EXPLORATION OF THE SEAS

VOYAGE INTO THE UNKNOWN

Committee on Exploration of the Seas
Ocean Studies Board
Division on Earth and Life Studies

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Preface

The ocean is Earth's least explored frontier. A well-planned, international program of ocean exploration that exploits new technology, takes advantage of recent international agreements, and establishes new partnerships could lead to untold discoveries about the ocean, its living and nonliving resources, and the many species that inhabit it. Our oceans influence global climate, and they contain unknown quantities of biological, chemical, and mineral resources. There is a growing recognition that we have much more to learn about the secrets our oceans hold.

In December 2000, the U.S. Congress instructed the U.S. National Academies to assess the feasibility and value of implementing a major, coordinated, international program of ocean exploration and discovery. A Committee on Exploration of the Seas was constituted, with members from the academic, legal, commercial, and nonprofit sectors who were experts in Earth science, biology, engineering, underwater archaeology, and national and international law and policy. The committee convened an international workshop and a series of working meetings to develop the report's findings.

Funding for a U.S. program in ocean exploration began in fiscal year 2000, but most of its work has been done in U.S. territorial waters. This report seeks to identify strategies for and benefits of an international effort. It is clear to the members of the committee that the success of any such program will require full international participation—from coordinating program administration and setting priorities for exploration, to planning and implementing expeditions, to informing the public of discoveries. But, as the committee's charge states, it is necessary first to detail the strengths, weaknesses, and gaps in current efforts, including those in the United States. We propose in this report an alternative framework for improving and expanding national and international ocean exploration programs.

A workshop in May 2002 was convened to make a first approximation of interest in the idea of establishing a global ocean exploration program.

Countries recognized for leadership, participation, and developing programs were invited to send participants to discuss program ideas. The meetings focused on existing exploration programs, areas of exploration for which international participation would be especially beneficial, existing and anticipated technology, and policy or legal arrangements that a new exploration program might require. The committee has consolidated the presentations and included a summary in Appendix D to this report. The committee is grateful to the Intergovernmental Oceanographic Commission of the United Nations Educational, Scientific and Cultural Organization for hosting the workshop. The Scientific Committee on Oceanographic Research was a great help in coordinating the meeting and sponsoring the participation of members from developing nations.

John Orcutt, *Committee Chair*
Shirley A. Pomponi, *Committee Vice-Chair*

Acknowledgments

This report was greatly enhanced by the participants of the meetings held as part of this study. The committee would first like to acknowledge the efforts of those who gave presentations at the meetings: Joe Baker, Patricio Bernal, Steven Bohlen, Bryndis Brandsdottir, Harry Breidahl, Melbourne Briscoe, Mario Caceres, Tommy Dickey, Rene Drucker-Colin, Sylvia Earle, Paul Egerton, John Field, Christopher Fox, Montserrat Gorina-Ysern, J. Frederick Grassle, Jeremy Green, James Greenwood, John Haines, Stephen Hammond, Su Jilan, Robert Knox, Suzanne Lacasse, Margaret Leinen, Eric Lindstrom, Larry Mayer, Craig McLean, Michael Meredith, Jean-Francois Minster, Barbara Moore, Alain Morash, Rob Murdoch, Nii Odunton, Annelies Pierrot-Bults, Fangli Qiao, Muthukamatchi Ravindran, Shubha Sathyendranath, Sergey Shapovalov, Sunil Murlidhar Shastri, Victor Smetacek, Kiyoshi Suyehiro, Tamaki Ura, Edward Urban, Jr., and James Yoder. These talks helped set the stage for fruitful discussions in the closed sessions that followed.

Edward Urban, Jr., Elizabeth Gross, and Maria Hood were a great assistance to the committee and staff in planning the International Global Ocean Exploration Workshop.

The committee is also grateful to Margot Bohan and Douglas White, who provided important material for this report, Alfred Duba, who helped make our New York meeting a successful one, and Kate Kelly, who improved the report with her thorough edit.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the National Research Council's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the institution in making its published report as sound as possible and to ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge.

The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following people for their participation in the review of this report:

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Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations nor did they see the final draft of the report before its release. The review of this report was overseen by **Donald Walsh**, International Maritime, Inc., and **Louis J. Lanzerotti**, Lucent Technologies. Appointed by the National Research Council, they were responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

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Executive Summary

In the summer of 1803, Thomas Jefferson sent Meriwether Lewis and William Clark on a journey to establish an American presence in a land of unqualified natural resources and riches. It is fitting that, on the 200th anniversary of that expedition, the United States, together with international partners, should embark on another journey of exploration in a vastly more extensive region of remarkable potential for discovery. Although the oceans cover more than 70 percent of our planet's surface, much of the ocean has been investigated in only a cursory sense, and many areas have not been investigated at all. During this journey, there is little doubt that discoveries will be made:

- A spectrum of marine natural products will have profound pharmaceutical potential.
- Vast new mineral and energy resources will be uncovered.
- The physical factors responsible for changes in climate will be identified.
- New ecosystems will alter our view of the origin of life.
- Artifacts will provide new information about the history of civilization.
- Surprising new species and organisms will be found.

In response to a request from the U.S. Congress to examine the feasibility and value of an ocean exploration program, the Ocean Studies Board of the National Research Council established the Committee on Exploration of the Seas (Box ES.1), whose findings are reported in this document. In addition to a public meeting, the committee convened an International Global Ocean Exploration Workshop in May 2002 to seek advice from the international community and discuss the possibilities for, and interest in, a global ocean exploration program.

BOX ES.1 STATEMENT OF TASK

This study will assess the feasibility and potential value of implementing a major, coordinated, international program of ocean exploration and discovery. The study committee will survey national and international ocean programs and strategies for cooperation between governments, institutions, and ocean scientists and explorers, identifying strengths, weaknesses, and gaps in these activities. Based primarily on existing documents, the committee will summarize priority areas for ocean research and exploration and examine existing plans for advancing ocean exploration and knowledge. These findings will then be used to help characterize the technology, human resources, organizational structures, and funding that would be needed to address the identified priorities in the United States and internationally. Finally, the committee will recommend strategies to facilitate such a program, including information regarding the countries and organizations likely to participate; the institutional arrangements needed (including the possibility of new treaties or laws); the technology and infrastructure needed (including manned and autonomous underwater vehicles, ships, observing systems, and data management systems); and an estimate of the potential costs.

This report provides rationale and support for the following recommendations:

- **A new program for ocean exploration is necessary.**
- **An international, top-down program is not feasible at the outset.**
- **The United States should lead by example and develop a national program with international representation.**
- **The United States should operate the program using an independent (nonfederal) entity.**
- **Federal funding for the independent organization should be provided through either the National Oceanographic Partnership Program (NOPP), the National Science Foundation (NSF), or the National Oceanic and Atmospheric Administration (NOAA).**

WHY ESTABLISH A NEW PROGRAM?

Exciting discoveries are made in the ocean sciences every year. From the identification of ecosystems that thrive without sunlight to the new pathways for photosynthesis recently identified in marine microbes, discoveries in our oceans continue to revolutionize and refine our theories of the origins of life here and the possibilities for life elsewhere in the universe. However, such discoveries are largely serendipitous. In the United States, ocean sciences rely on relatively few large, carefully managed assets—ships, submersibles, and laboratory facilities. Research funding is relatively more available for projects that will revisit earlier sites and discoveries and for improving current understanding than it is to support truly exploratory oceanography. A new program to provide opportunities for investigating new regions and that draws on research from a variety of disciplines, would speed discovery and application of new information.

A coordinated, international ocean exploration effort is not unprecedented—the International Decade of Ocean Exploration (IDOE), 1971-1980, was established by the Marine Sciences Act of 1966 and motivated both by anticipated discoveries of useful and important marine resources and by scientific curiosity. Questions about the health of the world's oceans led scientists to argue for systematic baseline surveys that were not possible from randomly spaced observations. The IDOE program recognized that exploration of the ocean required a sustained global effort with international participation, and justification for the program included issues of clear international interest. More information was necessary to describe the ability of the oceans to provide food for an expanding world population, to protect the United States and other nations from maritime threats to world order, to assuage the deterioration of water quality and waterfronts in coastal cities, to support expanded ocean shipping, and to locate new supplies of seabed oil, gas, and minerals. The objective of IDOE was to "achieve more comprehensive knowledge of ocean characteristics and their changes and more profound understanding of oceanic processes for the purpose of effective utilization of the ocean and its resources" (National Academy of Sciences, 1969). More specifically, it was expected that the program would help increase the yield from ocean resources, improve predictions of and responses to natural phenomena, and protect or improve the quality of the marine environment. IDOE was a great success—it provided observational databases on the physics, geochemistry, paleoceanography, biology, and geophysics of the ocean that fueled hypothesis-driven research for decades.

> **Recommendation: As was true when IDOE was proposed and supported, ocean exploration remains a necessary endeavor to identify and fully describe the resources the oceans contain. The pace at which we discover living and nonliving resources and improve our understanding of how the oceans respond to chemical, biological, and physical changes must increase.**

Every time a scientist happens upon some completely unexpected discovery in the ocean, it is a reminder of how little is known about this environment that is so critically important to the sustainability of the planet. We now recognize that different facets of the ocean—small-scale geological, biological, and genetic diversity; chemical, geophysical, and physical oceanographic properties—interact in complex ways, and our understanding of the ocean requires its examination as a whole system. The oceans play a critical role in the maintenance of the ecosystems of the Earth. Resources contained in the oceans currently supply a substantial portion of the world's food and fuel supply, and maintain global climate patterns. The oceans harbor as yet undiscovered organisms—new searches for life continue to discover previously unknown organisms. Only a portion of the potential of the oceans has been tapped.

It is difficult to predict what discoveries are still to come, but it is clear that ocean exploration will improve the accuracy of our predictions of global climate change, produce new products that will benefit humanity, inform policy choices, and allow better stewardship of the oceans and the planet as a whole. To reach this potential, ocean research should encourage cooperation between researchers from varied disciplines.

> **Finding: Currently ocean science funding in the United States is predominantly awarded to research in specific disciplines, such as biological, physical or chemical oceanography. Proposals for interdisciplinary work are hampered by a funding bureaucracy that is also discipline-based. Ocean exploration is an integrative activity that will encourage and support interdisciplinary efforts that seek to discover new contributions to the marine sciences.**

The very nature of scientific investigation leads oceanographers to seek out information to verify hypotheses and confirm earlier findings. The infrastructure and support needed for oceanographic work is expensive, limited, and highly scheduled to ensure efficiency in the pursuit of knowledge about the oceans. Much of the oceanographic research currently conducted re-investigates previously visited locations, limiting access to new regions and restricting long-term data collection. As a result, vast portions of the oceans have not been systematically examined for geochemical or biological characteristics. This is particularly true of the oceans in the southern hemisphere. Ground-breaking discoveries, such as hydrothermal vents, fueled intensive investigations of those regions, but they did not lead to investigations of new regions. As is being shown by an Australian-New Zealand expedition to seamounts and abyssal plains, systematic biological exploration in even a small portion of the ocean can provide a rich collection of new organisms. The one month journey collected more than 100 previously unidentified fish species and up to 300 new species of invertebrates (National Oceans Office, 2003). A very recent example of such an exploratory effort by the United States has been initiated by the Department of Energy. Although the Sargasso Sea is thought to exhibit limited biodiversity and a simple ecosystem (Holden, 2003), it is anticipated that determining the genomic structures of all organisms within the ecosystem may reveal new pathways of carbon sequestration and hydrogen generation (Whitfield, 2003).

Recommendation: Oceanographic research should encourage scientifically-rigorous, systematic investigations of new sites in the oceans. Exploration through time should be included in oceanographic research.

Oceans provide food, energy and mineral resources, products capable of treating human disease, and affect climate and global responses to changes in climate. A new large-scale program devoted to ocean exploration is necessary to:

- coordinate efforts in ocean discovery and capitalize on the wide array of available data;
- provide new resources and facilities for access by researchers;
- establish support for and promote interdisciplinary approaches to ocean investigations;
- develop outreach and public education tools to increase public awareness and understanding of the oceans;
- discover the living and nonliving resources of the oceans; and
- provide a multidisciplinary archive of ocean data to serve as a source of basic data upon which to develop hypotheses for further investigation.

Recommendation: A coordinated, broadly-based ocean exploration effort that meets the highest standards of scientific excellence should be aggressively pursued. An ocean exploration program should be initiated and contain the following characteristics, or goals, which can also be used to gauge its ultimate success:

- **The program should be global and multidisciplinary.**
- **The program must receive international support.**

- **The program should consider all three spatial dimensions as well as time.**
- **The program should seek to discover new living and nonliving resources in the ocean.**
- **The program should include development of new tools, probes, sensors, and systems for multidisciplinary ocean exploration.**
- **The program should reach out to improve literacy pertaining to ocean science and management issues for learners of all ages to maximize the impact for research, commercial, regulatory, and educational benefits.**
- **The program should standardize sampling, data management, and dissemination.**

Recommendation: To achieve the recommended goals, early efforts in ocean exploration should be selected using the following criteria:

- **Research is conducted in areas of international interest. Particularly salient are themes that are amenable to international cooperation and those suggested by International Global Ocean Exploration Workshop participants.**
- **Questions advance the current state of knowledge.**
- **Characteristics of the habitat, region, or discipline suggest a potential for bold, new discoveries.**
- **The results have a potential to benefit humanity.**

Recommendation: Several promising areas were identified as having broad international interest and are recommended as potential initial exploration themes:

- **marine biodiversity;**
- **the Arctic Ocean;**
- **the Southern Ocean and Antarctic ice shelves;**
- **deep water and its influence on climate change;**
- **exploring the ocean through time; and**
- **marine archaeology.**

INTERNATIONAL SUPPORT FOR AN OCEAN EXPLORATION PROGRAM

The involvement of many nations in ocean exploration efforts would expand an ocean exploration program's usefulness by broadening the base of human, mechanical, and financial resources available. In fact, international collaboration is necessary to support a truly global ocean exploration program. And the interests of individual nations must be served to promote such participation—something not readily achievable by a large-scale, internationally coordinated effort. The informal consensus of the workshop attendees was that a one-program-serves-all effort would be neither effective nor efficient. An international program could be best served by developing individual national ocean exploration programs to suit the needs of the countries involved. National priorities would be set and then partners sought for individual programs. Such bilateral and multilateral agreements have worked extremely well for ocean science programs such as the Ocean Drilling Program (ODP) and should serve well for ocean exploration.

Although many nations would likely be interested in participating in limited ocean exploration programs, relatively few have the resources necessary to provide significant financial support to a program. A U.S. national model should offer the example for other nations, and it should work to incorporate people from other nations to generate interest more broadly. The development of similar national programs elsewhere should be encouraged and anticipated. By developing distinct exploration programs for international cooperation to seek discoveries of specific resources or investigate regional features, the burden of international policy and agreements could be greatly reduced.

