B. Stark, refined the technique for inverting seismic τ-p data. They showed, on thermodynamic grounds, that the p-velocity in the core cannot decrease with depth. This fact places strong constraints on the velocity profile that can be built into a linear-programing inversion scheme. Application to a large data set has yielded the most reliable information on seismic velocity in the core.

Drs. Peter F. Worcester, Walter H. Munk, Robert A. Knox, Bruce M. Howe, and Bruce D. Cornuelle continue their research on ocean acoustic tomography. Dr. Howe analyzed the results of a 1983 experiment, and demonstrated tomography's effectiveness for measuring ocean mesoscale currents. Under Dr. Worcester's leadership, sophisticated receivers have been built. New sound sources capable of transmitting over long ranges, and of projecting signals that can be very precisely timed have been commercially built to specifications developed jointly with Woods Hole Oceanographic Institution.

Dr. Hugh Bradner continued his work in the neutrino astrophysics experiment DUMAND (Deep Underwater Muon and Neutrino Detection). He helped prepare sea tests of prototype arrays, and led studies of deep bioluminescence. There is strong evidence for motion-stimulated bioluminescence at depths greater than 4 km. This is of interest because biologists do not know what organisms could produce such stimulated light. The observations are of practical importance to DUMAND because they imply that bottom-moored photomultipliers will record background light at approximately the very low level of K^{40} decays.

Dr. Robert H. Stewart continues as project scientist for the Topex satellite project at the Jet Propulsion Laboratory. Satellite measurements will be used for studying variations of surface geostrophic currents on the basin-wide and global scale required by the World Ocean Circulation Experiment of the World Climate Research Program. Dr. Stewart, with the University of Texas, is developing a new tech-

Dr. Mark A. Zumberge steers laser light into an optical-fiber, earth strainmeter.



nique for monitoring global mean sea level with accuracy of 1-2 cm.

Dr. Richard L. Salmon continued developing numerical ocean general circulation models that can efficiently be solved by computer. The primary difficulty is to remove high-frequency motions without detriment to the essential physics. A current version takes only ½ second of supercomputer time to simulate one year of ocean circulation.

Dr. Hassan Aref and two graduate students performed numerical simulations of fluid flow. Topics include vortex dynamics, advection-diffusion equations, and stratified flows.

Dr. John W. Miles continued his work on nonlinear waves and chaotic motion in dynamical systems. Bernard D. Zetler continued his ocean-tide research.

Institute of Marine Resources

The universitywide Institute of Marine Resources (IMR), directed by Dr. Fred N. Spiess, is headquartered at Scripps. IMR scientists initiate cooperative studies, and implement the university's ocean-related education, research, and public service programs. IMR administers the California Sea Grant College Program and its research groups on the San Diego and Davis campuses. IMR's Scripps activities are discussed here, this year highlighting Dr. Bess B. Ward's research. Other Scripps IMR research is described briefly and will be featured in future years. The past several years of the entire IMR program is summarized in the *Institute of Marine Resources Six-Year Report 1979-1984.*

The California Sea Grant College Program, based at Scripps, is managed by Dr. James J. Sullivan. The program focuses on education, research, and public service. A marine advisory service disseminates the results of ocean research. Sea Grant supports aquarium/museum outreach programs on several campuses, and finances 51 graduate student research traineeships. Sea Grant-funded research encompasses living and nonliving resources, ocean technology, and coastal zone preservation and use. Last year Sea Grant supported 49 research projects at 12 academic institutions.

Dr. Richard J. Seymour heads the Ocean Engineering Research Group, and with Dr. Dimitri Alexandrou develops shallow-water, wide-swath acoustical bathymetry. The group's Coastal Data Information Program, under David Castel, studied harbor seiching in Hawaii.

Scientists in the multicampus UC Marine Bio-Optics Group, coordinated at Scripps by Karen S. Baker, experimentally and theoretically investigated the marine bio-optics of small-scale processes as well as mesoscale events. The researchers used multiplatform sampling, and observations from ships, satellites, and buoys.

Researchers in the Marine Natural Products Group, directed by Dr. William H. Fenical, focus on two aspects of marine plants and animals: (1) the organisms' chemical adaptations in competitive ecosystems, and (2) the application of marine natural products developing novel drug prototypes. Field experiments prove that the so-called secondary metabolites, produced mainly by soft-bodied marine organisms, underlie a sophisticated chemical defense adaptation. This adaptation has yielded several highly bioactive molecules, which have been patented and are being developed by collaborating pharmaceutical companies. The recently discovered pseudopterosins represent a new class of anti-inflammatory drugs that possess greater potency than industrial products.

Scientists in the Phytoplankton Resources Group, headed by Dr. William H. Thomas, study microalgae as sources of energy or protein, as well as the organisms' physiological ecology. Present field work on a Sierra Nevada lake focuses on potential acid precipitation problems.

Radiocarbon fallout from the 1954-1962 atmospheric nuclear bomb tests introduced a radiocarbon signature into organic and inorganic carbon pools in the ocean. Dr. Peter M. Williams and a Woods Hole Oceanographic Institution colleague are using this radiocarbon time clock, in conjunction with measurements on the magnitudes of the carbon pools, to formulate the pathways that carbon follows in the open-ocean water column in the Central North Pacific Gyre.

A summary of the Food Chain Research Group's recent work in the Southern California Bight appeared in a book, *Plankton Dynamics of the Southern California Bight,* edited by Dr. Richard W. Eppley.

Dr. Ward's nitrogen cycle studies include the nitrification process and nitrifying bacteria. Nitrous and nitric oxides influence atmospheric chemistry by catalyzing the destruction of the protective ozone layer, which has major implications for global climate. We think of modern industrialization and automobiles as the most obvious sources of nitrogen oxides, but production by nitrifying and denitrifying bacteria in terrestrial soils, estuarine sediments, and ocean waters is also a globally significant source. Potential long-term interactions among the nitrogen cycle of the sea, the chemistry of the atmosphere, and climate are subjects for research.

In regions like the Southern California Bight, nitrification rates are highest just below the photic zone. Nitrifiers are partially responsible for the formation of the primary nitrite maximum, a subsurface accumulation of nitrite found in many parts of the world ocean. Because they are inhibited by light, nitrifiers are not very active in near-surface waters, but at the base of the photic zone they compete with phytoplankton for ammonium. The nitrate produced by nitrification in this region can also nourish phytoplankton.

Statistical analyses of experiments, using ^{15}N tracers to measure phytoplankton assimilation rates and nitrification rates, indicate that the depth distribution of both processes is determined by two factors: light intensity and ammonium concentation. Ammonium concentration affects both processes positively, but light

Dr. Peter M. Williams, at the Mt. Soledad Radiocarbon Laboratory, processes a seawater sample to determine its dissolved organic radiocarbon content.

has opposite effects, promoting phytoplankton activity, and inhibiting nitrifiers. Where ammonium concentration is uniformly low, as in oligotrophic ocean waters, light intensity is more important. In oligotrophic waters, the supply rate of ammonium, rather than its concentration, probably is more related to in situ rates. Organic matter decomposition and nutrient regeneration at the base of the photic zone thus supply ammonium, which drives the peak in nitrification rates at this depth. In terms of nitrogen turnover, phytoplankton are more important in the photic zone, and nitrifiers are more important in deeper waters. In the middle region, both processes occur, causing locally enhanced nitrogen cycling rates.

Nitrifiers change ammonium to nitrate; denitrifiers change nitrate to nitrogen gas. These transformations require several enzymes and involve many of the same intermediates: nitrite, nitrous oxide, and nitric oxide. The gaseous intermediates link the ocean's nitrogen cycle with the atmosphere's. Oxygen concentration controls the production and consumption of nitrogen oxides by nitrifiers and denitrifiers: under reduced oxygen, nitrifiers produce unusually high proportions of nitrous oxide, and they may also produce nitric oxide. Under some conditions, denitrifiers produce nitrogen oxides, and under others, their net effect is to consume the gases.