> **Recommendation: Given the considerations presented, it is prudent to begin an exploration effort with a model for a U.S. national program that will encourage collaboration and capacity building and that would be likely to lead to the development of similar programs in other countries. Once other national programs are established, consortia of nations can voluntarily collaborate on program plans and pool resources using multilateral international agreements to undertake regional exploration or to pursue themes of shared interest.**

DOMESTIC SUPPORT FOR OCEAN EXPLORATION

There has been continued support for and success from oceanographic research in the United States, and a large-scale international exploration program could rapidly accelerate our acquisition of knowledge of the world's oceans. The current ocean-research-funding framework does not favor such exploratory proposals. Additional funding for exploration without a new framework for management and investment is unlikely to result in establishment of a successful exploration program. A new program, however, could provide the resources and establish the selection processes needed to develop ocean exploration theme areas and pursue new research in biodiversity, processes, and resources within the world's oceans. The current effort of the Office of Ocean Exploration at NOAA should not be expected to fill this role.

After weighing the issues involved in oversight and funding, perhaps the most appropriate placement for an ocean exploration program is under the auspices of the interagency NOPP, provided that the problems with routing funds to NOPP-sponsored projects is solved. This solution has the best chance of leading to major involvement by NOAA, NSF, and other appropriate organizations such as the Office of Naval Research. The committee is not prepared to support an ocean exploration program within NOAA unless major shortcomings of NOAA as a lead agency can be effectively and demonstrably overcome. A majority of the committee members felt that the structural problems limiting the effectiveness of NOAA's current ocean exploration program are insurmountable. A minority of the committee members felt that the problems could be corrected. If there is no change to the status quo for NOPP or NOAA, the committee recommends that NSF be encouraged to take on an ocean exploration program. Although a program within NSF would face the same difficulties of the existing NOAA program in attracting other federal (and nonfederal) partners, NSF has proven successful at managing international research programs as well as a highly-regarded ocean exploration program that remained true to its founding vision.

> **Finding: After exhaustive deliberation, the committee found that an ocean exploration program could be sponsored through NOPP, or through one of the two major supporters of civilian ocean research in the nation: NOAA or NSF.**
>
> **Recommendation: NOPP is the most appropriate placement for an ocean exploration program, provided the program is revised to accept direct appropriations of federal funds. If those funding issues are not resolved, NOAA (with consideration to the comments above) or NSF would be appropriate alternatives.**

MANAGEMENT OF A DOMESTIC EXPLORATION PROGRAM

In recent years, agencies have increasingly turned to nongovernmental groups to take on the day-to-day operations of large programs. The advantages of this approach are several. First, the process of competitive bidding for the management of the program leads to creativity in program design, cost savings, and incentives for excellent performance. Second, as programs build up and close down, there is no need to accommodate the personnel requirements through agency headcount. NSF chose the independent contractor route in selecting Joint Oceanographic Institutions to operate ODP, and has recently proposed a similar plan for management of the Ocean Observing Initiative and the Integrated Ocean Drilling Program (in this case the associated not-for-profit is an international corporation). Likewise, the National Aeronautics and Space Administration will be selecting an independent contractor to manage the International Space Station.

The advantages of an external contractor are potentially even greater for an ocean exploration program. For example, if NOPP were to lead the effort, management by an independent contractor would provide a neutral third party to balance the interests of the various agency partners and accept contributions from a variety of public and private sources. If NOAA were to lead the program, management by an external group could mitigate some of the perceived inadequacies in the present, internal-NOAA program. For example, the program would be an "arm's length" away from the pressures of the agency mission and subjected to regular external review. Depending on the choice of the external managing organization, grant processing, priority-setting, connection to the external community, and transparency of decision making could be improved. If NSF were asked to lead the program, the agency would almost surely choose this route rather than build internally the infrastructure to manage the exploration-specific assets and data system.

Management of large-scale ocean research programs can be effective and efficient through the use of independent contractors. Nonfederal operators can receive support from multiple government agencies and receive financial support from private sponsors. Independent audits of program performance can be used to ensure the program is achieving the desired outcomes.

> **Recommendation: A nonfederal contractor should be used to operate the proposed U.S. ocean exploration program. The original contract should be awarded following a competitive bidding process. The program should be reviewed periodically and should seek to leverage federal resources for additional private contributions.**

TECHNOLOGY AND INFRASTRUCTURE NEEDS

Rapid progress in ocean sampling devices now allows researchers access to new environments, including the extremes of hydrothermal systems and waters beneath the ice of the Arctic Ocean. The potential of new technology in satellites, underwater equipment, remote sensing technology, and observing systems has not yet been met. An ocean exploration program could access these new technologies to speed our discoveries of ocean resources and characteristics, while providing support for development of additional new tools necessary for interdisciplinary research.

Dramatic advances in our ability to explore the deep sea are attributable to research and development done by academic and private organizations. High-quality, long-term, multinational research programs have greatly increased our understanding of the processes that govern our planet. The Joint Global Ocean Flux Study, ODP, and the Global Ocean Observing System use tools, technology, and human resources developed and provided by a variety of nations. A new exploration effort should use existing equipment and technology whenever possible, but it will also require new methods and systems to adjust and improve in order to meet emerging needs. Additional resources for the development of innovative tools to support selected exploration voyages or investigations should greatly increase the capabilities, and discoveries, of oceanographic research. A global ocean exploration system could access observations from existing satellites, moored open-ocean sensors, data voluntarily contributed from various ships, and the global sea level network, as well as other observations that are not yet defined or routinely collected.

The science and technology results from several continuing large-scale research programs—the Tropical Ocean and Global Atmosphere program, the Ridge Interdisciplinary Global Experiment, and the Joint Global Ocean Flux Study—provide important information and experience that can be applied when designing an operational ocean exploration system that is effective, affordable, and consistent with our knowledge of the scales of ocean biology, chemistry, and physics (National Research Council, 1993).

Recommendation: An ocean exploration program should seek to access and encourage new developments in ocean technology.

The plans to acquire new equipment or use existing facilities should be tailored to meet the plans of the scientific program. Any new exploration program should seek to expedite the development and use of new technology for novel, multidisciplinary observations in new environments. In particular, the development of probes and sensors for in situ sampling and molecular analysis is a priority for biological sampling and for the identification of organisms and processes. A global ocean exploration program will no doubt stimulate such new technologies, and resources should be available to support it in selected exploration voyages or investigations.

Finding: Access to standard and new technology, including commercially available equipment and technology that is not used for and by research institutions, is necessary for an ocean exploration program to succeed. Access to commercially available assets, such as human occupied vehicles, remotely operated vehicles, and autonomous underwater vehicles, would increase flexibility and allow researchers more access to new environments, and thus promote the development of even more new technology.

Recommendation: The exploration program should seek to expedite the development and use of the new technology in new undersea environments. The list of equipment for an ocean exploration program should be tailored to meet the scientific program's plans.

In the past, the lack of standardized data collection efforts hampered long-term utility of very large data sets (e.g., IDOE). Standardization of data collection and reporting will allow the integration of information from a variety of projects. The long-term success of the program will depend on whether it can provide archives for access long after original exploration efforts end.

Recommendation: Data collection and reporting must be standardized to allow data sets from a variety of explorations to be integrated. The sampling techniques and reporting formats should be designed to be acceptable to the worldwide oceanographic community.

Data access and management policies are critical to the success of any large-scale research program. Despite the efforts of federal agencies and other parties, data sharing remains problematic across the ocean sciences. The success of an ocean exploration program could be greatly enhanced by allowing data to be shared soon after collection. Real-time data access is also a possibility that should be considered in the early stages of the program. An ocean exploration program, in particular, could benefit from accessing archives of both oceanographic and archaeological data to mine those data for new information and large-scale patterns.

Recommendation: Data access and management policies must be established before exploration begins. In particular, any exploration program should encourage oceanographers to improve their capacity to access and integrate data from many ocean sciences, extract new information from those data sets, and convey new insights to decision makers and the public. The proposed ocean exploration program should seek ways to contribute to or link exploration data to existing oceanographic and archaeological data archives.

Often only preliminary investigations can be conducted while oceanographic cruises are under way. Additional materials and equipment for sample processing on land must be accessed in order to uncover critical information. Discoveries by an ocean exploration program are very likely to occur as a result of additional, postcruise sample processing.

Recommendation: Support of postcruise science should be a major component of a global ocean exploration program. Researchers should be supported for activities that will enhance their shipboard work, such as sample analysis and data interpretation and presentation. Without direct support, many discoveries might not come to fruition.

EDUCATION AND OUTREACH IN AN EXPLORATION PROGRAM

The way an ocean exploration program is organized—both nationally and internationally—can make a difference in the effectiveness of public outreach and education efforts. By fostering collaborations among scientists and educators, an exploration program can ensure that educators are an integral part of the planning and conduct of the exploration activity, whether at sea or on land. To be successful educators must learn the science necessary to effectively use the curricula, and scientists must understand teachers' needs. Those collaborations cannot be an afterthought; they must be fully integrated throughout the process of ocean exploration. Informing government officials about program plans and accomplishments is critical to any large, federally funded program, and it will be important for all countries involved. This will require additional activities beyond those designed to reach the general public.

Recommendation: Strong education and outreach programs with global applications should be incorporated into any exploration program to bring new discoveries to the public, enfranchise the global community in ocean exploration, and develop and foster collaborations among scientists and educators in ocean exploration.

Ocean exploration provides rich content that easily captures the imagination of people of all ages. Any ocean exploration effort should seek to:

- bring new discoveries to the public in ways that infuse exploration into their daily lives and capture the inherent human interest in the ocean;
- enfranchise the global community in ocean exploration; and
- develop and foster collaborations among scientists and educators in ocean exploration.

Strong education and outreach programs with global applications should be incorporated into the exploration program. Capacity building—not only to multiply the program's usefulness, but also to develop and conduct international ocean exploration—must be integral to national and international ocean exploration programs.

Successful cooperation between educators and scientists relies on educators learning the science necessary to effectively use the curricula, and on scientists understanding teachers' needs. Educator-scientist partnerships could be accomplished through professional organizations (examples in the United States include the National Science Teachers Association, the National Marine Educators Association, and the American Geophysical Union) or through other model programs, such as the Centers for Ocean Science Education Excellence created through NSF, and the Bridge program (Virginia Institute of Marine Science, 2003) of NOPP. Professional development opportunities that immerse teachers in the world of scientific investigation can support the development of inquiry-based, standards-based educational materials and products. Educators and students, where appropriate, and science writers, artists, journalists, and others could participate in expeditions or shore-based activities, and postproject lesson plans could be developed by scientists and educators from the data collected.

Finding: In a large scale, international ocean exploration program, capacity building can serve to enlist additional countries in the efforts, increase the resources (e.g., trained personnel) available for future work, and aid partner nations in good stewardship of our shared oceans.

Recommendation: National exploration programs should strengthen participation in international exploration through exchange programs for scientists and educators from different countries and through training programs for educators who are preparing to set up exploration-

based programs in their own countries. All materials and resources developed or collected through the ocean exploration program should be archived to document the history of collaborations among scientists and educators involved in ocean exploration.

FINANCIAL SUPPORT FOR AN EXPLORATION PROGRAM

Access and flexibility are necessary to implement an ocean exploration program. Although assets for oceanographic research exist, a new ocean exploration program that seeks to enhance the current efforts, as proposed in this report, will require substantial assets. New oceanographic assets would increase the effectiveness of the program, while minimizing interference with the current research endeavors. Although the specific assets needed should be tailored to the exploration plans, approximations have been generated using previous programs and existing equipment.

Recommendation: To undertake a truly large-scale, ocean exploration program that would incorporate the disciplines discussed in this report, a specialized, dedicated flagship, and a modest fleet of underwater vehicles should be provided. Such a program would require first-year funding of approximately $270 million. Thereafter, annual operating costs would be about $110 million. A more moderate program, operating fewer assets, could be operated for approximately $70 million annually.

The scope of the proposed exploration program for the oceans will depend on annual funding. An important new ocean exploration program can be undertaken at various levels, and estimates of the return on that investment should be made accordingly. If funds are limited, the theme areas the program seeks to address should be scaled back; apportionment of program initiatives should prevent sacrifices of postcruise data analysis and data bank maintenance and support. In any such initiative, the input of the research community should be sought to assist in identifying necessary trade-offs. The proposed exploration office should be responsible for implementing program activities and operations—congressional earmarking can obstruct program integrity and success. With broad, interdisciplinary involvement, open forums for discussion of program goals and choices, and accountable management of the program, a large-scale, international ocean exploration initiative is likely to succeed in providing economic, scientific, and environmental benefits for all.

Recommendation: Especially at the lower levels of funding presented in this report, the efficient, effective use of resources must be ensured and should involve the following:

- **decision-making should be informed by the research community, program managers and administrators, and legislators; and**
- **a clear statement of program goals must be used to drive the choices of capitalization.**

SUMMARY

A large-scale ocean exploration program should be initiated. An extraordinary leap in our understanding of the functioning of the oceans and their role in global climate and life support systems is likely. International partners should be sought to share in the costs and benefits of the program.

The ocean is a critical component of the planet's biodiversity and a crucial vehicle for developing new understanding of biological, geological, chemical, and physical processes, both here on Earth and throughout the cosmos. However, public awareness of the oceans' significance to the planet is extremely limited. "[The American public possesses] only superficial knowledge of the oceans, their functions, and their connection to human well being," according to a survey by the Ocean Project, a consortium of aquariums; zoos; and science, technology, and natural history museums (Belden et al., 1999).

Although more than 1,500 people have successfully climbed Mount Everest, more than 300 men and women have journeyed into space, and 12 men have walked on the moon, only 2 people have descended and returned in a single dive to the deepest parts of the ocean, and they spent less than 30 minutes in the cloud of sediment on the ocean bottom. Those numbers are indicative of humanity's instincts to chart the unknown. Every year, new technologies become available to help us probe our oceans in new ways. At the same time, our living marine resources are in danger from harm by overuse, the climate of our planet is changing, and the need for cures for human suffering is as great as ever. A global ocean exploration program that encompasses all of those facets—opening new areas of inquiry and solving problems—is feasible and justifiable and should be vigorously pursued.

1

Introduction

The oceans are our common global heritage. They cover 70 percent of the Earth's surface, regulate our weather and climate, and connect the people of many nations. The oceans sustain a large portion of Earth's biodiversity, and they provide humanity with substantial living and nonliving resources. The oceans still conceal artifacts that document human civilizations' relationships with the seas and with one another. Histories of trade routes, coastal civilizations, and maritime technology can be found within the oceans.

Despite our intimate connection with the sea much of the world's oceans and ocean floor remain unexplored.[1] This is the last frontier on Earth—and the potential for discovery is largely untapped. Discoveries made in the past three decades offer exciting economic and scientific opportunities, and they speak to the need to continue expeditions in search of the unknown (Watkins, 2002). For example, in 1976 organisms, including crabs and clams, were discovered at the Galapagos Rift hydrothermal vent field by a geologist conducting the first photographic survey of the region (Lonsdale, 1977; Weiss et al., 1977; Spiess et al., 1980). Maps and photographs lead to manned submersible dives the following year, and the discovery of massive tube worm colonies. Those unique chemosynthetic life forms were photographed inadvertently, but knowledge of their existence has revolutionized our understanding of where and how life occurs and intensified our discussions of the possibility of life on other planets (Rothschild and Mancinelli, 2001). The vent communities also provide new materials for use in biomedical research. Exciting archaeological discoveries of vessels, pottery, and even ancient coastal villages are shedding new light

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[1] Some estimates suggest about 95 percent of the world's oceans and 99 percent of the ocean floor are unexplored (National Oceanic and Atmospheric Administration, 2000).

on human history. Exploration of the oceans must continue—not only to discover new phenomena and seek new information, but also to facilitate a more integrated and comprehensive understanding of the marine environment and the interconnected processes that control it.