In certain areas of the world ocean, upwelling creates highly productive surface waters coupled with oxygen-depleted subsurface waters. The oxygen minimum region underlying the upwelling system off Peru is a good example. Steep oxygen gradients create a situation where nitrification and denitrification occur near each other, and close to a good supply of organic matter to drive the cycle.

Dr. Ward works with scientists from Bigelow Laboratories in Maine, and from Harvard University, to investigate the nitrogen cycle in the oxygen minimum region off Peru. Very high concentrations of nitrite and nitrous oxide were found close to the ocean's surface in a zone of low oxygen concentration. Nitrifying bacteria are the probable source of the nitrous oxide. Nitrifiers, enumerated with an immunological assay developed by Dr.

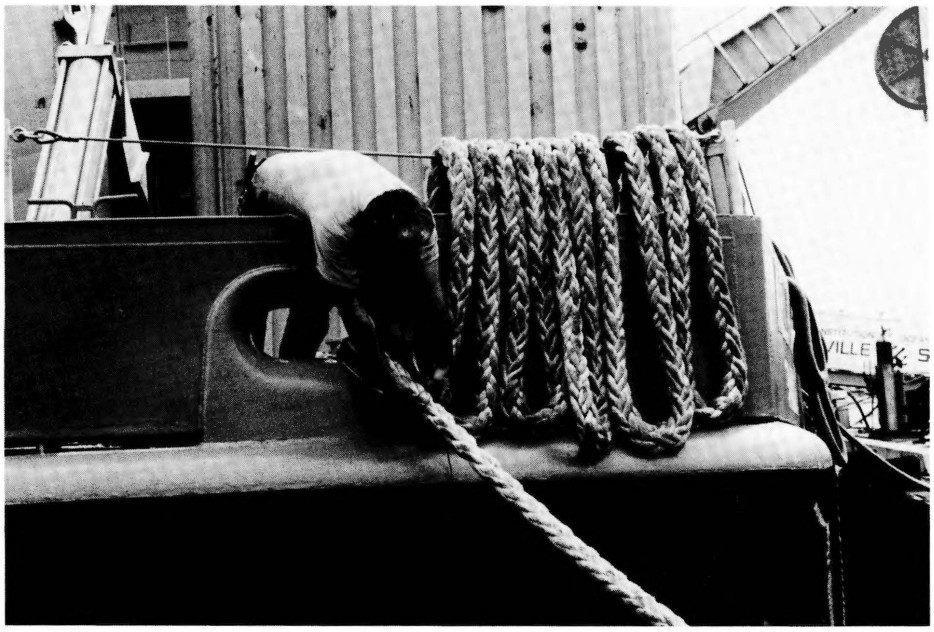
Ward, were found to be ten times more abundant in this high-nitrite layer than in waters on either side of the layer. Their autotrophic activity (cell production), measured by a radiotracer technique, was also enhanced in this layer. Just below the nitrous oxide maximum was a region where nitrous oxide was greatly depleted, implying consumption by denitrifying bacteria. This arrangement can lead to rapid cycling of nitrogen between oxidative and reductive processes, and high fluxes of trace nitrogen gases from ocean to atmosphere.

Dr. Ward also studies another way in which nitrifying bacteria may participate in the atmosphere's trace gas cycle—by oxidizing methane. Although the nitrogen oxides actively influence atmospheric chemistry, other gases play important roles without being particularly reactive. Carbon dioxide absorbs radiation from the earth and thus prevents its dissipation into space, causing a long-term global warming trend with major climatic implications. Other trace gases, including methane and freon, contribute to this greenhouse effect. Methane is an end product of organic carbon decomposition in anoxic environments like marsh soils, estuarine sediments, and the deep layers of some lakes. Methane is also found in the open ocean; the processes responsible for its production in this environment remain mysterious.

The surface ocean is a small net source of atmospheric methane. It might be a bigger source, if not for nitrifying bacteria. Dr. Ward has shown that marine nitrifying bacteria can incorporate methane into cell material and oxidize it to carbon dioxide. Nitrifiers may be partly responsible for methane oxidation in the ocean; in other environments, special methane-oxidizing bacteria are responsible. Dr. Ward is now studying this process and the biochemistry and ecology of methane oxidation by nitrifying bacteria. Methane is a competitive inhibitor of ammonia oxidation, and appears to be metabolized by the same enzyme system that handles ammonia. *Nitrosococcus oceanus,* an important marine nitrifying bacterium, has a relatively high affinity for methane as an alternative substrate.

On a recent cruise to the Cariaco Trench, Dr. Ward and an associate used a radiotracer method to measure methane oxidation rates. The Cariaco Trench is a unique marine environment, with an oligotrophic surface layer overlying a deep, enclosed basin that is oxygen depleted. This deep layer contains high concentrations of sulfide and methane, the result of organic matter decomposition in the absence of oxygen. Therefore, this layer supplies methane to the surface layer. Much of the deep-layer methane flux is oxidized in the surface layer before it can reach the sea surface and escape to the atmosphere.

Dr. Ward hopes to compare methane oxidation rates in the surface layer with ammonia oxidation rates in the same samples to see if there is a relationship between the two processes. Nitrifying bacteria probably contribute little to the observed methane oxidation rates in this system. The Cariaco Trench resembled a temperate lake, in that highest methane oxidation rates were found just at the interface where oxygen disappears and methane and sulfide appear. An interesting finding from this study was the methane oxidation in the trench's deep anoxic layer. Anaerobic methane oxidation is an enigmatic process; its occurrence is well substantiated, but the mechanisms and microorganisms responsible for it have not been discovered.



R/V Melville.

Seagoing Operations

R/V Robert Gordon Sproul

DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
06/13-07/10/85		Channel Islands	Sea lion studies	San Diego	B. Le Boeuf (UCSC)	T. Beattie
07/15-07/29/85		San Diego Trough	Ocean mixing processes	San Diego	L. Armi	T. Beattie
08/01-08/07/85		Southern California Bight	Microfossil studies	San Diego	R. Casey (Rice Univ.)	T. Beattie
08/29-09/17/85		San Nicolas Basin	Tracer studies	San Diego	J. Ledwell (LDGO)	T. Beattie
09/23-09/24/85		Santa Catalina Basin	Benthic biology	San Diego	M. Laver	T. Beattie
10/01-10/02/85		Southern California Bight	Current studies	San Diego	D. Thistle (FSU)	T. Beattie
10/07-10/08/85		Southern California Bight	Plankton production	San Diego	R. Eppley	T. Beattie
10/18-10/26/85		Santa Monica Basin	Tracer studies	San Diego	J. Ledwell (LDGO)	T. Beattie
11/04-11/09/85		Southern California Bight	Marine biology	San Diego	R. Vetter	T. Beattie
11/15-11/16/85		Southern California Bight	Marine biology	San Diego	K. Smith	T. Beattie
01/28-01/29/86		San Diego Trough	Equipment testing	San Diego	R. Davis	T. Beattie
02/03-02/10/86		Southern California Bight	Southern California Basin studies	San Diego	W. Fredericks (UW)	T. Beattie
02/15-02/25/86		San Nicolas Basin	Tracer studies	San Diego	J. Ledwell (LDGO)	T. Beattie
03/03-03/08/86		Santa Monica Basin	Marine biology	San Diego	H. Felbeck	T. Beattie
03/28-03/31/86		San Diego Trough	Equipment testing	San Diego	P. Worcester	T. Beattie
04/02-04/09/86		Southern California Bight	Food chain studies	San Diego	R. Eppley	T. Beattie
04/17-04/20/86		33°N 121°W	Equipment testing	San Diego	P. Worcester	T. Beattie
04/27-04/29/86		Santa Catalina Basin	Equipment testing	San Diego	K. Smith	T. Beattie
05/09-05/18/86		NE Pacific	Ocean bottom seismology	San Diego	J. Orcutt/C. Cox	T. Beattie
06/09-06/15/86		NE Pacific	Ocean bottom seismology	San Diego	J. Orcutt	T. Beattie
06/20-06/22/86		Southern California Bight	Ocean bottom seismology	San Diego	L. Dorman	T. Beattie

TOTAL DISTANCE STEAMED: 13,821 nautical miles OPERATING DAYS: 149

R/V Thomas Washington

DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
09/17-10/16/85	Papa-Tua I	O'Gorman Fracture Zone	Ocean bottom seismology	Manzanillo	J. McClain (UCD)	A. Arsenault
10/19-11/17/85	Papa-Tua II	East Pacific Rise	Sea Beam	Manzanillo	P. Lonsdale	T. Desjardins
11/21-12/26/85	Papa-Tua III	Moctezuma Trough & Mathematician Seamount	Sea Beam	Pago Pago	J. Mammerickx	T. Desjardins
12/31-01/28/86	Papa-Tua IV	Lau Basin/Tonga Trench	Petrology & Sea Beam	Tongatapu	J. Hawkins	A. Arsenault
02/01-02/14/86	Papa-Tua V	Lau Basin/Havre Trough	Sea Beam & geochemistry	Auckland	H. Craig	A. Arsenault
02/17-03/15/86	Papa-Tua VI	North Fiji/Woodlark Basin	Geochemistry	Rabaul	H. Craig	T. Desjardins
03/16-03/22/86	Papa-Tua VII	Transit		Palau		T. Desjardins
03/25-04/27/86	Papa-Tua VIII	Philippine Trench, Sulu & Celebes Seas	Benthic microbiology	Guam	A. Yayanos	T. Desjardins
04/29-05/11/86	Papa-Tua IX	Mariana Trough	Geochemistry & Sea Beam	Sasebo	H. Craig	T. Desjardins
06/15-06/27/86	Papa-Tua X a	Yellow Sea	Geology, physical oceanography	Sasebo	J. Milliman (WHOI)	T. Desjardins
06/28-07/03/86	Papa-Tua X b	Yellow Sea	Physical oceanography	Sasebo	P. Hsueh (FSU)	T. Desjardins

TOTAL DISTANCE STEAMED: 46,644 nautical miles OPERATING DAYS: 256

R/V New Horizon

DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
07/01-07/23/85		Southern California Bight	California Current studies	San Diego	L. Haury	P. Munsch
07/26-08/05/85		Santa Catalina Basin	Benthic studies	San Diego	K. Smith	P. Munsch
08/09-08/23/85	CalCOFI 8504	Southern California Bight	Physical, chemical, biological studies	San Diego	E. Venrick	P. Munsch
08/29-09/04/85		San Nicolas Basin	Tracer studies	San Diego	J. Ledwell (LDGO)	P. Munsch
10/02-10/03/85		San Diego Trough	Bottom Lander studies	San Diego	R. Jahnke	P. Munsch
10/07-10/17/85		Santa Monica Basin	Flux of organics	San Diego	R. Jahnke	P. Munsch
10/22-10/24/85		San Diego Trough	Instrument testing	San Diego	L. Regier	P. Munsch
10/28-10/30/85		San Diego Trough	Equipment tests	San Diego	P. Worcester	P. Munsch
11/01-11/15/85	CalCOFI 8512	Southern California Bight	Physical, chemical, biological studies	San Diego	G. Anderson	P. Munsch
11/21-12/11/85		East Pacific Rise	Deep Tow	San Diego	F. Spiess	P. Munsch
12/14-12/15/85		Southern California Bight	Bottom Lander studies	San Diego	R. Jahnke	P. Munsch
12/27-01/02/86		Southern California Bight	Ocean bottom seismology	San Diego	L. Dorman	P. Munsch
01/10-01/17/86		Santa Catalina Basin	Benthic biology	San Diego	K. Smith	P. Munsch
01/20-01/29/86		Southern California Bight	Bottom Lander studies	San Diego	R. Jahnke	P. Munsch
02/03-02/07/86		San Clemente Basin	Ecological physiology	San Diego	D. Cowles (UCSB)	P. Munsch
02/15-02/22/86		Off Patton Escarpment	Ocean bottom seismology	San Diego	L. Dorman	P. Munsch
03/06-03/12/86		San Diego Trough	Clear water	San Diego	T. Hayward	P. Munsch
03/15-03/22/86		San Diego to Monterey	Squirts & jets	San Diego	T. Hayward	P. Munsch
04/10-04/17/86		Southern California Bight	Bottom Lander	San Diego	Jahnke/Reimers	P. Munsch
04/22-04/27/86		San Diego Trough	Ocean bottom seismology	San Diego	L. Dorman	P. Munsch
05/01-05/07/86		Southern California Bight	Geology	San Diego	D. Hammond (USC)	P. Munsch
05/10-05/20/86		Southern California Bight	Organic flux study	San Pedro	R. Jahnke	P. Munsch
05/21-05/27/86		San Nicolas Basin	Biology	San Diego	J. Childress (UCSB)	P. Munsch
06/18-06/28/86	Bempex I	Transit		Honolulu		L. Davis

TOTAL DISTANCE STEAMED: 21,280 nautical miles OPERATING DAYS: 215

R/V Melville

DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
06/18-07/20/85	Alcyone I	0°-140°W	Equatorial circulation & air/sea heat exchange maximum	Honolulu	D. Luther/R. Knox	C. Johnson
07/26-08/10/85	Alcyone II	40°N 160°W	Ocean atmosphere studies	Honolulu	H. Craig	C. Johnson
08/13-09/08/85	Alcyone III	28°N 155°W	Primary production studies	Honolulu	R. Eppley	C. Johnson
09/13-10/01/85	Alcyone IV	30°N 157°W	Deploy ISHTE Lander	Honolulu	L. Olson (UW)	A. Phinney
10/06-11/09/85	Alcyone V	Central North Pacific	Benthic biology	Honolulu	K. Smith	C. Johnson
11/09-11/18/85	Alcyone VI	Transit		San Diego		A. Phinney
12/06-12/26/85	ICE I	East Pacific Rise	Mid-ocean geology	Manzanillo	R. Ballard (WHOI)	C. Johnson
12/30-01/19/86	ICE II	Transit		Punta Arenas		
01/22-2/25/86	ICE III	North of Falkland Plateau	Physical oceanography	Punta Arenas	W. Nowlin (TAMU)	R. Haines
03/02-04/04/86	ICE IV	Weddell Sea ice edge	AMERIEZ community productivity	Punta Arenas	D. Ainley (Pt. Reyes)	R. Haines
04/07-05/02/86	ICE V	Transit	Instrument recovery	San Diego		C. Johnson
05/18-06/13/86		32°W 124°W	Benthic biology	San Diego	K. Smith	C. Johnson
06/23-07/07/86		Fieberling Guyot	Deep Tow	Hilo	P. Lonsdale	C. Johnson

TOTAL DISTANCE STEAMED: 38,921 nautical miles OPERATING DAYS: 347

ORB

DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
01/21-01/24/86		San Diego Trough	Acoustic array	San Diego	V. Anderson	T. Hoopes
04/14-04/17/86	SSNI Test	32°-47°N, 117°-38°W	Surface acoustic measurements	San Diego	R. Horn	T. Hoopes