As defined by the President's Panel on Ocean Exploration (National Oceanic and Atmospheric Administration, 2000), exploration is discovery through disciplined, diverse observations and the recording of findings. Ocean exploration has included rigorous, systematic observation and documentation of the biological, chemical, physical, geological, and archaeological aspects of the ocean in the three dimensions of space and in time. This definition of exploration is much broader than the definition one would find, for example, within the context for the extractive industries, where exploration is a search for hydrocarbon or mineral deposits. More general approaches allow researchers to develop and ask questions that are not rooted in specific hypotheses and that often lead to unexpected answers—a difficult task to promote within the current approaches to research funding.

Exploration is an early component of the research process; it focuses on new areas of inquiry and develops descriptions of phenomena that inform the direction of further study. It is the collection of basic observations that later allow hypotheses to be posed to connect those observations with the laws of physics, chemistry, and biology. In some disciplines, such as physics, exploration has been pursued aggressively, and the resources are best invested in testing hypotheses and conducting controlled experiments. In other disciplines, the system under investigation is so vast, complex, or remote that exploration is still the necessary first step. Outer space, the human genome, and the oceans are excellent examples. This nation and others have invested heavily in the exploration of outer space and the functioning of the human genome, and each program has both captured the imagination of the public and produced tangible, valuable discoveries. No similar systematic program exists for ocean exploration, despite its promise.

In June 2000, a panel of experts from the ocean science community was convened to fulfill a presidential request to provide recommendations for a national ocean exploration strategy (National Oceanic and Atmospheric Administration, 2000). In October, the President's Panel on Ocean Exploration recommended that the United States add a national program of ocean exploration to its current marine research portfolio (National Oceanic and Atmospheric Administration, 2000). That program would provide the opportunity to explore the Earth's oceans through broad-based observations and through interdisciplinary and cross-cultural investigations. The panel's vision was to "not only go where no one has ever gone, but to 'see' the oceans through a new set of technological 'eyes,' and record those journeys for posterity" (National Oceanic and Atmospheric Administration, 2000).

In December 2000, the U.S. Congress requested that the U.S. National Academy of Sciences conduct a study to examine the possibility of developing and implementing an international ocean exploration program. An ad hoc study committee was formed under the advisement of the National Research Council's (NRC) Ocean Studies Board to address the charge (Box ES.1).

This report constitutes the work of the NRC's Committee on Exploration of the Seas, and it contains recommendations for the implementation of an international ocean exploration program. International input was sought during a May 2002 workshop, which was hosted by the Intergovernmental Oceanographic Commission (IOC). Participants representing national and international organizations from 22 nations addressed the committee and discussed ideas for an international program. Summaries of the workshop sessions are included in the report as Appendix D.

HISTORY OF OCEAN EXPLORATION

People have explored the oceans since the dawn of human history, even as we used oceans as highways to new lands. Scientific exploration of the oceans can be traced back at least to Captain James Cook's three Pacific expeditions between 1768 and 1779. At that time, most of the globe was unexplored and maps were drawn as much from imagination as from experience. By the time Cook died, he had mapped much of the Pacific's shoreline—from Antarctica to the Arctic.

Cook's explorations opened the way for Darwin's voyages on the *Beagle* (1831-1836). The scientific bonanza from Darwin's observations, which led to his theory of evolution, was the consequence of including a naturalist on the expedition, almost as an afterthought. The influence of discovery associated with those expeditions is nearly impossible to overestimate in terms of science and popular culture alike.

The first expedition undertaken purely for the sake of science was the voyage of the RMS *Challenger* (1872-1876), which set out to investigate "everything about the sea" (Figure 1.1). The researchers made physical, chemical, biological, and geological measurements in all the oceans except the Arctic. With support from the British Admiralty and Royal Society, the expedition systematically collected observations of the oceans, stopping every two hundred miles. The results were staggering: they filled 50 volumes (Murray, 1895). The researchers discovered thousands of new species, and

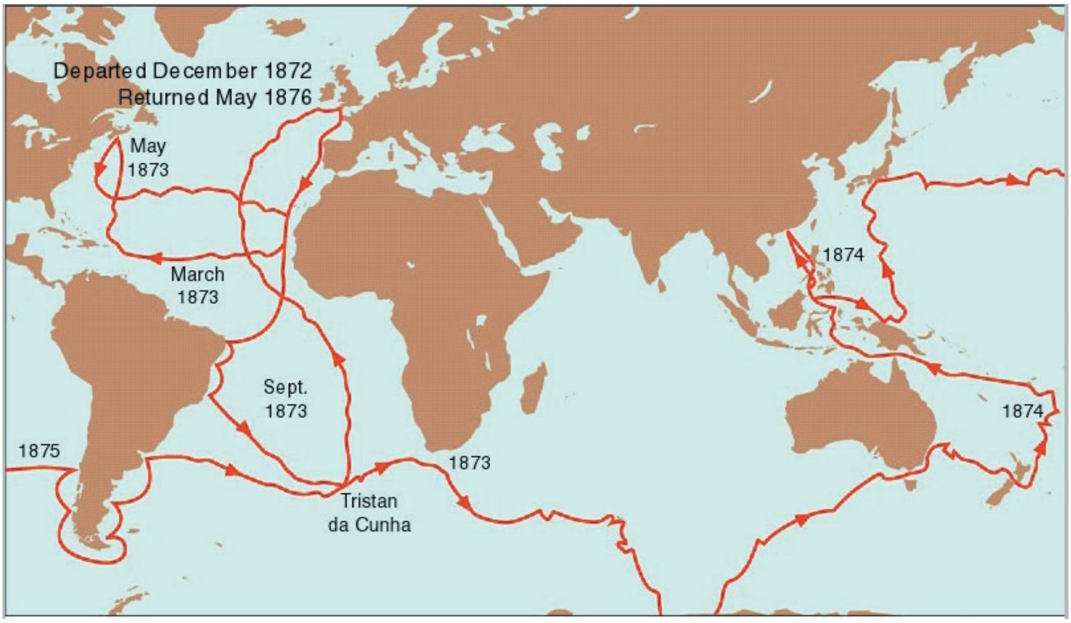

FIGURE 1.1 Expedition route of HMS *Challenger*. (From *Oceanography: An Invitation to Marine Science* (Non-Info Trac Version) 4th edition by Garrison. © 2002. Reprinted with permission of Brooks/Cole, a division of Thomson Learning: www.thomsonrights.com, fax 800-730-2215.)

they observed that the oceans are not deepest at the middle and that ocean sediments are far more homogeneous than are those found on land.

The 1925-1927 *Meteor* expedition, undertaken by the German navy, was one of the first modern oceanographic research cruises. The *Meteor* traversed the South Atlantic 13 times, collecting 67,400 soundings and detailed current, salinity, temperature, and oxygen measurements at 310 stations. The *Meteor* conducted plankton tows, collected a large number of bottom samples, and executed systematic atmospheric (using instrument balloons and kites) and geologic studies. The expedition captured the imagination of people around the world, demonstrating conclusively the power of ocean exploration for educating the public.

The economic depression of the 1930s stifled opportunities to follow up on the success of the *Meteor* expedition. During World War II, the value of oceanographic information assumed new importance with the advent of submarine warfare, and national security drove data-gathering efforts. With the exception of participants in the International Decade of Ocean Exploration (IDOE) broad international cooperation was not encouraged in the Cold War years, and the best data were not often made freely available.

The landmark achievements of oceanographic exploration over the past 50 years have been well documented in NRC's *50 Years of Ocean Discovery: National Science Foundation 1950-2000* (National Research Council, 2000a), and are not reiterated here with the exception of those activities that represented efforts to achieve international cooperation because those efforts informed the committee's deliberations on the proposed organization and structure of a new international exploration program.

The International Geophysical Year (IGY; 1957-1958) was a significant step for the improvement of international cooperation on large-scale oceanographic projects and other studies of the physics of the planet. Observations collected during IGY resulted in several breakthroughs, including the body of work that led to the formulation of the theory of plate tectonics.

One visible program that resulted from international cooperation during IGY was the Indian Ocean Expedition. The Indian Ocean was the least explored of the world's oceans, and it held much promise for major discoveries. Advice and ideas from 40 scientists representing a variety of nations and all oceanographic disciplines were used to develop the program. Originally, planning and direction were accomplished by a contract with the National Academy of Sciences, but beginning in 1964 the National Science Foundation (NSF) managed the program. The scientific community continued to provide program direction. Loose coordination among the three major oceanographic institutions (the Lamont-Doherty Earth Observatory of Columbia University; the Scripps Institution of Oceanography in La Jolla, California; and the Woods Hole Oceanographic Institution in Massachusetts) resulted in disparate data sets. Because the data gathered on different cruises by different research groups could not be integrated, the usefulness of the resulting databases was severely compromised.

Nautical Archaeology

Archaeologists uncover information on ancient civilizations, and marine archaeologists examine sunken communities or ships for tools, pottery, and cargo, for example, that can reveal details about a culture. Marine archaeology was slower to develop than the ocean sciences. Despite the sustained efforts of archaeology generally, marine archaeology has been hampered by the difficulty of locating and excavating sites. Underwater archaeology dates to the late 1800s, and from the beginning the field relied on advances in technology to improve identification of and access to sites. From diving bells to tethered diving helmets, each new contraption increased the amount of time divers could spend under water. But it was not until the advent of the self-contained underwater breathing apparatus—SCUBA—in the middle of the twentieth century that ready access to shallow ocean bottoms could be achieved. Scuba allowed the systematic excavation of sites, and it allowed divers to complete delicate work in fragile ships' hulls. In the 1960s archaeologists began to dive to direct true excavations of underwater relics, and the field of underwater archaeology soon became one of the most important branches of its field.

International Decade of Ocean Exploration

For the purposes of this report, the most significant modern precursor to the proposed program in ocean exploration was IDOE (1971-1980). This systematic program of ocean exploration was motivated both by anticipated uses of marine resources and by scientific curiosity. Questions about the health of the world's oceans led scientists to argue for systematic baseline surveys that were not possible from randomly spaced observations. The IDOE program, a good example of exploration, which was established as a result of the congressional Marine Sciences Act of 1966, reflected the view that exploration of the ocean required a sustained global effort with international participation.

Justification for IDOE was based on the oceans as a source of food for an expanding world population; maritime threats to world order; waterfront deterioration in coastal cities; increased pollution in coastal areas; expanding requirements for seabed oil, gas, and minerals; and expanding ocean shipping. The National Academies of Science and Engineering involved the U.S. marine science community in planning IDOE. The resulting report, *An Oceanic Quest: The International Decade of Ocean Exploration* (National Academy of Sciences, 1969), specified science and engineering programs and resources needed to address goals. The stated objective of the program was "to achieve more comprehensive knowledge of ocean characteristics and their changes and more profound understanding of oceanic processes for the purpose of effective utilization of the ocean and its resources." More specifically, it was expected that the program would help increase the yield from ocean resources, improve predictions of and responses to natural phenomena, and protect or improve the quality of the marine environment.

Some important features distinguished the IDOE programs from other marine science initiatives of the day. At that time, cooperation between

U.S. and foreign investigators was unique. The emphasis on long-term and continuing studies required resources from several groups, and partnerships between government and private parties in the United States evolved. A steering committee was formed to develop and refine criteria for the proposed programs. Keystone programs—among them the Mid-Ocean Dynamics Experiment, for the exploration of physical oceanographic eddies, and Climate: Long-range Investigation, Mapping and Prediction (paleoceanographic mapping of global temperatures at the last glacial maximum)—were called for in the NRC report. The Geochemical Ocean Sections (geochemical mapping of the oceans) program was brought into IDOE after it was developed independently.

NSF was responsible for planning, management, and funding of IDOE, initially with a budget of $15 million. IDOE began as an office in NSF's Division of National and International Programs, separate from the research program that contained ocean and earth sciences. When NSF was reorganized in 1975, IDOE, the NSF oceanography section, and the oceanographic facilities and support section were combined to form NSF's Ocean Sciences Division. A working group was established at NSF that consisted of program managers and members of the research community. The IDOE working group set the ground rules for IDOE funding, one of which was that projects had to be multiple-institution initiatives. Although the working group did not try to promote specific science goals, it did encourage projects that fell into one of four categories: environmental quality, living resources, seabed assessment, or environmental forecasting (National Research Council, 1999).

One important force behind the adoption of IDOE was the advocacy of Vice President Hubert Humphrey (Wenk, 1972). With his support, the U.S. Marine Council successfully sought and secured commitments from other nations, and in 1968, the IOC of the United Nations Education, Scientific, and Cultural Organization recommended support for IDOE. United Nations support for the program was obtained in Proposition 3 of General Assembly Resolution 2467 (XXIII), which was cosponsored by 28 nations. This resolution ensured government-to-government support for the program.

The Marine Council and the NRC report called for significant participation in IDOE by other federal agencies. In the first year, it became clear that such an arrangement was unworkable. Each agency had its own mission, which did not necessarily coincide with the kinds of projects identified for emphasis by IDOE program managers. Proposals from agency scientists did not fare well in peer review because the scientists often were unfamiliar with the process and were unknown to academic reviewers. Program management was another challenge. Even when an IDOE objective fell squarely within the mission of a given agency, funding procedures, management style, and long-range research objectives became obstacles. In the first year of the program, half of the funds were transferred from NSF to other federal agencies, with few tangible results. The one exception was the North Pacific Experiment for environmental forecasting, because it addressed the Office of Naval Research's interests directly. Over time, the North Pacific Experiment was jointly funded by the Office of Naval Research and IDOE, with close coordination of managers from both agencies.

International participation did not materialize to the desired extent because other nations were not able to organize themselves as quickly as the United States had done. The U.S. IDOE submitted annual plans and programs to IOC and received the endorsement of member states. Nevertheless, scientists from other countries did not receive financial support in a timely manner. IOC had little funding for international participation, and U.S. IDOE funds could not be used to support scientists from other nations. Two international programs created through bilateral agreements were exceptions: the French-American Mid-Ocean Undersea Study and the U.S.-U.S.S.R. follow-on to the Mid-Ocean Dynamics Experiment, which was truly cooperative in planning and execution (National Research Council, 2000a). The French-American Mid-Ocean Undersea Study, which was to conduct a detailed exploration of a section of the Mid-Atlantic Ridge, was already in the planning phase when IDOE was established, and it was carried out jointly by the two nations during the early years of the program.

Despite some criticisms that international participation could have been more robust, IDOE is considered a major success. It provided the observational database on the physics, geochemistry, paleoceanography, biology, and geophysics of the ocean that fueled hypothesis-driven research for decades. The oceanographic research community recognized the achievements that were possible only through large, multidisciplinary, cooperative programs. When IDOE ended, program funding remained at NSF and was redistributed into the research sections along the disciplinary lines of the major physical, chemical, geological, and biological programs within IDOE. The research community proposed important follow-on programs, such as the Ridge Interdisciplinary Global Experiments, an initiative to study the midocean ridges and hydrothermal vent ecosystems, and the Joint Global Ocean Flux Study, a geochemical follow-on to the Geochemical Ocean Sections. However, none of these programs embraced the interdisciplinary emphasis on exploration that had been envisaged for IDOE.