TOTAL DISTANCE TOWED: 80 nautical miles OPERATING DAYS: 8

FLIP

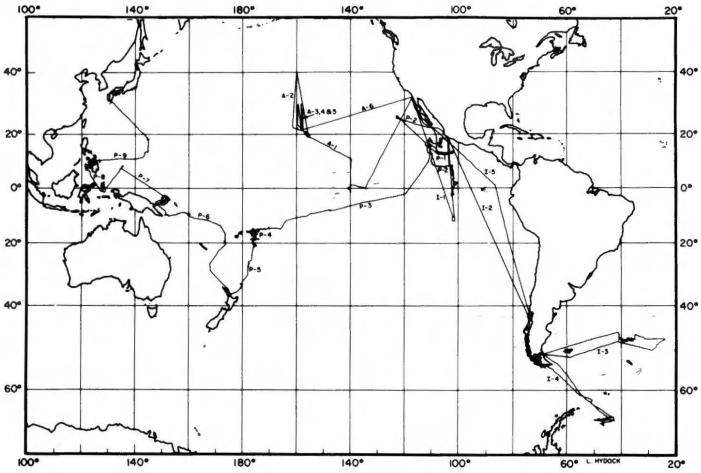
DATE	EXPEDITION	AREA OF OPERATION	WORK PERFORMED	PORTS OF CALL	CHIEF SCIENTIST	CAPTAIN
08/08-08/12/85		San Diego Trough	Horizontal array	San Diego	F. Fisher/NORDA	D. Efird
08/26-08/30/85		San Diego Trough	Equipment testing	San Diego	R. Pinkel	D. Efird
09/23-09/29/85		San Diego Trough	Horizontal array	San Diego	F. Fisher/NORDA	D. Efird
10/10-11/01/85		San Diego Trough	Horizontal array	San Diego	F. Fisher/NORDA	D. Efird
01/27-02/09/86	Ocean Dynamics	32°-45°N, 121°-05°W	Sonar work	San Diego	R. Pinkel	D. Efird
03/20/86		32°-50°N, 117°-32°W	Equipment testing	San Diego	S. Beck	D. Efird
04/23-05/19/86	Contrack IX	Stations San Diego to Honolulu	Ambient noise measurements	San Diego	F. Fisher	D. Efird
05/20/86				San Diego	F. Fisher	D. Efird

TOTAL DISTANCE TOWED: 5,400 nautical miles OPERATING DAYS: 90

RESEARCH VESSELS OF SCRIPPS INSTITUTION OF OCEANOGRAPHY

	MELVILLE	*NEW HORIZON*	*ROBERT GORDON SPROUL*	*THOMAS WASHINGTON*	FLIP	ORB
TYPE:	Oceanographic research	Oceanographic research	Offshore supply	Oceanographic research	Floating Instrument Platform	Oceanographic Research Buoy
YEAR BUILT:	1969	1978	1981	1965	1962	1968
YEAR ACQUIRED BY SCRIPPS:	1969	1978	1984	1965	1962	1968
OWNER:	U.S. Navy	University of California	University of California	U.S. Navy	U.S. Navy	U.S. Navy
LENGTH:	74.2 m	51.8 m	38.1 m	63.7 m	108.2 m	21.0 m
BEAM:	14.0 m	11.0 m	9.8 m	12.0 m	6.0 m	13.7 m
DRAFT:	4.9 m	3.7 m	2.5 m	4.4 m	3.4/91.4 m	fwd. 1.5 m aft. 1.6 m
DISPLACEMENT FULL (metric tons):	1,882	698	513	1,235	1,359	294
CRUISING SPEED (knots):	10	10	9.5	10	varies*	varies*
RANGE (nautical miles):	9,000	6,000	3,500	9,000	varies*	varies*
CREW:	23	12	5	23	6	5
SCIENTIFIC PARTY:	29-39**	13-19**	12-18**	22	10	10

1985-86 Total nautical miles steamed: 126,146 1985-86 Total operating days: 1,065 *Depends on towing vessel **With berthing vans



MAJOR CRUISES (JULY 1985 – JUNE 1986)

R/V Thomas Washington
P-1 – P-9 = PAPA-TUA Expedition Legs 1-9

R/V Melville
A-1 – A-6 = ALCYONE Expedition Legs 1-6
I-1 – I-5 = ICE Expedition Legs 1-5

R/V Robert Gordon Sproul
Local Operations

R/V New Horizon
Local Operations

Graduate Department

The Graduate Department of the Scripps Institution of Oceanography offers instruction leading to Ph.D. degrees in oceanography, marine biology, and earth sciences. Because of the interdisciplinary nature of the ocean sciences, the department provides a choice of seven curricular programs through which the student may pursue a five-year Ph.D. degree. Each of these curricular groups has prerequisites for admission in addition to the departmental requirements. The curricular programs are described below. For application procedures and more information, please write to Graduate Department, A-008, Scripps Institution of Oceanography, La Jolla, California 92093.

Applied Ocean Sciences. This interdepartmental curriculum combines the resources of the Scripps Graduate Department with those of the Department of Applied Mechanics and Engineering Sciences and the Department of Electrical Engineering and Computer Sciences, on the UC San Diego campus. Engineers gain a substantial education in oceanography, and oceanographers receive training in modern engineering. Instruction and basic research include the applied science of the sea, and structural, mechanical, material, electrical, and physiological problems within the ocean.

Biological Oceanography. Biological oceanographers study the interactions of marine organisms with the physical-chemical environment and with each other. Research and instruction in this curriculum range from food-chain dynamics and community structure to taxonomy, behavior, physiology, and zoogeography.

Geological Sciences. This curriculum applies observational, experimental, and theoretical methods to the understanding of the solid earth and solar system and how they relate to the ocean and atmosphere. Principal subprograms are marine geology and tectonics, sedimentology, micropaleontology and paleooceanography, petrology, geochemistry, and cosmochemistry. Expedition work at sea, and field work on land are emphasized as essential complements to laboratory and theoretical studies.

Geophysics. This curriculum is designed to educate the physicist (theoretician or experimentalist) about the sea, the solid earth on which the waters move, and the atmosphere with which the sea interacts. Students gain understanding of the nature of the earth while they master new field, laboratory, and mathematical techniques.

Marine Biology. The marine biology curriculum emphasizes the biology of marine organisms—animals, plants, and prokaryotes. The research and teaching encompass a range of biological disciplines, including behavior, neurobiology, developmental biology, and comparative physiology/biochemistry.

Dr. John W. Miles instructs his graduate seminar on nonlinear waves.

Marine Chemistry. Marine chemists are concerned with chemical and physical properties of seawater as well as the chemical processes operating within the oceans, in the marine atmosphere, and on the seafloor. Research programs are based on the interactions of seawater components with the atmosphere, with sedimentary solid phases, and with marine plants and animals.

Physical Oceanography. Studies in physical oceanography include observation, analysis, and theoretical interpretation of the general circulation of ocean currents and the transport of dissolved and suspended substances and heat; the distribution and variation of oceanic properties; the propagation of sound and electromagnetic energy in the ocean; and the properties and propagation of ocean waves.

Graduate Students and Degree Recipients

In the fall of 1985, 36 new students were admitted to graduate study. Of these, 12 were in marine biology, 5 in geological sciences, 3 in marine chemistry, 5 in geophysics, 5 in physical oceanography, 3 in applied ocean sciences, and 3 in biological oceanography. Enrollment at the beginning of the academic year was 176. UC San Diego awarded 10 Master of Science degrees and 30 Doctor of Philosophy degrees to the students listed below.

Doctor of Philosophy Degrees Awarded, with Titles of Dissertations

Earth Sciences

Richard G. Adair, "Microseisms in the Deep Ocean: Observations and Theory."

Joan S. Gomberg, "The Structure of the Crust and Upper Mantle of Mexico as Inferred from Seismic Data."

Craig R. Lindberg, "Multiple Taper Spectral Analysis of Terrestrial Free Oscillations."

Donald L. Reed, "Structure and Stratigraphy of the Eastern Sunda Forearc, Indonesia: Geologic Consequences of Arc-Continent Collision."

Thomas J. Sereno, Jr., "The Propagation of High Frequency Seismic Energy through Oceanic Lithosphere."

Peter M. Shearer, "Anisotropy in the Oceanic Lithosphere—The Ngendei Seismic Refraction Experiment."

Deborah K. Smith, "The Statistics of Seamount Populations in the Pacific Ocean."

Marine Biology

Robert K. Cowen, "Ecology and Population Biology of the Sheephead, *Semicossyphus pulcher*."

JoAnne Engebrecht, "Genetic Regulation of Bacterial Bioluminescence."

Steven D. Feldkamp, "Swimming and Diving in the California Sea Lion, *Zalophus californianus*."

Amir Neori, "Excitation Spectra of Chlorophyll *a* Fluorescence *in vivo*: Their Correlation with Photosynthetic Action Spectra and Their Use in the Study of Algal Photoadaptation."

Teresa M. Czerniak Present, "Patterns and Processes of Energy Allocation between Growth and Reproduction in the Marine Shore Fish, *Hypsoblennius jenkinsi*."

Jeff Schweitzer, "Studies of the Elasmobranch Central Electrosensory System, with Emphasis on Functional Organization of the Electroreceptive Midbrain in the Thornback Ray."

Gary E. Ward, "Dephosphorylation of Sperm Guanylate Cyclase during Sea Urchin Fertilization."

George D. F. Wilson, "The Systematic Position of the Ilyarachnoid Eurycopidae (Crustacea, Isopoda, Asellota)."

Oceanography

Donald B. Altman, "Laboratory Studies of Internal Gravity Wave Critical Layers."

William M. Balch, "Exploring the Ammonium and Nitrate Transport of Marine Phytoplankton with Nutrient Analogues."

Christian de Moustier, "Deep Seafloor Acoustic Backscattering Measurements Using Sea Beam."

Timothy F. Duda, "Observations of Horizontal Flow, Vertical Shear and Microstructure in the Upper Ocean."

Bruce M. Howe, "Ocean Acoustic Tomography: Mesoscale Velocity."

Arthur J. Miller, "Barotropic Planetary-Topographic Oscillations in Ocean Basins."

Joan M. Oltman-Shay, "Infragravity Edge Wave Observation on Two California Beaches."

Charles K. Paull, "I. Florida Escarpment: Chemosynthetic Communities, Geochemical Processes and Geological Consequences. II. Stable Isotopic Signal Carriers in Fine Pelagic Sediments."

Brian W. Sullivan, "Natural Products Chemistry of Burrowing Sponges of the Genus *Siphonodictyon*."

Mark S. Swenson, "Quasi-Geostrophic Solitary Wave Models of Rings and Blocks."

Jonathan D. Trent, "A Study of Macroaggregates in the Marine Environment."

Marco Weydert, "Measurements of Acoustic Backscatter of the Deep Sea Floor Using a Deeply Towed Vehicle. A Technique to Investigate the Physical and Geological Properties of the Deep Sea Floor and to Assess Manganese Nodule Resources."

Robin G. Williams, "The Internal Tide off Southern California."

William G. Wright, "The Behavioral Ecology of the Intertidal Limpet *Lottia gigantea*: Interaction between Territoriality, Demography, and Protandric Hermaphroditism."

Deborah L. Zmarzly, "Distribution and Ecology of Shallow-Water Crinoids (Echinodermata) in the Marshall Islands, with Emphasis on Their Symbiotic Organisms."

Master of Science Degrees

Earth Sciences

Richard J. Willis

Marine Biology

J. Fernando Arcos-Cordero

Oceanography

Mark T. Burch
Richard L. Culver
Philip T. Hammer
William C. O'Reilly
Russell B. Quinney
Kenneth H. Rubin
James D. Ryan
Anastasios A. Tselepides

Facilities & Collections

Shore Facilities

Analytical Facility. Instruments at the facility include a Philips automated X-ray fluorescence spectrometer with computerized control and data analysis; three X-ray diffraction systems, including a Philips APD 3600/02 with computer-aided search/match mineral files; a Perkin Elmer atomic absorption/fluorescence spectrometer with heated graphite analyzer and metal hydride systems; a Beckman amino-acid analyzer; a Hewlett-Packard computerized GC/mass spectrometer and four H/P gas chromatographs with EC, FI detectors; a superconducting IBM nuclear magnetic resonance spectrometer; a Leco CO_2 and SO_2 analyzer; a Coulo metrics total carbon/CO_2 analyzer; a P/E radio-recording computerized infrared spectrometer; a P/E UV-VIS 124 spectrometer; a Cambridge S-4 scanning electron microscope with Ortec EEDS II energy-dispersive X-ray spectrometer; an Hitachi H-500 scanning transmission electron microscope with an Ortec EDS X-ray spectrometer; a Zeiss 9 TEM; a Balzer's freeze etch system; diamond knife microtomes; a Cameca"Camebax" electron microprobe with three automated crystal spectrometers, polarized light optics, SEM, TEM capabilities, Ortec EDS X-ray system, and a Canberra/DEC computer system.

The facility also has several complete sample preparation laboratories, including "wet" chemical, rock-processing, biological EM, photographic, vacuum evaporation/sputtering, sedimentation, and grinding/lapping.

Aquarium Facilities. There are two research aquarium facilities; each is provided with a dual-line system that delivers seawater at ambient temperatures, a single-line chilled seawater system, and compressed air. The Experimental Aquarium (250 m^2) is equipped with 5 rooms for controlled experiments, 20 tanks with capacities from 425 to 2,200 liters, 9 seawater trays, counter space, sinks, and lockers. The Marine Biology Aquarium (280 m^2) is equipped with 26 tanks with capacities from 750 to 1,500 liters, 16 seawater trays, counter space, and sinks.

Cardiovascular Research Facility. This facility, shared by the Physiological Research Laboratory and the UC San Diego School of Medicine, consists of an experimental animal colony, equipment for measuring circulatory and cardiac functions in conscious, unrestrained animals, and an instrumentation development laboratory.

Diving Facility. The research diving program is housed in two separate facilities that contain the mechanical gear, wet equipment storage locker, and showers.

The scientific diver training and certification program, which orginated at Scripps in 1951, is the oldest of its type in the country. The program consists of a nonrecreational 100-hour training class in the use of open-circuit scuba, which may lead to University of California research diver certification. This class is open to faculty, staff, and students who must conduct underwater research. Each year an average of 130 Scripps/UC San Diego personnel participate in the scientific diving program. These individuals conduct their research throughout the oceans of the world, including the Antarctic.

Hydraulics Laboratory. This laboratory has a wind-wave channel $43 \times 2.4 \times 2.4$ m, with a tow cart for instruments and models; a two-layer stratified flow channel, test section $1.1 \times 1.1 \times 16$ m; a 15×18-m wave-and-tidal basin with an adjustable simulated beach; a 40-m glass-walled wave-and-current channel; a granular fluid mechanics test facility that comprises a $6 \times 12 \times 3$-m concrete basin, a $10 \times 1 \times 1$-m fluidizing channel, and three sand-storage and calibration tanks each 4 m high by 5 m in diameter, all serviced with a high-flow, slurry pumping system; a 16-m oscillatory flow tunnel; and an insulated, refrigerated, cylindrical seawater tank 10 m deep and 3 m in diameter equipped with artificial lighting. All wave generators in the laboratory incorporate servo systems and can be controlled by computer or magnetic tape. Microcomputer-based

Scripps staff and students at work at Scripps Supercomputer Users Remote Facility.

data acquisition and data processing systems are used in conjunction with the various facilities.

Kendall Frost Mission Bay Marsh Reserve (Mission Bay, San Diego). Approximately 16 acres of Mission Bay marshland belong to the university and constitute a marsh preserve and wildlife refuge designated for teaching and research. The reserve is the last fragment of the once extensive Mission Bay salt marsh. This property is one of 26 natural reserves used for teaching and research in the University of California Natural Reserve System. A small laboratory is located on the preserve. For more information write to the Reserve Manager, UC San Diego Natural Reserve System, A-001, La Jolla, California 92093.

Marine Science Development and Outfitting Shop. This shop is equipped with precision tools and machinery. A staff of toolmakers and diemakers designs and fabricates research equipment and instrumentation for various Scripps laboratories and other educational and governmental organizations throughout the United States.

Mass Spectrographic Equipment. Nine mass spectrometers are available: they include two 15-cm, Nier-type spectrometers, and one 6-cm Micromass instrument for isotopic analysis of light elements; a 15-cm, Nier-type spectrometer for rare gases; a 25.4-cm double-collection mass spectrometer for He^3/He^4 ratio measurements; a Hewlett-Packard gas chromatograph-quadrupole mass spectrometer for qualitative separation and analysis of organic compounds; a 30-cm-radius, solid-source mass spectrometer for geochronology and isotope dilution analysis; a small, portable, helium mass spectrometer for field use; and a 3-cm mass spectrometer for stable isotope tracer measurements.

Petrological Laboratory. This facility provides thin-sectioning, microprobe sample preparation, and rock-surfacing services to staff, students, and associated research groups. All types of submarine and subaerial igneous, metamorphic, and sedimentary materials in various states of lithification are prepared here with plastic-vacuum techniques and other types of impregnations.