LESSONS FROM EARLIER OCEANOGRAPHIC PROGRAMS

Discussions in past NRC reports (National Research Council, 1999, 2000a), the capsulated summary of the Indian Ocean Expedition, and experiences of the members of the Committee lead to the following finding.

Finding: A new era for ocean exploration should build on lessons from earlier experiences. Primary among them are the following:

- **A program (IDOE) housed entirely within one agency (NSF) can have difficulty engaging other federal agencies as partners in exploration.**
- **An exploration program entirely within a mission-oriented agency can have difficulty remaining independent from the agency mission.**
- **A program that sets out long-term goals and priorities, but that selects proposals for funding by a competitive process, can be quite successful.**
- **Decadal achievements can be significant, but there is a need and a demand for a more sustained effort.**
- **Bilateral, international efforts are more likely to be successful in joint planning, funding, and execution than are large-scale international programs, but they require careful planning and tailoring of projects to the interests of the partners.**
- **Coordination is essential to ensure that data sets from different projects can be integrated into a global picture.**

EXPECTATIONS FOR A GLOBAL OCEAN EXPLORATION PROGRAM

Progress in oceanography over the next decade will occur both in the traditional marine science disciplines and, as this report will show, through ocean exploration at the fringes and intersections of those disciplines. Multidisciplinary ocean exploration will most likely lead to discoveries that might refocus basic research regarding the oceans' contributions to global climate change, the hydrodynamics of midocean ridges, and the nature of coastal processes. New international collaborations, with new capabilities in technology, should be combined to maximize discoveries and benefits from a large-scale ocean exploration effort.

The ocean provides physical and cultural connections for people from many nations. An ocean exploration program could open a dialogue to increase public awareness of the oceans as a common global bond, highlighting the importance of the oceans in their lives. Exploration presents a spirit of challenge and rich opportunities to engage students, educators, and the public in the excitement of search and discovery through the pursuit of knowledge about our planet and our people.

ORGANIZATION OF THE REPORT

This report is organized into eight chapters and a series of appendixes. Chapter 2 describes the benefits of initiating a global ocean exploration program, and Chapter 3 presents recommendations for broadly defined and specific goals of a new international ocean exploration program. Areas of particular promise are emphasized for the early phases of a new program. Chapter 4 discusses international arrangements, and Chapter 5 presents discussion and recommendations for a new program's domestic structure. The existing technology and infrastructure that might be applied to a global effort are presented in Chapter 6, and developing technologies are identified. In Chapter 7, outreach, education, and capacity building are discussed. Proposed funding is discussed in Chapter 8 to provide readers with the committee's best estimate of costs for equipment, center operations, and staff support. Appendix C includes the agenda and list of participants for the International Global Ocean Exploration Workshop, and Appendix D is the summary of the workshop presentations and discussions. A list of oceanographic and fishery vessels of the world fleet is presented in Appendix E to introduce current global capacity for shipboard ocean research. Details of each ship are limited, however, and the seaworthiness of some vessels is not established. Appendix F is a list of international autonomous underwater vehicles.

2

Justification for a New Ocean Exploration Program

The ocean supports us—whether we live in land-locked or coastal communities—in myriad ways. Living resources provide food, and exploration of marine biological and chemical diversity has led to the discovery of drugs to treat cancer and infections. Oil and natural gas extracted from the oceans have already been used to meet much of the energy needs of our societies. With the application of new technology to locate, extract, and exploit potential ocean resources, such as methane hydrates, renewable ocean energy, and seafloor minerals, the value of the oceans to society will continue to expand.

Improved understanding of the oceans is necessary to better manage our living marine resources. The oceans provide a very large portion of Earth's food supply (Figure 2.1; Food and Agriculture Organization of the United Nations, 1998). The Food and Agriculture Organization of the United Nations estimated capture fisheries (primarily marine) produced 83 million metric tons of fish in 2001. Approximately 16 kg (or 36 pounds) of fish per person on Earth were either captured or produced in that year. Appropriate fisheries management depends a great deal on knowledge of fish stocks, distribution, and life histories. Additional information about ocean circulation patterns, chemistry, seafloor terrain and fish distributions, for instance, should assist attempts to improve fisheries management.

Marine organisms also supply a host of unique compounds for medical uses. The ancient horseshoe crab (*Limulus polyphemus*) supplies blood used in common toxin-screening tests, and its eyes continue to provide researchers with a model of how vision works. The nerve cells of the long-finned squid (*Loligo pealei*) include "giant axons" that are used by neurobiologists as an analogue to understand mammalian neurobiology. These cells are approximately 100 times the diameter of a mammal axon, allowing experimentation and analysis that would otherwise be exceedingly difficult or impossible. *Discodermolide*, a compound extracted from marine sponges,

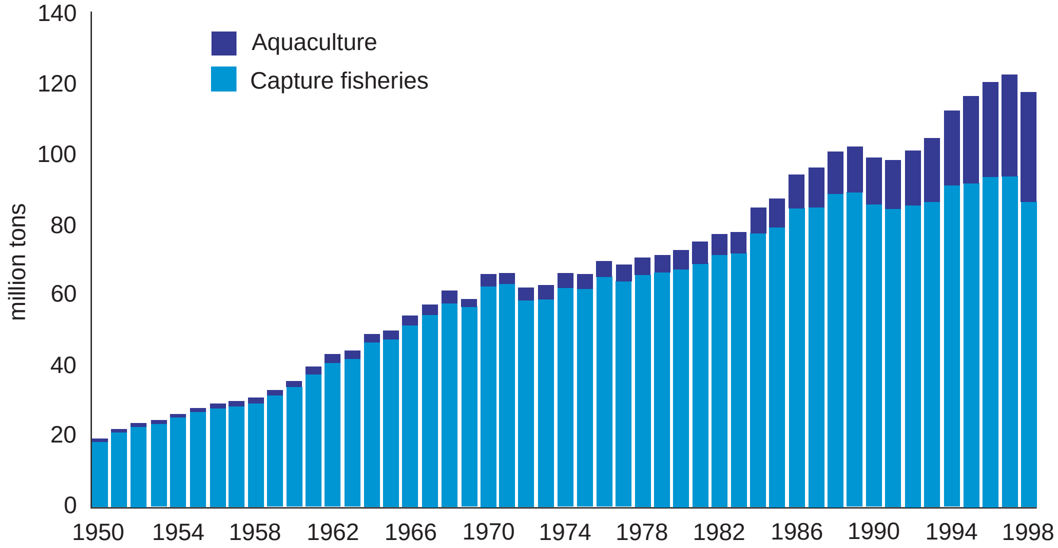

FIGURE 2.1A World capture fisheries and aquaculture production (used with permission from the Food and Agriculture Organization of the United Nations). Note: Aquaculture quantities prior to 1984 are estimates.

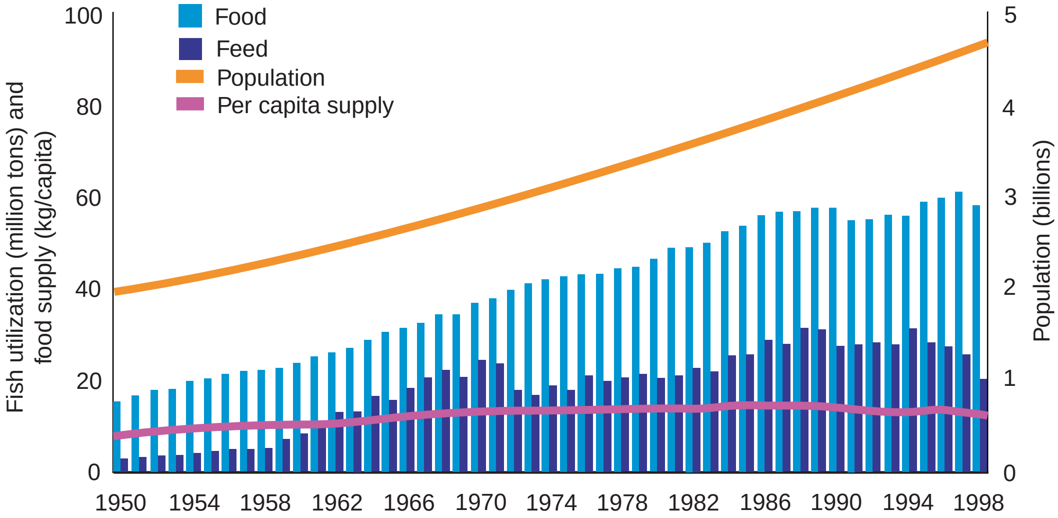

FIGURE 2.1B World fish utilization and supply, excluding China (used with permission from the Food and Agriculture Organization of the United Nations).

has been shown to stop the growth of cancer cells in laboratory tests. The discovery of microorganisms within deep ocean sediments that could inhibit cancer cell growth has opened a door to the search for new compounds for use in medicine (Figure 2.2) (Mincer et al., 2002; Feling et al., 2003). These examples are among the hundreds of uses for marine organisms and compounds. Vast numbers of organisms remain to be discovered, and they will yield additional important benefits for humankind. Responsible exploitation of the genetic diversity of life in the ocean, including new and existing fisheries, requires a thorough understanding of those resources and their variability over time.

As the human population expands, so will the need for energy and mineral resources. In 2002, the coastal zones of the United States provided 25 percent of the country's natural gas production and 30 percent of the U.S. oil production (Minerals Management Service, 2003). The Minerals

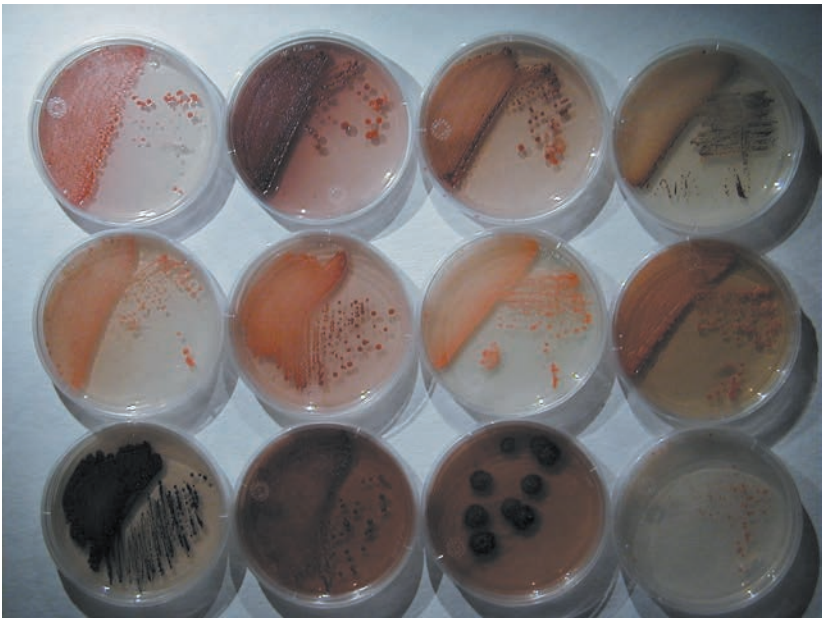

FIGURE 2.2 Twelve different strains of the microbial group *Salinospora*. These newly discovered microorganisms, which inhabit the mud at the bottom of the sea, produce new antibiotics and anticancer agents that are believed to be a completely new source of new drugs (used with permission from W. Fenical).

Management Service estimates the majority of undiscovered gas and oil is in coastal areas albeit in deeper and deeper water on the continental slope.

The oceans sustain a large portion of Earth's biodiversity in complex food webs; microbial life; extreme, deep habitats including within the seafloor, and hydrothermal vents; and dynamic coastal environments. Indeed, the midwater environment of oceans harbor an ecosystem whose biomass is larger than that of the terrestrial biota. The complex biological systems both rely on and support the global cycling of carbon and nutrients, and they are estimated to sustain half of all carbon-based life on this planet (Figure 2.3; Field et al., 1998).

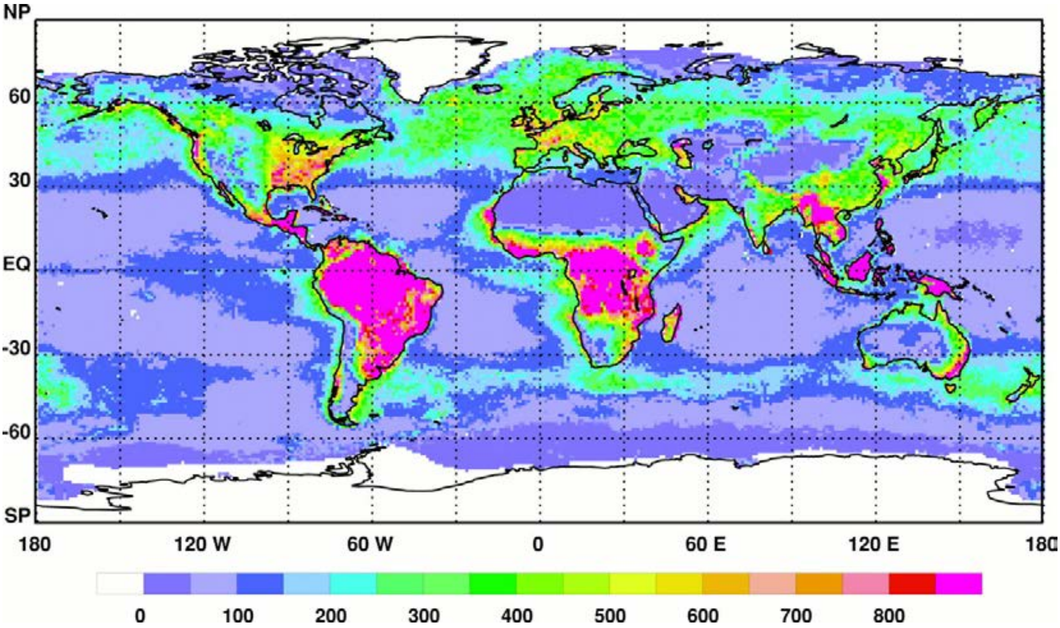

FIGURE 2.3 Global annual net primary productivity (in grams of carbon [C] per square meter per year) for the biosphere, calculated from the integrated Carnegie-Ames-Stanford Approach-Vertically Generalized Production Model. The spatial resolution of the calculations is 1 x 1 for land and 1/6 x 1/6 for the oceans. Input data for ocean color from the Coastal Zone Color Scanner sensor are averages from 1978 to 1983. The land vegetation index from the Advanced Very High Resolution Radiometer sensors is the average from 1982 to 1990. Global net primary productivity is 105 picograms of C per year (105 x 10^{15} g of C per year), with 46 percent contributed by the oceans and 54 percent contributed by the land. (Reprinted with permission from Field et al., 1998. Copyright 1998 American Association for the Advancement of Science; http://www.sciencemag.org.)

Appreciation for the role of the oceans in global climate patterns and change continues to grow (Sutton and Allen, 1997; Rahmstorf, 2002). The oceans regulate climate by absorbing solar energy and redistributing it via global circulation patterns resulting in identifiable systems of climate and weather. Our knowledge of interannual climate variations has improved to the point that scientists are now be able to forecast El Niño climate disturbances months in advance (Chen, 2001).

With all of the benefits the oceans provide come potentially harmful—sometimes disastrous—hazards to human health. Tsunamis, for example, are legendary in their power to devastate coastal communities (e.g., Satake et al., 1995). In the United States, a single hurricane can cause billions of dollars of damage (Figure 2.4; Federal Emergency Management Agency,

FIGURE 2.4 Damage from Hurricane Andrew that occurred in Florida on August 24, 1992. Many houses, businesses, and personal effects suffered extensive damage from one of the most destructive hurricanes ever recorded in the United States. One million people were evacuated, and 54 died in this hurricane.

2003), and coastal erosion threatens to destroy 25 percent of dwellings within 150 m of the coast (Heinz Center, 2002). Major earthquake faults offshore coastal states in the western United States are among the most potentially hazardous in the world given the concentrations in population and economic productivity. Although more difficult to estimate in monetary terms, water pollution and marine habitat degradation decrease the aesthetic value and the biotic richness of our coastal waters. Habitat degradation also threatens human health: viruses, bacteria, and infectious diseases that can be transmitted to human populations contaminate coastal waters (National Research Council, 1999).

Finding: The oceans play a critical role in the maintenance of the ecosystems of the Earth. Resources contained in the oceans currently supply much of the world's food and fuel supply, and maintain global climate patterns. The oceans harbor as yet undiscovered organisms—new searches for life continue to discover previously unknown organisms. Only a portion of the potential of the oceans has been tapped.

Recommendation: As was true when the International Decade of Ocean Exploration (1971-1980) was proposed and supported, ocean exploration remains a necessary endeavor to identify and fully describe the resources the oceans contain and uncover processes with far-ranging implications for the study of Earth as a whole. The pace at which we discover living and nonliving resources and improve our understanding of how the oceans respond to chemical, biological, and physical changes must increase.

INTERDISCIPLINARY EXPLORATION IS NEEDED

Every time a scientist happens upon some completely unexpected discovery in the ocean, it is a reminder of how little is known about this environment that is so critically important to the sustainability of the planet. We now recognize that different facets of the ocean—small-scale geological, biological, and genetic diversity; chemical, geophysical, and physical oceanographic properties—interact in complex ways, and our understanding of the ocean requires examination as a whole system. It is difficult to predict what discoveries are still to come, but it is clear that ocean exploration will improve the accuracy of our predictions of global climate change, produce new products that will benefit humanity, inform policy choices, and allow better stewardship of the oceans and the planet. To reach this potential, ocean research should encourage collaboration between researchers from varied disciplines.

> **Finding: Currently ocean science funding in the United States is predominantly awarded to research in specific disciplines, such as biological, physical or chemical oceanography. Proposals for interdisciplinary work are hampered by a funding bureaucracy that is also discipline-based. Ocean exploration is an integrative activity that will encourage and support interdisciplinary efforts that seek to discover new contributions to the marine sciences.**

ACCESS TO NEW REGIONS IS NEEDED

Successful marine science proposals habitually pursue information about regions, areas, and phenomena that have been described previously. For instance, repeated visits to unique sites, such as the hydrothermal vents of the spreading seafloor ridges, have allowed repeated sampling of both the vent systems and sites along the cruise track. Although the data sets have improved our understanding of ocean processes and dynamics, this "yo-yo" phenomenon is the result of selective funding for research proposals that build on established data sets and access vessels already scheduled—not exploratory investigations of new systems. Similar data collected outside of these focused study areas are extremely rare. The current ocean research support framework does not favor such exploratory proposals.

Highlighting this emphasis on previously-visited regions is the compilation of requests for access to the U.S. fleet of research vessels filed with the University-National Oceanographic Laboratory System. A summary of all vessel requests from 1998 through those filed for 2008 shows a strong emphasis on the coastal regions, with large tracts of the open ocean, particularly the southern hemisphere, largely uninvestigated (Figure 2.5A). In fact, the majority of the vessel requests for the southern hemisphere have yet to receive research funding, and are proposed for 2004 and beyond—few U.S. research cruises have been conducted in those regions (Figure 2.5B). Of the funded cruises, even fewer have been equipped with *Alvin* or a remotely operated vehicle (Figure 2.5C).

Vast portions of the oceans have not been systematically examined for geochemical or biological characteristics. Ground-breaking discoveries, such as hydrothermal vents, fueled intensive investigations of those regions, but it did not lead to systematic, large-scale investigations of new regions. (e.g., the Ridge 2000 program [Pennsylvania State University, 2000]). As is

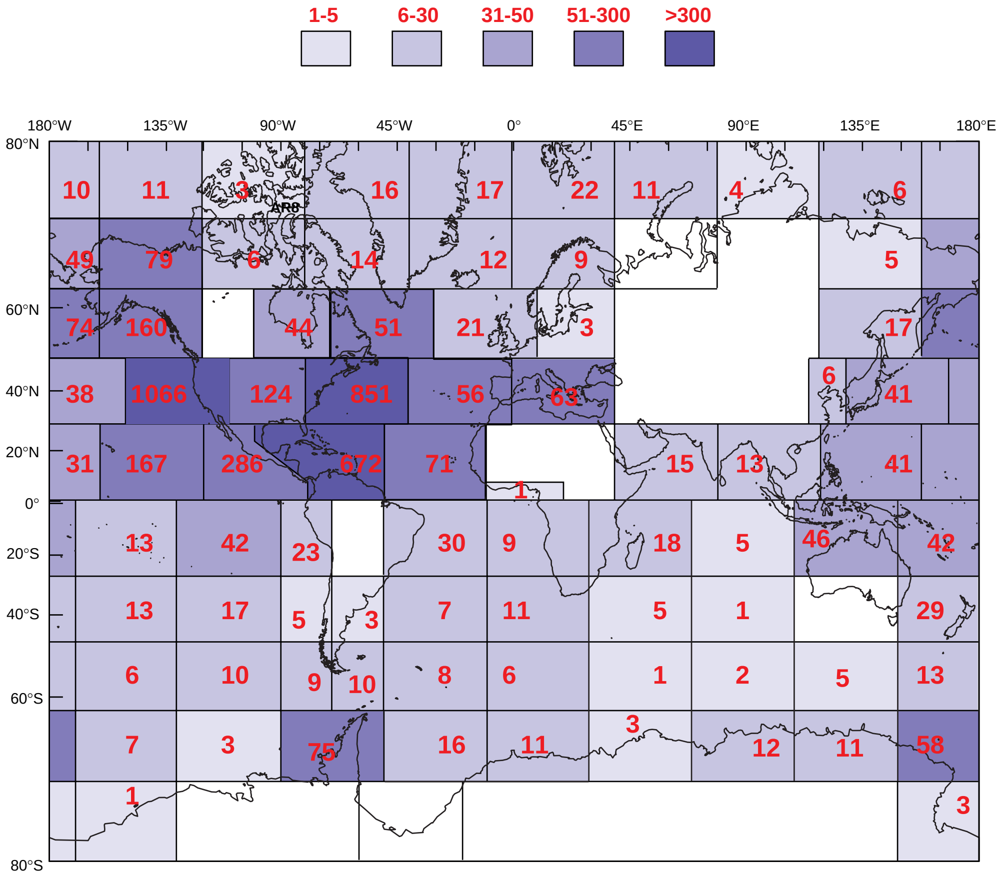

FIGURE 2.5A

FIGURE 2.5 (A) All vessel requests for 1998-2008 showing a strong emphasis on the coastal regions, with large tracts of the open ocean, particularly the southern hemisphere, largely uninvestigated. (B) The number of research cruises that actually have been funded (1998-2003). (C) Funded research cruises that were equipped with *Alvin* or a remotely operated vehicle. (Data obtained from the University-National Oceanographic Laboratory System.)

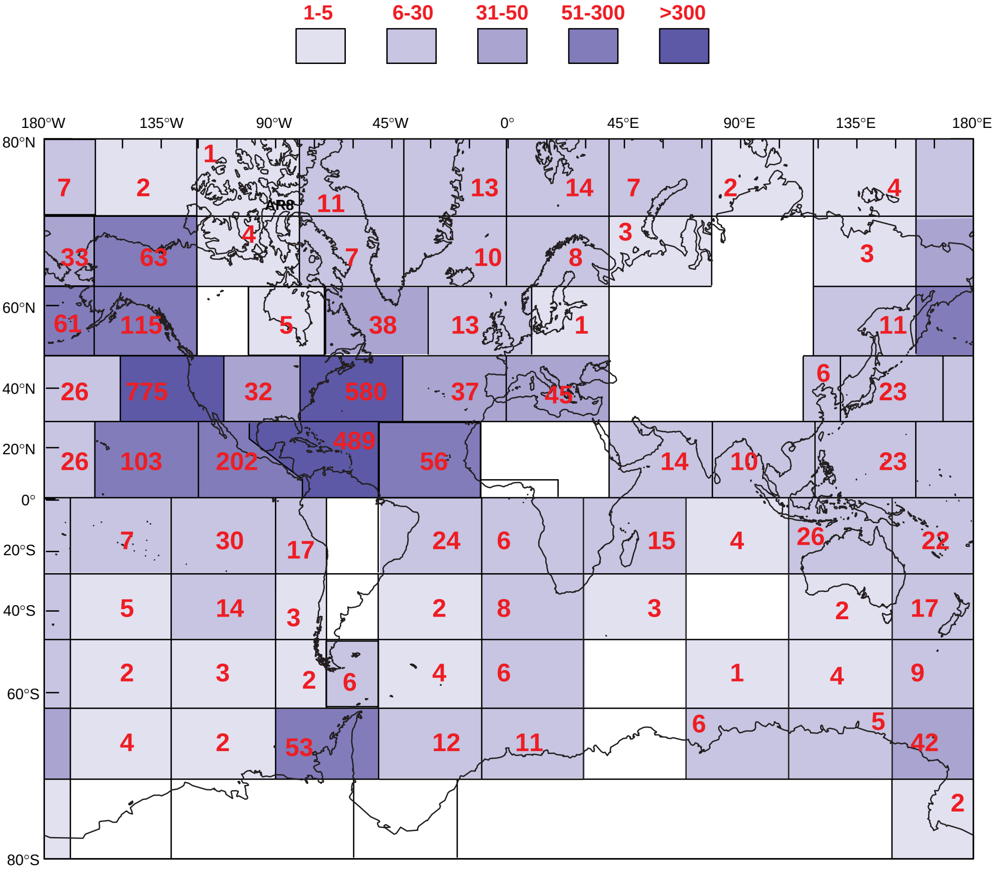

FIGURE 2.5B

being shown by an Australian-New Zealand expedition (National Oceans Office, 2003), systematic biological exploration in even a small portion of the ocean can provide a rich collection of new organisms. This recent effort explored deep sea habitats of the seamounts and abyssal plains and has identified new species and improved our understanding of the distributions of previously-identified organisms. This one month journey collected more than 100 previously unidentified fish species and up to 300 new species of

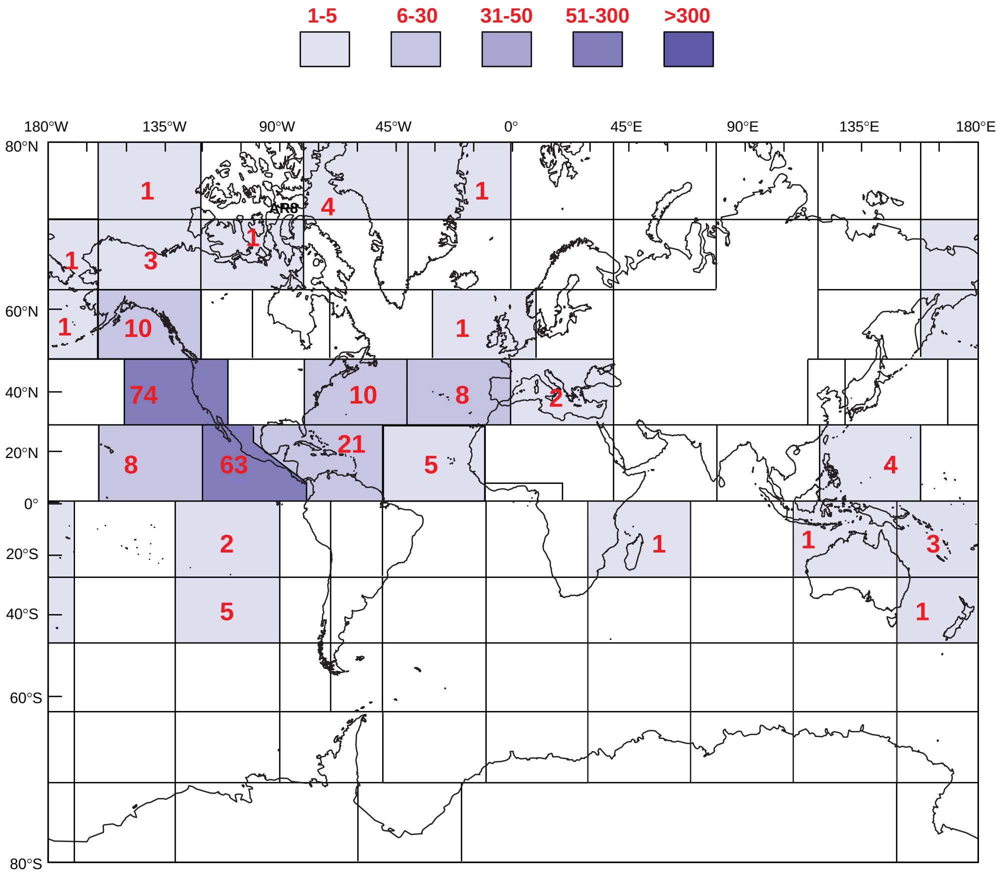

FIGURE 2.5C

invertebrates (Figure 2.6; National Oceans Office, 2003). This type of systematic, organized exploration is not currently under way in the United States and highlights the types of exciting discoveries that the oceans still hold. A very recent, but limited, example of such an exploratory effort by the United States has been initiated by the Department of Energy to investigate the genomic structures of all organisms within an oceanic ecosystem (Whitfield, 2003). Although the Sargasso Sea is thought to exhibit limited

FIGURE 2.6 This is a member of the lantern shark family (*Dalatiidae*), which belongs to a new species recently recognized but yet to be described, was discovered off the coast of New Zealand in May 2003 (used with permission from the National Oceans Office [Aus], the Ministry of Fisheries [NZ], CSIRO [Aus], and the National Institute of Water and Atmospheric Research [NZ]). They are small sharks that range in size from 20 to 80 cm long, and they get their name from the dark patches on the undersides of the belly and tail, which are light organs. The light is made using chemicals to hide the shark's silhouette from predators beneath it.

biodiversity and a simple ecosystem (Holden, 2003), it is anticipated that this work may reveal new pathways of carbon sequestration and hydrogen generation (Whitfield, 2003).

In addition to the regional needs for exploration, ocean research that investigates changes over time is limited. Exploring the fourth dimension—time—has typically not received sufficient attention. Expeditions to new areas for short periods can provide "snapshots" of the state of the ocean, but they are inadequate for explaining change or transient events, many of which pose considerable hazard to humans and our structures. Examples include phenomena such as El Niño, rapid climate change, volcanic eruptions, and earthquakes (National Research Council, 2001).