Physiological Research Laboratory Pool Facility. This facility includes a holding pool for large marine mammals and fish, and a ring pool of 10-m radius equipped with a variable-speed trolley to carry instruments for hydrodynamic and biological studies of humans and other mammals. A central island within the ring pool contains small, dry laboratories and a "wet" laboratory equipped to handle large animals. A channel through the island permits transfer of animals from the ring pool into the laboratory.

Radio Station WWD. Owned and operated by Scripps and licensed to the National Marine Fisheries Service (NMFS), station WWD provides worldwide communications services to Scripps, NMFS, and other governmental and university ships. Weather advisories are routinely provided to the fishing fleet as well as to scientific vessels. Western Union services (TWX-Telex) are provided to the San Diego campus. WWD has computerized its radio and TWX-Telex for local users.

San Vicente Lake Calibration Facility (48 km from Scripps). This facility, operated by the Marine Physical Laboratory, is equipped for testing and calibrating acoustic transducers used in oceanographic research. The equipment is located on an 8 × 15-m

The new San Diego supercomputer. Below, *the supercomputer building on the UCSD campus.*

enclosed platform in water 40 m deep and offers an unobstructed range of 1,372 m.

Scripps Computing Facilities include:

Prime Computer Facility. Scripps's general-purpose computer center consists of a Prime 750 minicomputer, tape and disk drives, terminals, printers, and plotters. The facility is open 24 hours a day.

SSURF: Scripps Supercomputer Users Remote Facility. SSURF provides remote user access to the new San Diego Supercomputer Center, which is situated on the UCSD campus. The Supercomputer Center gives UCSD scientists access to some of the most powerful computers available for computationally intensive studies. The facility at Scripps provides a high-

speed link to the center, enabling two-way transfer of data and interactive use. SSURF also provides electronic mail access to most of the major public networks in the country, including ARPAnet and Bitnet.

In addition to providing access to computers across the country, this facility provides substantial computing capacity for local processing. The computer is a VAX 785 with the VMS operating system. There are several plotters, printers, and tape drives available around the clock.

Scripps Library. The library has outstanding collections in oceanography, marine biology, and marine technology, in addition to extensive resources in atmospheric sciences, ecology, fisheries, geology, geophysics, and zoology. The library currently receives more than 3,700 serial titles and has more than 189,000 volumes, including an extensive technical reports and translations collection, and a rare book collection featuring accounts and journals of famous voyages of discovery. A large map collection contains bathymetric, geologic, and topographic maps and charts of world areas and oceans.

The library also houses the archives of the Scripps Institution of Oceanography, which include official Scripps records, personal papers, photographs, and other material documenting the history of oceanography and of Scripps.

Scripps Pier. The 305-m pier serves as a launching site for small boats used for local oceanographic work, provides space for on-site studies, and supports the seawater system that supplies the aquaria and laboratories.

Scripps Satellite Oceanography Facility. This facility enables oceanographers to receive and process satellite imagery. Data transmitted in real time by the NOAA and NIMBUS polar orbiting satellites are received by the 5-m tracking antenna and stored on computer-compatible tapes. In addition to real-time coverage, retrospective archives of worldwide data are also available. The most commonly used sensors include the Advanced Very High Resolution Radiometer (AVHRR) and Coastal Zone Color Scanner (CZCS), which provide information in the infrared and visible portions of the spectrum. Scanning Multichannel Microwave Radiometer (SMMR) data, from which sea-surface winds may be derived, are also processed at the facility. The central processor is an HP 3000 Series II computer dedicated to the facility. This processor has 2 megabytes of main memory and 250 megabytes of disk storage. Tape drives capable of operating at 800, 1,600 or 6,250 bpi densities assure complete versatility. A high-resolution color display station allows users full interaction with the satellite imagery at near-real-time rates for most common operations. Current applications include tracking of drifting buoys via the ARGOS data collection system, near-real-time support of research vessels and aircraft by remote detection of chlorophyll concentrations, and sea-surface temperature determination. A four-day course, taught every quarter by the facility staff, gives potential users an overview of the available tools as well as several hours of hands-on experience.

Seawater System. Pumps located on Scripps Pier deliver seawater to the laboratories and aquaria of Scripps and the Southwest Fisheries Center. The seawater system uses three high-speed sand filters and two concrete storage tanks with a total capacity of 439,060 liters. Delivery capacity is 5,300 liters per minute.

Shipboard Technical Support Services Unit. The Shipboard Technical Support Services Unit is an amalgamation of several groups that serve both Scripps and the oceanographic community at large. The group provides technical and data-collection services aboard Scripps's research vessels, supplying and maintaining shipboard scientific facilities (computers and geological, biological, physical, and chemical data-acquisition systems); logistic support for these facilities; and postcruise data processing, distribution, and archiving. Shipboard Technical Support Services also furnish data collection equipment and highly trained technicians for University National Oceanographic Laboratory System (UNOLS) ships and international programs.

The ship support administrative organization comprises the shipboard computer group, resident technicians, geophysical technicians, geological data center, and the physical and chemical oceanographic data facility.

The Shipboard Computer Group is composed of programers and engineers who support VAX/UNIX computers ashore and at sea through programing, interface design, and maintenance. A shore-based VAX 750, available for use by the Scripps community, supports the VAX 730s on the ships. These computers are installed permanently on R/V *Thomas Washington* and R/V *Melville,* and they are interfaced to navigational and scientific instruments, including the R/V *Thomas Washington* Sea Beam system.

Resident technicians are knowledgeable guides who dive, rig, handle explosives, operate geological sampling gear (box corers, piston corers, dredges, etc.), operate net tows and trawls, and perform a wide variety of other tasks on Scripps research vessels. They also handle logistics for distant expeditions, and receive and store scientific equipment for future cruises.

The ***geophysical technicians*** provide and operate the analog and digital seismic reflection systems using air guns or water guns and refraction systems. They maintain the magnetometers and echo-sounding systems installed on Scripps vessels.

The ***Geological Data Center*** furnishes a wide variety of services from the staffing of cruises (Sea Beam operators) to data processing, distributing, and archiving. Navigation, depth, magnetics, and Sea Beam data are computer-processed for entry into the digital data base and for production of cruise reports and plots. A

Christopher K. Garrod and Alliant Corporation representative Steve Ross assemble a new computer.

multidisciplinary index of all samples and measurements made on major Scripps cruises is also maintained by the data center.

Workers in the ***Oceanographic Data Facility*** (ODF) collect data and samples for investigators from Scripps and other institutions. ODF also maintains an inventory of water samplers and other equipment, which is available at cost to qualified users. The more sophisticated or costly equipment may be used only when accompanied by ODF technicians, who operate and maintain the equipment at sea.

The group participates in expeditions by making high-precision hydrographic measurements, specializing in Neil Brown Instrument Systems CTD (conductivity, temperature, depth) work, and shipboard determinations of salinity, dissolved oxygen, nutrients (silicate, phosphate, nitrate, and nitrite), alkalinity, and total CO_2 from water samples collected with multiple-bottle samplers.

ODF resources include a chemistry laboratory, an electronics shop, a CTD and deep-sea reversing thermometer calibration laboratory, and a data processing and computer facility. The processing equipment includes a Hewlett-Packard 1000 minicomputer as a shore-based processor, and seven Tektronix 4050 series microprocessors used primarily at sea to monitor CTD data acquisition.

A new IBM 9000 computer-based data-acquisition system has been developed for both shipboard and shore-based data processing. This software system was used on a Pacific cruise to 24°N. It is capable of block-averaging data in real time, and it provides scientists with preliminary data output and data-plotting facilities aboard ship. Tape drives, plotters, and printers are used with both seagoing and shore-based systems.

For administrative purposes, the Scripps scientific collections have also been made part of the Shipboard Technical Support Services Unit. For further information see the Special Collections section.

Thomas Wayland Vaughan Aquarium-Museum. The aquarium-museum helps to increase public understanding and appreciation of the ocean through museum exhibits on oceanographic topics, a variety of educational programs, and displays of living marine animals from local waters and the tropical Pacific.