Finding: The very nature of scientific investigation leads oceanographers to seek out information to verify hypotheses and confirm earlier findings. The infrastructure and support needed for oceanographic work is expensive, limited, and highly scheduled to ensure efficiency in the pursuit of knowledge about the oceans. As a result, much of the oceanographic research currently conducted re-investigates previously visited locations, limiting access to new regions and restricting long-term data collection.

Recommendation: Oceanographic research should encourage scientifically-rigorous, systematic investigations of new sites in the oceans. Exploration through time should be included in oceanographic research.

UNIQUE APPLICATIONS OF NEW CAPABILITIES

The development and adoption of technology and rapid advancement of data processing and storage have been keys in the advancement of ocean science. Inevitably, chance discoveries enabled by new technology have identified useful concepts (Box 2.1). The development of a scalar magnetometer was used in the discovery of plate tectonics and deep-towed vehicles and submersibles led to the discovery of life forms that have chemosynthetic metabolic pathways that are independent of photosynthesis.

Exciting new technologies allow access to regions, and on geographical scales, that the previous generation of oceanographers would not have dreamt possible. Satellites provide a platform for both remote sensing equipment capable of measuring such things as global ocean temperature, and can act as relay stations for real-time data downloading from oceanographic systems around the globe. Increased computer storage enables researchers to compile and store enormous datasets that were previously unimaginable and allow for rapid mathematical and graphical analysis of data. The great leaps in ocean technology over the past 20 years—from remotely operated vehicles to the satellite-based remote sensing systems—now provide access to new locations and should be capitalized on to improve our knowledge of the oceans. Chapter 6 describes many of the existing and new technologies that support ocean research.

The data collected during exploration provide a legacy for research, commerce, education, and regulation. Ocean explorers have an obligation to collect data systematically and to pass their observations along quickly for use by others in ways that could be entirely unforeseen. Freedom of

BOX 2.1 DEEP SEA FUEL CELL

The continental margins contain the Earth's largest remaining source of fossil fuel in the form of methane hydrates. Some 5 to 25 percent of this methane is consumed by microbes in the shallow surface sediments. However, because the habitats generally are anaerobic (lacking free oxygen), it has long been a puzzle how those organisms oxidize methane to provide energy for their life functions. Using samples collected by a remotely operated vehicle from methane seeps near Eel River, California, scientists from the Monterey Bay Aquarium Research Institute, the Pennsylvania State University, and the Woods Hole Oceanographic Institution obtained the first direct identification of the *Archaea* that consume methane near anoxic methane seeps and hydrates. The by-products of this reaction are free hydrogen and carbon dioxide. The process involves a novel symbiotic relationship with sulfate-reducing bacteria that maintain a low enough partial pressure of hydrogen to keep the methane reaction energetically favorable. What is intriguing about this chance discovery is the possibility that the organic process could be used to "mine" deep-sea deposits of methane hydrate, which could be supplied to clean-burning fuel cells in the form of free hydrogen. The process would not exacerbate global warming because the carbon dioxide would remain in the deep sea.

access to data is essential for fostering innovation and the conversion of the investment into scientific discoveries, commercial products, and the development of sound ocean policy. Sampling procedures should be standardized to ensure quality control, and data should be publicly available, insofar as possible, in real time. Although commercial investment can require restrictions to protect proprietary data and to foster development of discoveries, such cases should be regarded as exceptions.

There are aspects, regions, and dimensions of the world's oceans that arguably will not advance in our understanding without a new systematic, coordinated exploration program for collecting the fundamental data from which unifying, predictive theories can emerge. Is there a paradigm that will explain the first-order patterns of biomass or biodiversity in the deep sea based on variations in temperature, nutrient availability, hydrothermal circulation, or other environmental factors? Researchers cannot begin to understand this question now because there are no systematic data sets that allow comparison of different regions. Because of their inaccessibility some regions have been overlooked in the earlier phases of exploration. Little is known of tectonic history or circulation patterns in the Arctic Ocean, for example. Because of the difficulty in mounting expeditions to the Arctic, conducting exploratory research (for example, by collecting systematic observations broadly in all scientific dimensions that can be practically accommodated) is the most cost-effective way to advance our understanding of this region that is so sensitive to climate change.

> **Finding: Rapid progress in ocean sampling devices now allows researchers access to new environments, including the extremes of hydrothermal systems, the seafloor, and waters beneath the ice of the Arctic Ocean. The potential of new technology in satellites, underwater equipment, remote sensing technology, and observing systems has not yet been met.**
>
> **Recommendation: An ocean exploration program should seek to access and encourage new developments in ocean technology.**

A NEW PROGRAM OF OCEAN EXPLORATION IS NECESSARY

Systematic, or coordinated, ocean exploration is not a current practice within the United States. New discoveries about the oceans are often the result of serendipitous circumstances, for instance, the inadvertent discovery of entirely new ecosystems at hydrothermal vents. Exciting discoveries about the oceans occur frequently, but the rate could be greatly enhanced by pursuing new research topics in new regions of the oceans.

A limited national ocean exploration effort has recently begun and is operated through the National Oceanic and Atmospheric Administration. Since 2001, the National Oceanic and Atmospheric Administration's Office of Ocean Exploration has sought to "…explore and better understand our oceans. The office supports expeditions, exploration projects, and a number of related field campaigns for the purpose of discovery and documentation of ocean voyages" (National Oceanic and Atmospheric Administration, 2003a). It is the committee's sense that this fledgling national effort is too limited in scope. The education and outreach efforts are laudable, and the office has made the important step of committing 10 percent of their budget to those activities. However, uncertainty in the annual budgeting process makes long-term planning difficult, and the funding levels to date hover at $14 million. As no future vision for the program has yet been released it is difficult for this committee to determine whether this young program can be adapted to fill the role outlined in this report, but the program has not capitalized on much of the scientific expertise in the United States and relies on heavily leveraging funds and assets against other oceanographic research programs.

Currently the pursuit of ocean data is largely an independent, researcher-driven effort with only scattered attempts at public education. As a largely publicly-funded endeavor, oceanographers have a responsibility to communicate their findings clearly not only to the funding agencies, but to the broader public. Large numbers of people live near oceans and many depend on it for their sustenance or livelihood, but few understand the complexity of the ocean ecosystem or its importance to society. Although efforts to educate the public in both formal and informal settings are increasing through programs such as the National Science Foundation's Centers for Ocean Science Education Excellence program, outreach and education in the marine sciences is largely uncoordinated. Few members of the public appreciate the role the oceans play in our lives, and the relationship between the oceans, atmosphere, and land. Good public policy demands that the public engage in the excitement of ocean research, exploit public interest through education about the wealth and limitations of the ocean, and promote citizen and decision-makers understanding about ocean issues and policy. Chapter 7 discusses some of the outreach and education possibilities in more detail.

Finding: Oceans provide food, energy and mineral resources, products capable of treating human disease, and affect climate and global responses to changes in climate. A new large-scale program devoted to ocean exploration is necessary to:

- **coordinate efforts in ocean discovery and capitalize on the wide array of available data;**
- **provide new resources and facilities for access by researchers;**
- **establish support for and promote interdisciplinary approaches to ocean investigations;**
- **develop outreach and public education tools to increase public awareness and understanding of the oceans;**
- **discover the living and nonliving resources of the oceans; and**
- **provide a multidisciplinary archive of ocean data to serve as a source of basic data upon which to develop hypotheses for further investigation.**

Recommendation: A coordinated, broadly-based ocean exploration effort that meets the highest standards of scientific excellence should be aggressively pursued. An ocean exploration program should be

initiated and exhibit the following characteristics, which can also be used to gauge its ultimate success:

- **The program should be global and multidisciplinary.**
- **The program must receive international support.**
- **The program should consider all three spatial dimensions as well as time.**
- **The program should seek to discover new living and nonliving resources in the ocean.**
- **The program should include developments of new tools, probes, sensors, and systems for multidisciplinary ocean exploration.**
- **The program should reach out to increase literacy pertaining to ocean science and management issues for learners of all ages to maximize the impact for research, commercial, regulatory, and educational benefits.**
- **The program should standardize sampling, data management, and dissemination.**

3

Promising Areas for Ocean Exploration

Ocean exploration is a vast field and the variety of specific discovery plans seems endless. Biological, chemical, geological, physical, and archaeological investigations, and interdisciplinary combinations thereof, are within the purview of an ocean exploration program. Programs also might seek to discover new information about specific regions or ecosystems. Some areas, both geographic and topical, are particularly timely and could return exceptionally valuable discoveries.

Certainly there are important aspects of ocean research that have advanced well beyond the exploratory phase. Important geophysical observations on the shape of ocean basins, the locations of earthquakes, and the variations in seafloor magnetization that were collected during and after World War II were elegantly assembled into the theory of plate tectonics. This powerful theory provides researchers with an excellent first-order understanding of the age and history of Earth's ocean basins, and it is the starting point for investigating earthquakes and volcanoes. Few surprises would be likely to emerge from an ocean exploration program that focused on measuring the geologic age or the tectonic history of the seafloor. As a result of coordinated international programs, such as the World Ocean Circulation Experiment, similar arguments likely could be made about our understanding of the general circulation of the ocean.

Just as for experiments designed to test a specific hypothesis, the design of an exploration program must be based on solid scientific (or archaeological) information that allows an assessment of the amount of observation or measurement that is necessary to answer the question being asked or to observe new phenomena. For example, before the Mid-Ocean Dynamics Experiment, which was designed to investigate the nature of mesoscale variability in the sea, a series of preliminary experiments was done to define the time-and-space resolution necessary to elucidate the Mid-Ocean Dynamics Experiment measurements.

Recommendation: To achieve the recommended goals (as outlined in Chapter 2), early efforts in ocean exploration should be selected using the following criteria:

- **Research is conducted in areas of international interest. Particularly salient are themes that are amenable to international cooperation and those suggested by International Global Ocean Exploration Workshop participants.**
- **Questions advance the current state of knowledge.**
- **Characteristics of the habitat, region, or discipline suggest a potential for bold, new discoveries.**
- **The results have a potential to benefit humanity.**

Recommendation: Several promising areas were identified as having broad international interest and are recommended as potential initial exploration themes:

- **marine biodiversity;**
- **the Arctic Ocean;**
- **the Southern Ocean and Antarctic ice shelves;**
- **deep water and its influence on climate change;**
- **exploring the ocean through time; and**
- **marine archaeology.**

Studies in those areas will reveal additional insights into living and nonliving resources (fisheries, bioproducts, energy resources, mineral deposits); human history; and how changes in physical, chemical, and biological properties of the ocean and seafloor affect our environment and climate. The list clearly is not exhaustive, but it identifies some areas in which international interest has been demonstrated, and for which major discoveries are likely. Two of these exploration themes, marine biodiversity and the Arctic Ocean, are used later in this report as examples for the project selection process for ocean exploration programs.

MARINE BIODIVERSITY

Exploitation of the genetic diversity of ocean life and long-term management of commercial fisheries will require a thorough knowledge and cataloging of resources. To date, just a fraction of the world's marine species have been scientifically named or taxonomically identified (Winston, 1992; World Resources Institute, 2001). New species, including corals, fishes, and plants, are discovered on virtually every expedition that seeks to uncover them. Even microorganisms, such as *Archaea*, a primitive form of life, have been discovered by happenstance in places where conditions of temperature and pressure are so extreme, no life would be expected (National Research Council, 1995). The recent realization of the abundance and distribution of deep, cold-water corals (Box 3.1, Figure 3.1) is another example. Ocean exploration offers the opportunity to make such discoveries in a coordinated and systematic way.

If little is known about the biodiversity in the oceans, even less is known about the abundance of organisms, their ecological functions, how food webs are structured, and how vast areas of the oceans are interconnected through biological interactions. A reliable, well-organized, and accessible inventory of existing and newly discovered marine species will promote scientific and public understanding of marine ecosystems. The Census of Marine Life is an exciting program of international research for assessing and explaining the diversity, distribution, and abundance of marine organisms throughout the world's oceans (Consortium for Oceanographic Research and Education, 2002). Collaborative projects involving more than 60 institutions from 15 countries began the Census of Marine Life in 2000 with funding from the Alfred P. Sloan Foundation and the National Oceanographic Partnership Program member agencies. The Ocean Biogeographic

BOX 3.1 DEEP, COLD-WATER CORALS

Recent confirmation of the extensive distribution of deep, cold-water coral reefs (*Lophelia* and *Madrepora* sp.) surprised and alarmed the fisheries management community and conservation organizations. Cold-water corals occur in the North Atlantic and North Pacific Oceans to depths of 2,000 m, and they are estimated to grow very slowly, between 6 and 25 mm per year. Without the photosynthetic symbionts that allow tropical coral to thrive, the metabolism of these organisms remains a mystery, but researchers believe they feed on carbon litter that falls to the ocean floor. Fishermen have been aware of these corals for some time, as they have harvested fish that live above these systems and pull in large pieces of the living coral (Figure 3.1). The distributions of these unique ecosystems are only now beginning to be confirmed (Freiwald et al., 1999; Huvenne et al., 2002), mapped (De Mol et al., 2002), and explained (Hovland and Thomsen, 1997; Roberts et al., 2003)—another example of the mysteries the oceans still hold for us.

FIGURE 3.1 A cold-water coral from Alaska (Malakoff, 2003).

Information System, the information component of the Census of Marine Life, will be a critical component of an integrated ocean observing system. Currently managed as a federation of database sources, the Ocean Biogeographic Information System is expected to develop into a globally distributed network of species-based, geographically referenced databases that will be available to a variety of users, including ecosystem managers, fisheries organizations, and coral-reef-monitoring programs.

Because even remote areas of the ocean contain detectable amounts of contaminants (Group of Experts on the Scientific Aspects of Marine Environmental Protection, 2001), the extent to which humans directly and indirectly affect marine ecosystem health and productivity can be observed, if not yet quantified. Ultimately, a better understanding of marine systems and the effects of human activities on them will enable wiser stewardship of the oceans' vast resources. The marine biodiversity theme area highlights the interdisciplinary nature of the proposed ocean exploration program, the proposal and funding selection process, and the utility of such a program. A few particularly exciting areas for exploration of marine biodiversity include microbial life within the ocean, extreme environments such as hydrothermal vents, the subseafloor biosphere, coral reefs, seamounts, and continental shelves.

Microbial Ocean

Although thousands of organisms can be identified in a single drop of seawater, the vast majority of those organisms cannot be cultured in a laboratory. New genetic tools are allowing researchers to unlock the secrets of identity, taxonomy, spatial diversity, and function of microbes in the ecosystem. Chance discoveries from exploring the microbial genome have highlighted how important these organisms are to the cycling of chemicals and energy in the open ocean and between the ocean and the seafloor. Opportunities abound for fundamental discoveries with great societal benefit. Many drugs in use are derived from chemicals produced by terrestrial microbes. Recent research suggests chemicals produced by marine microbes could be developed into new formulations for treating diseases (Feling et al., 2003), and several are currently in development, primarily for treatment of cancer (Pomponi, 2001). The advantage of exploring marine microbial diversity is that fermentation of microbes can provide a sustainable supply. At least three federal programs could form the basis for an integrated program of microbial ocean exploration and research. Through its Microbial Observatories program, the National Science Foundation (NSF) funds the study of novel microorganisms through time and environmental gradients. Drug discovery is the goal of two interagency programs that could, but do not currently, include exploration of the microbial ocean: the International Cooperative Biodiversity Groups (the National Institutes of Health, NSF, and the U.S. Agency for International Development) and the Centers for Oceans and Human Health (the National Institute of Environmental Health Sciences and NSF). An ocean exploration program would extend the reach of those programs more thoroughly into the oceans. Likewise, discoveries from the ocean exploration program would provide new resources for their drug discovery programs.