Aquarium-museum scientific staff provides UC San Diego and Scripps researchers with aid and information on marine organism maintenance, fish diseases, local species distributions, and other related topics. Through its collecting facility, the aquarium supplies scientists with living specimens.

This year more than 43,000 students in educational groups toured the aquarium-museum. The aquarium is open to the public daily; admission is free.

Scripps Aquarium Associates, the aquarium-museum public membership group, offers ocean-related activities to its members, including local excursions, lectures, family activities, scuba and snorkeling expeditions, a calendar, and a newsletter.

Underwater Research Areas. These include the following two parcels adjacent to Scripps that are also part of the Scripps Shoreline, Knoll and Underwater Reserve of the University of California Natural Reserve System.

Scripps Shoreline Reserve. Scripps Shoreline Reserve consists of a 100-acre tract of seashore and ocean where marine plants and invertebrates are protected for scientific purposes. Employees and students of the university may collect from this area with a permit. This reserve is also identified by the California Department of Fish and Game as the San Diego Marine Life Refuge.

Scripps Submerged Land Area. This area of approximately 3.25 km^2 is leased by the University of California from the city of San Diego. It lies seaward and to the north of Scripps and includes the head of the Scripps Submarine Canyon.

Special Collections

Benthic Invertebrates. The collection contains some 29,000 lots of specimens sorted into major taxonomic groups such as Coelenterata, Echinodermata, and Mollusca. All are accessioned with collection data, and more than 35 percent are identified to species. Specimens; several catalogs of holdings (Decapod and Stomatopod Crustacea, Brachiopoda, and Echinodermata); and IBM-compatible dBase III catalog data for various groups are available to qualified students and researchers.

Geological Core Locker. This geological "library" contains a collection of several thousand deep-sea sediment cores kept under refrigeration, and bulk assemblages of rocks and manganese nodules dredged from the major ocean basins. These materials are available to scientific investigators and students.

Marine Botany Collection. A small herbarium of marine benthic algae is composed of specimens from the U.S. Pacific coast, chiefly from the San Diego area, or collected during Scripps expeditions in the Pacific Ocean. There are some 1,600 sheets of pressed seaweeds, identified and arranged in taxonomic order. The specimens, although primarily used for teaching, are available for examination by any botanist or interested student.

Marine Invertebrates. Included in this collection of more than 60,000 documented whole zooplankton samples are accessioned holdings from expeditions, the continuous CalCOFI program, and special projects. Samples represent zooplankton collected with nets, ranging from surface neuston to bathypelagic midwater trawls. The major emphasis of the collection has been in the northeastern Pacific, but an increasing number of samples are also available from other oceanic and continental slope regions. The collection includes identified specimens for some of the major taxonomic groups. Samples are supplemented with physical and chemical data.

Marine Vertebrates. This collection contains more than 2 million specimens, with 3,200 cataloged species, including 128 primary types. Approximately 300 collections are added each year. Although the collection is worldwide, it specializes in deep-sea fishes and eastern Pacific shorefishes. The marine vertebrate collection contains large holdings of shorefishes from the Gulf of California and Panama and an extensive skeletal collection of dried preparations and cleared-and-stained specimens in glycerin.

Oceanographic Data Archives. Tide-gage records have been taken daily from the Scripps Pier since 1925. Monthly tide-gage records from 1947 to 1967 and from 1980 to the present are available in the Scripps Library archives. Records before 1947 and from 1967 to 1980 can be obtained by writing Chief of the Datums and Information Branch, James R. Hubbard, C-233, NOAA/NOS, 6011 Executive Blvd., Rockville, MD 20852.

Data from more than 20,000 hydrographic casts from Scripps cruises are managed by the Shipboard Technical Support Services Unit. The Marine Life Research Group manages an additional 45,000 stations of hydrographic data as well as daily temperature and salinity records from data collected at Scripps Pier and other shore stations along the California coast.

Historical meteorological and oceanographic data for the Pacific are kept in the NORPAX data library. These data include marine weather and sea-surface temperature observations from 1854 to the present; National Oceanographic Data Center files to 1976; and monthly pressure, temperature, and precipitation at selected World Meterological Organization stations.

Scripps Core Repository of the Ocean Drilling Program. The Scripps core repository (under lease agreement with the Ocean Drilling Program at Texas A&M University) houses the West Coast repository for cores collected by the Deep Sea Drilling Project in the Pacific and Indian oceans. Core samples are made available to qualified researchers throughout the world under policies established by the National Science Foundation and implemented through Joint Oceanographic Institutions, Inc. and Texas A&M University.

Loading R/V Melville.

Appendixes

Appendix A
Publications

Introduction

The results of Scripps research are published in many different forms. These publications range from short contractual reports to long taxonomic descriptions. Scripps publications are distributed by subscription, exchange, or government contract.

Below is a complete listing of Scripps publications for fiscal 1986. Detailed information on the availability of each series is included.

Bulletin

The *Bulletin of the Scripps Institution of Oceanography* is an irregularly published series for lengthy, in-depth scientific papers written by Scripps scientists. For information about subscriptions and a list of volumes available please write to University of California Press, 2223 Fulton Street, Berkeley, California 94720.

The most recent volumes are listed below.

v.25 **Wilson**, George D. F. Systematics of a Species Complex in the Deep-Sea Genus *Eurycope*, with a Revision of Six Previously Described Species (Crustacea, Isopoda, Eurycopidae). 1983. 68p.

v.26 **Matsui**, Tetsuo and Richard H. **Rosenblatt**. Review of the Deep-Sea Fish Family Platytroctidae (Pisces: Salmoniformes). In Press. 159p.

CalCOFI Publications

The work of the California Cooperative Oceanic Fisheries Investigations (CalCOFI), in which the Scripps Institution of Oceanography, the California Department of Fish and Game, and the National Marine Fisheries Service cooperate, is published in a variety of formats. Peer-reviewed scientific articles are published annually in the *California Cooperative Oceanic Fisheries Investigations Reports*. Maps of physical, chemical, climatological, and biological factors measured by CalCOFI researchers during the program's 36-year history are published irregularly in the *California Cooperative Oceanic Fisheries Investigations Atlas* series. Data reports, containing the processed data from specific cruises carried out under CalCOFI sponsorship, are published irregularly in the SIO reference series and in the CalCOFI data report series. To obtain copies of any of these publications, write to CalCOFI Coordinator, Scripps Institution of Oceanography, A-027, La Jolla, California 92093.

Contributions

This annual publication is a compilation of selected reprints authored by the Scripps faculty and staff. The *Scripps Institution of Oceanography Contributions* is available ONLY on an exchange basis to other scientific, research, and educational institutions. For exchange information please write to Scripps Institution of Oceanography Library, Exchange Department, C-075C, La Jolla, California 92093.

The articles listed below were published in the 1985 volume and may also be found in the publications cited. Information about a specific reprint can be obtained by writing directly to the author in care of Scripps Institution of Oceanography, La Jolla, California 92093.

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Appendix B

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DSDP—Deep Sea Drilling Project
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MLRG—Marine Life Research Group
MPL—Marine Physical Laboratory
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NU—Neurobiology Unit
ORD—Ocean Research Division
PRL—Physiological Research Laboratory
SC—Scientific Collections
SGP—Sea Grant Program
SOMTS—Ship Operations and Marine Technical Support
SPP—Science and Public Policy
VL—Visibility Laboratory

Appendix C

Awards and Honors

Dr. Victor C. Anderson
Received the Admiral Charles B. Martell Technical Excellence Award.
Dr. George E. Backus
Awarded the gold medal of the Royal Astronomical Society of the United Kingdom.
Dr. Andrew A. Benson
Awarded the diploma of Docteur Honoris Causa by the Université Pierre et Marie Curie.
Dr. Wolfgang H. Berger
Corecipient of Senior U.S. Scientist award from the Alexander von Humboldt Foundation.
Dr. Paul K. Dayton
Elected a fellow of the American Association for the Advancement of Science.
Dr. J. Freeman Gilbert
Awarded the Geological Society of America's Day Medal.
Dr. Walter F. Heiligenberg
Received a Javits Neuroscience Investigator Award from the National Institutes of Health.
Dr. Robert R. Hessler
Elected a fellow of the American Association for the Advancement of Science.
Dr. Charles D. Keeling
Elected a fellow of the American Association for the Advancement of Science.
Dr. H. William Menard
Awarded the William Bowie Medal from the American Geophysical Union.
Dr. Walter H. Munk
Corecipient of Secretary of the Navy Research Chair in Oceanography.
Received honorary doctorate of science degree from the University of Cambridge.
Dr. Jerome Namias
Received a special certificate from the Department of Commerce and National Oceanic and Atmospheric Administration for pioneering work in long-range weather forecasting.
Dr. William A. Nierenberg
Received Distinguished Technical Contribution Award from the I.E.E.E. Oceanic Engineering Society.
Dr. Pearn P. Niiler
Elected a fellow of the American Geophysical Union.
Dr. Roger R. Revelle
Awarded honorary doctorate from the University of Rhode Island.
Dr. Fred N. Spiess
Presented the Acoustical Society of America's Pioneers of Underwater Acoustics Medal.
Received the Marine Technology Society's 1985 Lockheed Award for Ocean Science and Engineering.
Dr. Claude E. ZoBell
Received the Centennial Recognition Award from Utah State University.

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National Science Foundation	$22,489,840	37.14
Navy, Department of the	12,288,309	20.30
Commerce, Department of	2,481,456	4.10
National Aeronautics and Space Administration	1,302,349	2.15
Health and Human Services, Department of	1,169,923	1.93
Energy, Department of	923,496	1.52
Army, Department of the	690,886	1.14
Interior, Department of the	518,282	0.86
Air Force, Department of the	378,977	0.63
Defense, Department of	15,175	0.03
Other	26,609	0.04
Total Federal Government	$42,285,302	69.84
State General Funds	12,844,325	21.21
Private Gifts and Grants	4,288,643	7.08
Overhead Funds	1,807,561	2.99
State of California	325,992	0.54
Endowment Funds	140,951	0.23
Local Government	37,729	0.06
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*Includes Overhead

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In Memoriam

James L. Faughn. September 18, 1985. Captain Faughn joined Scripps in 1947, and served to his retirement in 1974, mainly under the job titles of "assistant to the director," and "staff officer." He was a man of many trades: marine superintendent; captain of the research vessels *Horizon, Stranger, Alpha Helix, Thomas Washington,* and other ships; ship scheduler; ship construction supervisor; physical oceanographer; and business officer of three administrative units of Scripps.

H. William Menard.

February 9, 1986. Dr. Menard, marine geologist, came to Scripps and the Institute of Marine Resources in 1955, and became a professor in 1961. He remained at Scripps (with two leaves of absence to serve first on the staff of President Lyndon Johnson's science advisor, and then as director of the United States Geological Survey) until his death. He was a leader in mapping the ocean floor, and used marine geological and geophysical data to develop theories of geological structure; he played a leading role in the work that led to the plate tectonics theory.

Joanne Sorrells Morton. October 17, 1985. Joanne Morton was an administrative assistant for four years in the Ocean Engineering Research Group of the Institute of Marine Resources. She worked at Scripps from 1980 through 1984.

J. F. T. (Ted) Saur. August 24, 1985. Ted Saur joined Scripps as a specialist in the Ocean Research Division in 1975. He was instrumental in starting the Ships-of-Opportunity Program and remained with the Ocean Research Division until his death.

All correspondence pertaining to this specific report should be directed to: Technical Publications, A-033B, Scripps Institution of Oceanography, La Jolla, California 92093.

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Aerial view of Scripps Nimitz Marine Facility.

Inset satellite images:
Top: Appearance of fish community at seamount (white cross at left of "El Bajo Gorda" call out) off Baja Peninsula correlated by satellite imagery with water mass movements.
A. P. Klimley and S. B. Butler

Middle: Satellite Image
AVHRR image of the Denmark Strait region
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Bottom: AVHRR image of a mesoscale eddy dipole off Pt. Conception off the southern California coast.
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Outside Back cover:
Aerial of center of Scripps Institution.

Inset:
Satellite infrared (AVHRR) image of the California Current system south of Pt. Conception showing 20 drifting buoy tracks.
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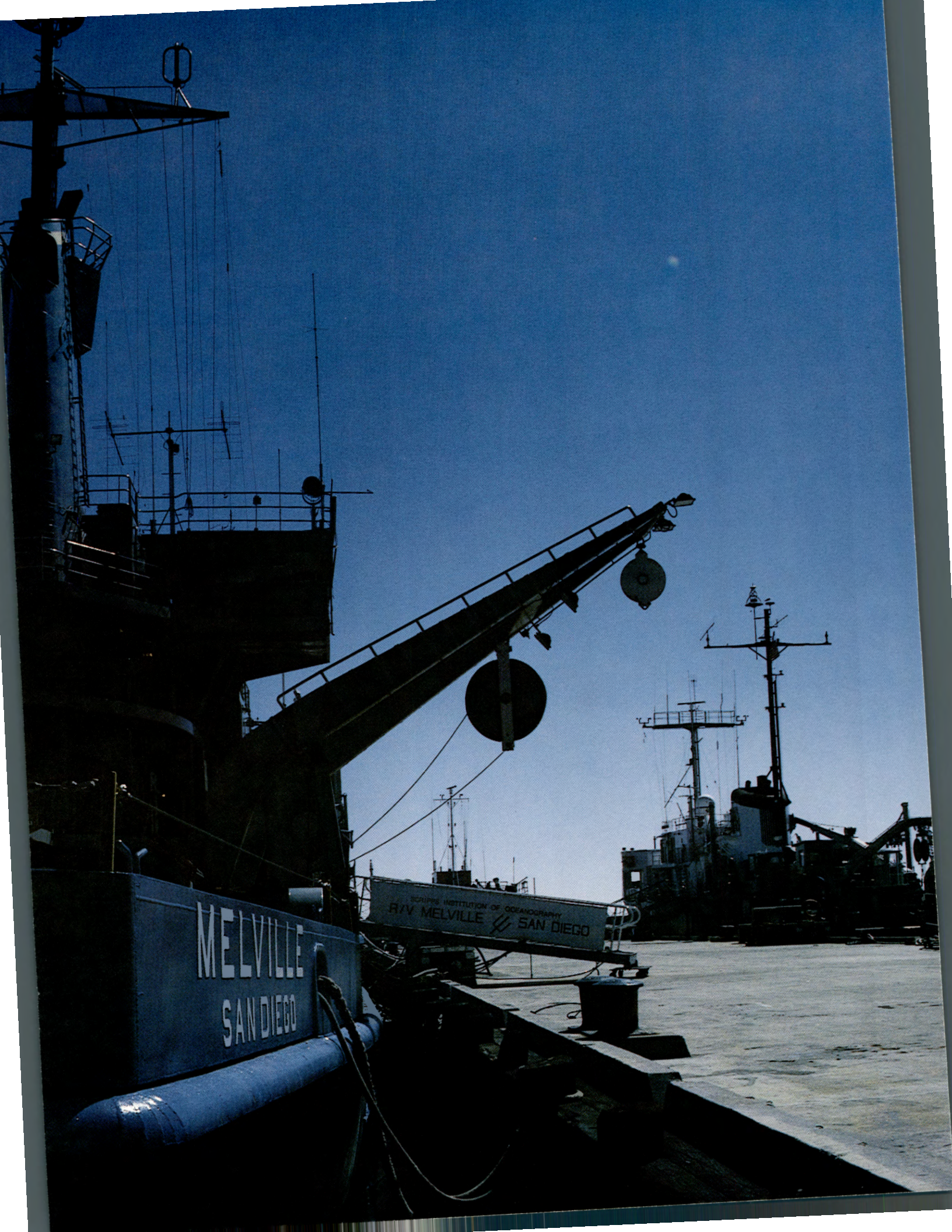
Inside Back cover:
Ships at Nimitz Marine Facility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