Extreme Environments

The ocean floor harbors some of Earth's most extreme environments, with high pressures, temperatures ranging from close to freezing to more than 400 °C, and fluids with chemical compositions that support unique life forms. The public—and marine scientists—were surprised when Jacques Piccard and Donald Walsh found life in the deepest part of the ocean, at the bottom of the Mariana Trench in the Pacific Ocean. Until a quarter of a century ago the deep sea was viewed as a hostile environment with low biomass and a limited supply of food from surface waters above. The discovery in 1977 of luxuriant ecosystems associated with deep-sea hydrothermal vents dramatically altered our views of life in the deep ocean (Figure 3.2). Those ecosystems are unlike any other on Earth, and they do

FIGURE 3.2 The surprise discovery of complex marine ecosystems that exist independent of sunlight and photosynthesis revolutionized our understanding of the possibilities for ecosystem support. The tube worms, crab, and fish pictured here all depend on chemosynthetic bacteria expelled from the seafloor at the hydrothermal vents (Lutz et al., 2001; used with permission from Richard Lutz, Rutgers University; Stephen Low Productions; and the Woods Hole Oceanographic Institution).

not depend on organic matter sinking from the sunlit surface ocean. Rather, microorganisms at the base of those ecosystems use chemosynthesis rather than photosynthesis to convert hydrogen, hydrogen sulfide, and methane from the high-temperature fluids at the vents into energy (Figure 3.3). The discovery of the vent ecosystems greatly increased the known range of environments suitable for life in the universe. More than 500 new species have been described from those vents in the past 25 years, and this probably represents less than one-tenth of one percent of the estimated biodiversity of vent communities worldwide. Because the vent organisms live in extreme

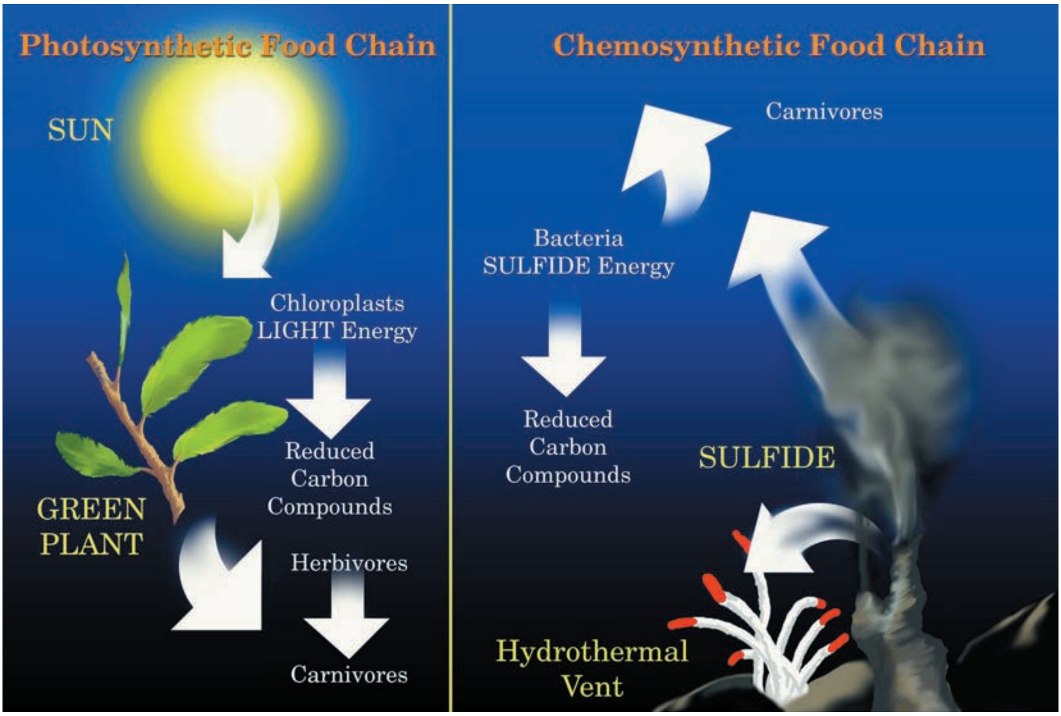

FIGURE 3.3 Instead of photosynthesis, vent ecosystems derive their energy from chemicals in a process called chemosynthesis. Both methods involve an energy source, carbon dioxide, and water to produce sugars. Photosynthesis gives off oxygen gas as a byproduct, while chemosynthesis produces sulfide (used with permission from E. Paul Oberlander, Woods Hole Oceanographic Institution).

environments, they produce substances unknown on land—many of which are being studied for pharmaceutical, commercial, and biotechnological purposes. For example, the commercially available enzyme most widely used today to replicate DNA is derived from an enzyme found in microbes discovered near hydrothermal vents. It is likely that other chemicals with applications in extreme industrial processes will be discovered and commercialized. There are potential opportunities for synergy with existing programs that support research in extreme environments. NSF's Ridge Interdisciplinary Global Experiments (RIDGE), and the new RIDGE 2000 (Pennsylvania State University, 2003) programs are examples of integrated research that form the basis for development of an international organization (Inter-RIDGE) to coordinate national efforts for the study of midocean ridges. Inter-RIDGE provides support for the University-National Oceanographic Laboratory System assets to be deployed, primarily to known sites of interest. Coordination with an ocean exploration program would promote the discovery and characterization of new and unstudied extreme environments.

Subseafloor Biosphere

In 1991, scientists working in the submersible *Alvin* on the midocean ridge in the eastern Pacific witnessed a "blizzard" of microbes and microbial debris being spewed out of the seafloor (Haymon et al., 1993). The material rose more than 30 m above the ocean bottom and formed a white layer 10 cm thick on the seafloor. Since then, this phenomenon of rapid effusion of microbial material has been observed several times in the vicinity of seawater volcanic eruptions. Microbes also have been detected in cores recovered by the Ocean Drilling Program (ODP) several hundred meters below the bottom. This serendipitous discovery led to the hypothesis that a massive, deep subseafloor biosphere exists in the rocks and sediments that make up the seafloor. Volcanic, rather than solar, energy catalyzes chemical reactions that generate life-sustaining materials from rocks and seawater. This is an ecosystem the extent and character of which is almost completely unknown, and yet its biomass could be greater than the combined biomass present in the entire ocean above the seafloor. Continued exploration, in collaboration with ODP, could provide a better understanding of life on Earth, as well as the possibility of life on other planets, and might reveal microorganisms and new substances with pharmaceutical or other commercial applications.

Coral Reefs

Coral reefs are among the most productive, diverse, and economically important ecosystems on the planet. Although they cover only 0.2 percent of ocean area, they provide habitat for one-third of marine fishes. The systems provide ecological services—including shoreline protection and habitat—that support an estimated one million different species. Economically, healthy coral reefs are essential to sustainable fisheries and income from tourism (e.g., Cesar, 2000). Tourism at coral reef sites contributes about $1.6 billion annually to Florida's economy alone, and globally coral reefs are especially critical to the economic well-being of developing nations, providing fisheries resources and social and cultural benefits. The declining health of coral reef ecosystems (Figure 3.4) has been widely reported for tropical oceans around the world—likely the result of overfishing, eutrophication, and pollution from land runoff; increased disease susceptibility; and harvesting of corals for international trade (World Resources Institute, 1998; National Oceanic and Atmospheric Administration, 2002a). Global warming has been suggested as the largest long-term threat to coral reefs, as evidenced by the bleaching of vast tracts of coral coinciding with ocean warming during El Niño events. Although much is understood regionally about the declining health of coral reefs, it is clear that there is much to be investigated and learned.

Seamounts

The summits of seamounts—volcanic, underwater mountains—are rich and functionally important marine ecosystems. Seamounts are unusually productive; by the 1980s nearly 600 species of invertebrates had been described from those systems (Wilson and Kaufman, 1987). More recently, 850 macro- and mega-faunal species have been described—29 to 34 percent of them new to science and possibly endemic to seamount ecosystems (de Forges et al., 2000). They disrupt the deep currents and cause upwelling of nutrient-rich water. Although the major seamounts are known from ship and spacecraft topographic mapping, many small but ecologically critical seamounts have not yet been identified. A recent survey of fish aggregation and spawning areas in the western Pacific has revealed an extensive array of seamounts, providing a good foundation for future efforts to choose sites for marine protected areas that will serve to maintain fisheries production and safeguard biodiversity. Exploration and discovery of seamounts in other places also could lead to discovery of new fisheries and other living resources.

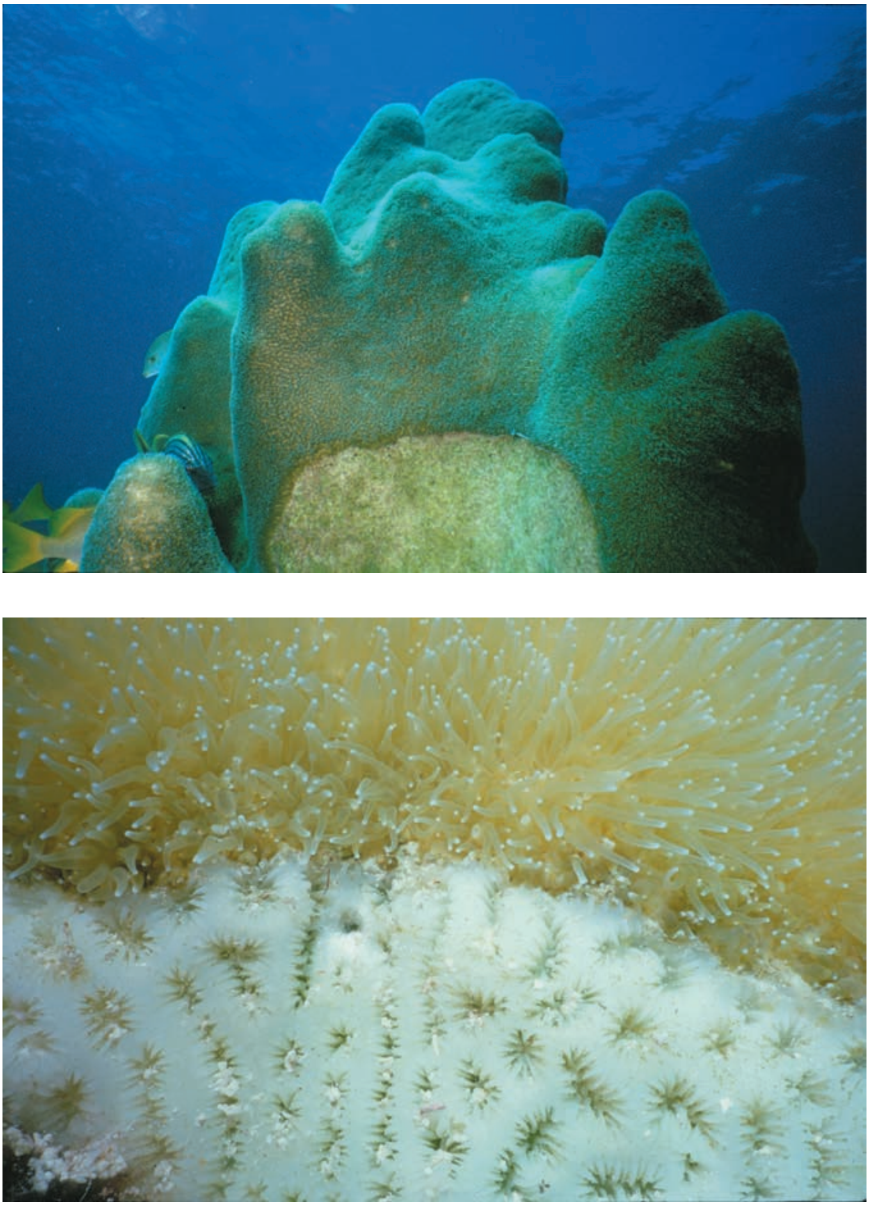

FIGURE 3.4 (A) A diseased colony and (B) a coral (*Dendrogyra cylindrical*) infected with the coral disease white plague type II (used with permission from L. Richardson). The disease progression, caused by a bacterial pathogen (*Aurantimonas coralicida*), results in tissue loss exposing the coral skeleton.

Continental Shelves

The organisms that live within the sediments on continental shelves, especially temperate banks and intertidal areas, include numbers of species rivaling those of tropical-forest insects. Sediment-dwelling organisms are thought to link the seafloor ecosystem with the water column above and ultimately to support the marine food web. NSF's Continental Margins Research program provides a focus for coordinated, interdisciplinary, hypothesis-based research on the physical, chemical, and biological processes critical for margin formation. The Coastal Ocean Processes research effort investigates processes that dominate the transport and fate of material within the continental margins. An ocean exploration program would complement such programs by examining new areas to determine how those systems function and to elucidate the effects of human activity. Discoveries of new habitats and processes could provide the basis for additional investigations in Margins and the Coastal Ocean Processes.

Unfortunately, the seafloor in many coastal areas has been degraded or destroyed by trawling, dredging, and coastal construction (National Research Council, 2002). International workshop participants emphasized that ocean exploration should not focus exclusively on offshore oceanic environments. Equally important is the exploration of the coastal ocean because this is where the consequences of human activity will be most severe. There are several U.S. programs for near-shore coastal mapping and monitoring. One is the Southeast Area Monitoring and Assessment Program, a combined state, federal, and university program for the collection, management, and dissemination of fishery-independent data and information in the southeastern United States (Gulf States Marine Fisheries Commission, 2003). Federal funding is provided by the National Marine Fisheries Service and the data are used primarily by fisheries management councils in the respective regions. Such programs generally are not exploratory, but they could benefit from exploration, particularly if new living resources were identified. Similar benefits of exploration could be seen in coastal waste management, marine minerals exploitation, and environmental matters associated with ocean energy.

ARCTIC OCEAN

The broad continental margins of the Arctic Ocean basin contain unknown quantities of living and nonliving resources. Those areas have been the target of numerous heroic, and in earlier times, often tragic visits by explorers. Variations in ice cover affect marine ecosystems and the physical oceanography of the North Atlantic, which directly influence the habitability of northern North America and Eurasia. Little is known about the seafloor or the fundamental processes that create new ocean crust there or about the deep-sea ecology of this isolated basin. Hence, the Arctic Ocean is high on the list for exploration, particularly for the waters beneath the ice (Box 3.2). Below-ice exploration will require new technology; including development of a new generation of specialized autonomous underwater vehicles or other probes that can be lowered through holes drilled through hundreds of meters of ice. The Arctic is the second theme area discussed in this report as particularly promising for an exploration program, and it is revisited in later chapters.

New exploration efforts in the Arctic will build on earlier work by the SCICEX program. Beginning in 1993, and continuing with annual cruises from 1995-1999, U.S. Naval submarines carried academic researchers into the Arctic Ocean (Edwards and Coakley, in press). Typical cruises lasted 30 or more days, and geophysical, cryospheric, and oceanographic data were collected. NSF provided support for the researchers and equipment. The program continues as of this publication, although researchers are no longer brought aboard the Naval vessels; crew members now collect data on behalf of the researchers. Among the important discoveries in the Arctic, SCICEX provided early observations of the increasing intrusion of warm Atlantic waters into the Arctic Ocean, and documented the decline of the thickness of the ice canopy.

The International Arctic Science Committee (IASC), a nongovernmental consortium of national science programs, is one source of international coordination and funding for Arctic research. NSF's Office of Polar Programs will represent the United States on the committee. That office coordinates review and funding of Arctic research in other NSF programs, such as ODP. IASC member organizations identify scientific priorities for cooperative projects. As proposed in the structure for an international global ocean exploration program (Chapter 4), IASC could provide recommendations for coordinated programs in Arctic research to the international advisory committee. Because programs supported by IASC are terrestrial (International Arctic Science Committee, 2003), an Arctic Ocean exploration program could provide complementary information regarding marine resources. The synergy possible between the ocean and terrestrial programs could catapult our understanding of this important ecosystem forward and improve our ability to manage its resources wisely.

BOX 3.2 THE FOURTH INTERNATIONAL POLAR YEAR IN 2007

The year 2007-2008 will mark the 125th anniversary of the First International Polar Year (IPY; 1882-1883), the 75th anniversary of the Second Polar Year (1932-1933), and the 50th anniversary of the International Geophysical Year (IGY; 1957-1958). IPY and IGY were major initiatives resulting in step changes in our understanding of polar phenomena and the role of the polar regions in global processes. IGY in particular was momentous, triggering among other things the space age, the human exploration of the polar regions, and spawning the World Data Centres, the World Climate Research Programme, the Scientific Committee on Antarctic Research, and the Antarctic Treaty System. Although enormous progress has been made in the last 50 years, much fundamental and globally relevant polar research remains to be completed.

IPY is an initiative to intensify polar research on a global scale by assembling national scientific research programs into a cohesive, international entity. The first IPY (IPY-1; 1882-1883) was proposed in 1879, at which time it was determined that once eight international monitoring stations in the Arctic or Antarctic were secured the IPY-1 research program would begin—the goal was realized in 1882 when the United States joined the enterprise. Through IPY-1, significant advances were realized, particularly in geophysics (e.g., identification of the ionosphere), engineering (instrumentation in extreme environments), and analytical science (standardization of techniques). After this success, a subsequent polar year was initiated in 1932 (IPY-2), primarily as an effort to investigate the global implications of the newly discovered "Jet Stream." Although IPY-2 focused solely on the Arctic Region, the endeavor was an astounding success. The program was able to persevere through the Great Depression and provide significant advances in describing Earth systematics. To reflect the expanding body of knowledge and the global implications of the polar data set compiled, the third IPY (IPY-3) was renamed IGY. The scientific achievements resulting from IGY include the theory of plate tectonics, identification of the ionosphere and ozone layer, the launch of satellites for

Arctic Ice and Climate Change

The first time the Arctic Ocean had a sea ice cover was in the middle Paleogene (40 million years ago). Properties of the Arctic Ocean before glaciation (in the "warm polar ocean") are unknown and can be posited only by applying new technology for sampling ocean sediments below the ice. Those sediments could reveal a history that could be studied to predict remote sensing observations, and mapping of Antarctic bedrock. The number of monitoring stations expanded from a total of 11 in the Arctic and Antarctic (1882) to over 8,000 global locations (1957). The international venture included over 67 nations, representing a landmark in international cooperation. Both the United States and the Soviet Union participated, despite the height of Cold War tensions, and territorial rivalries among national governments in Antarctica were suspended, leading to the eventual ratification of the Antarctic Treaty (1961).

In spite of these substantial efforts, the relative inaccessibility and challenging environment in the Arctic and Antarctic have hampered polar research; consequently, polar regions remain poorly understood, relative to other, more accessible areas. This need has been recognized, and in June 2002, at the international symposium "Perspectives of Modern Polar Research" in Bad Durkeim, Germany, a fourth IPY (IPY-4) was proposed for 2007. IPY-4 will attempt to continue the legacy of significant advances in science and technology, international cooperation, and understanding of geophysical processes that have typified previous IPY and IGY initiatives. In addition, IPY-4 will capture a broader and more integrative perspective than IGY, by incorporating interdisciplinary components from outside geosciences. Although the scientific objectives of IPY-4 will evolve, the overarching goal will be to collect synoptic measurements in the polar regions to address the specific scientific directives. A partial list of objectives include determining the causes and effects of climatic variability, monitoring lithosphere dynamics, coordinating in situ and remote sensing of oceanographic and terrestrial conditions, assessing the response of the polar environment to fluctuations in solar intensity, and evaluating the socioeconomic impact of environmental changes. Significant advances in technology and communication will facilitate the data collection processes, and expand the educational opportunities and dissemination of information resulting from IPY-4. More information on IPY-4 is available through the National Research Council (2003a).

what is likely in the near future as a result of global warming. Exploration of the Arctic Ocean is therefore a high priority—particularly for nations in the far Northern Hemisphere.

There is now evidence that the surface salinity in the high-latitude North Atlantic Ocean is decreasing. This could increase the speed of climate change by suppressing the formation of North Atlantic Deep Water

(NADW). Under normal conditions, the combination of low temperature and high salinity produces dense surface water that sinks into the deep ocean and spreads laterally as part of global deep-ocean circulation. If the surface ocean freshens, the intensity of formation of NADW could result in less intense surface currents and less poleward transport of heat. The path of the Gulf Stream also could be altered, with serious implications for winter conditions in northern Europe.

The formation of NADW has other effects on global climate. It carries greenhouse gases and heat to the ocean bottom, out of contact with the atmosphere for hundreds of years. Extraction of fresh water from the ocean via evaporation, which increases NADW salinity, provides water for the global hydrological cycle. A better understanding of the global climate system requires detailed information about ocean circulation, its vulnerability to change, and the processes that govern water mass formation rates (National Research Council, 1994, 2001).

Retrospective exploration of deep ocean water temperatures over time could provide insights about trends in global climate change. Surface water temperatures can be measured from space with limited accuracy but high resolution. New systems, including the Array for Real-Time Geostrophic Oceanography, measure the temperature of the oceans to depths of 1,000 m with an average resolution of 300 km. New programs will extend the ability to sample ocean temperatures in shallow waters, but deep water variability is still unexplored. This is particularly unfortunate because the highly variable surface layers of the ocean could mask longer term trends associated with rapid climate change. Exploration of the deep ocean could be applied to explain the forces that have shaped abrupt climate changes in the past, as inferred from the paleoceanographic record, and extrapolated to predict what will shape them in the future (Figure 3.5).

Arctic Seafloor

The tectonic history of the western Arctic Ocean is basically unknown. The ultra-slow spreading of the Arctic midocean ridges gives rise to spectacular topographic relief and a complex crustal architecture. Volcanic activity is low, and major portions of the ridge are composed of rocks from the mantle. We know virtually nothing about this type of midocean ridge or the mechanism of building new crust there. Studies of Arctic midocean ridges will complete our picture of how the Earth is regularly repaved by submarine volcanic and tectonic activity.

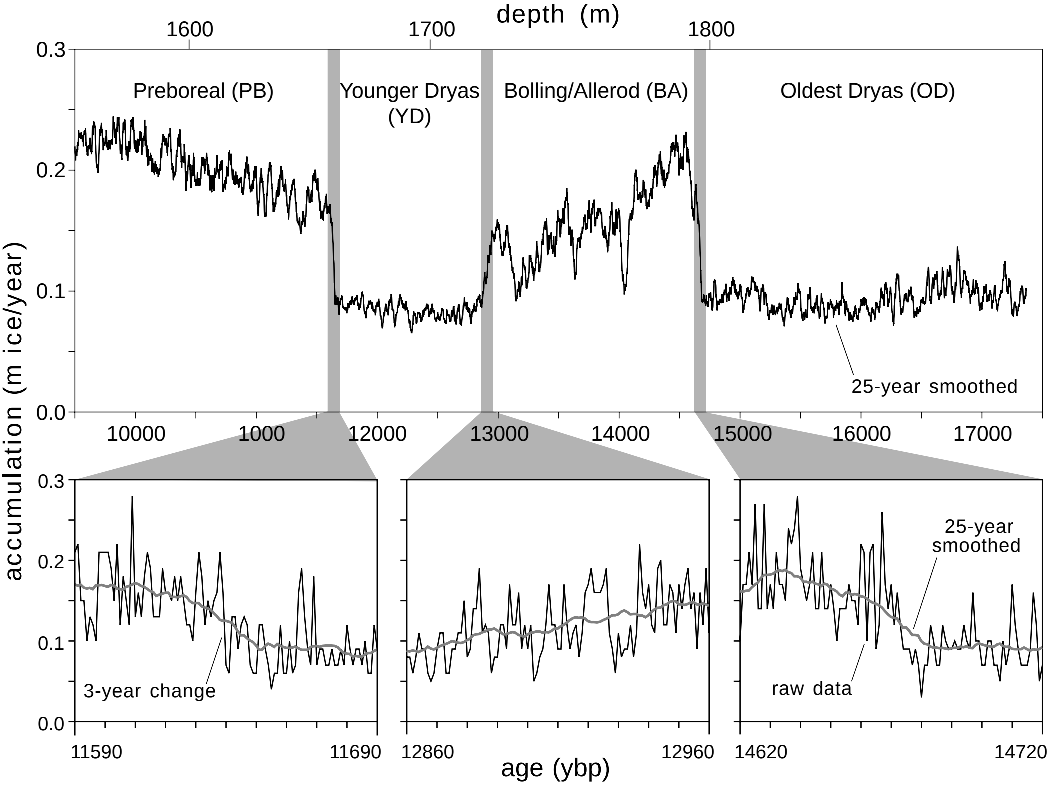

FIGURE 3.5 In Greenland the ice accumulation rate was low during the Younger Dryas; both the start and the end of that period show as abrupt changes (modified from Alley et al., 1993).

The isolation of the Arctic Ocean and its separation from all other ridge systems raises fundamental questions about the evolution and ecology of Arctic vent fauna. The hydrographic barriers and geologic features that enclose the Arctic Ocean's spreading centers pose a significant directional barrier to dispersal of vent species. The recent recovery of a few specimens of vent fauna during dredging along the Gakkel Ridge (Figure 3.6) confirms the existence of vent ecosystems in the region and offers unique opportuni-

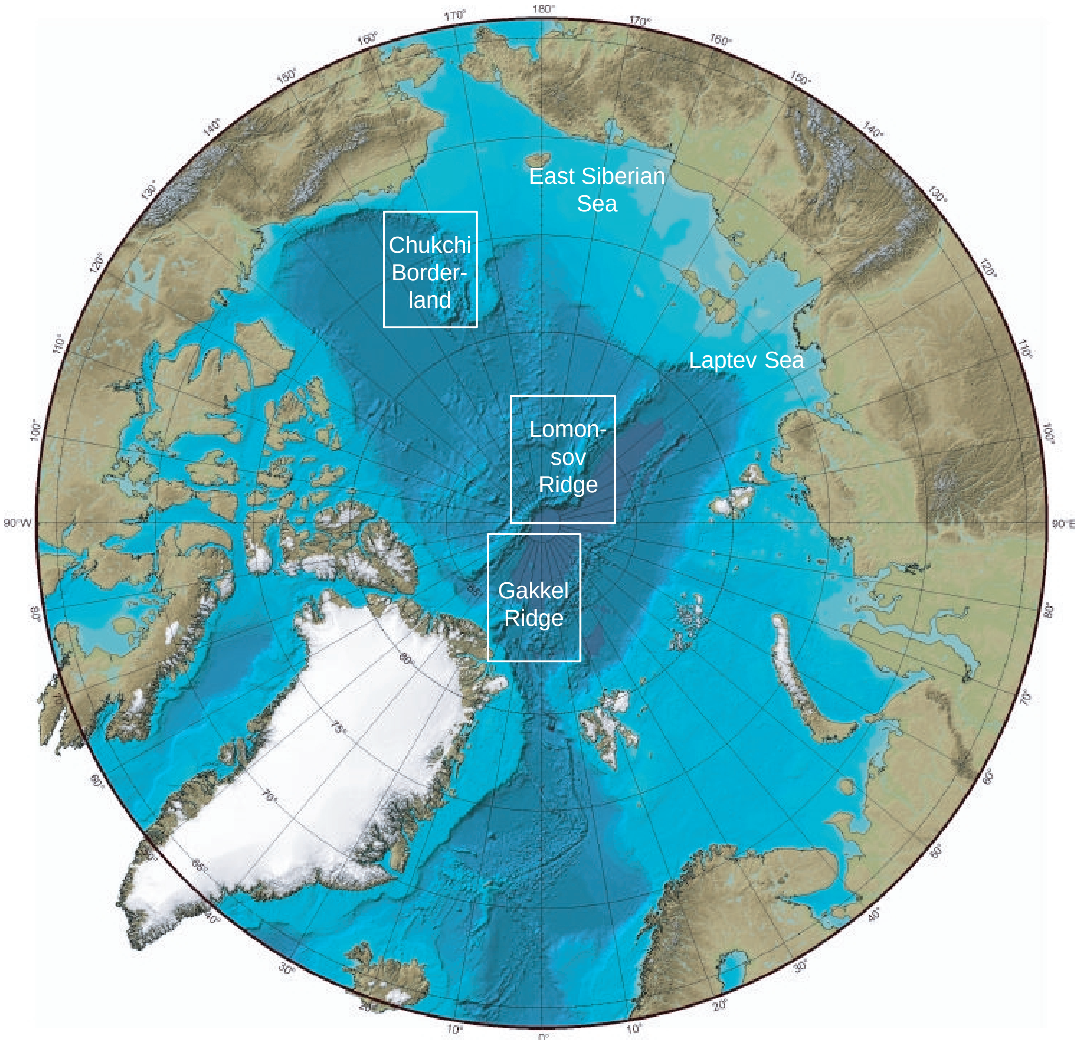

FIGURE 3.6 Arctic Ocean map showing the Gakkel Ridge (used with permission from M. Jakobsson).

ties to characterize Arctic vent systems. Indeed, those isolated ecosystems could contain life forms that hold keys to explaining the evolution of life in hydrothermal vents and to the discovery of processes and substances with industrial and pharmacologic applications.

SOUTHERN OCEAN AND ANTARCTIC ICE SHELVES

Oceanographic observations of the Southern Ocean are scarce, particularly during the austral winter, when ice formation doubles the size of Antarctica. Even during the austral summer some regions are inaccessible to ships (Box 3.3). Among them are the waters below the floating ice shelves, which are home to highly specialized organisms. Those waters are extremely cold and dense—they cascade down the adjacent continental margin and contribute to the formation of the Antarctic bottom water with its unique physical and chemical properties. This is one of the most important oceanographic processes on Earth. It is a principal mechanism of deep water formation and transport. Vast areas of the Southern Ocean seafloor are unmapped, yet the basin's bathymetric and age patterns contain records of the disintegration of the Gondwana supercontinent and the opening of the Drake Passage. Many believe the latter to have been an important key event in the development of the current global climate. The Southern Ocean is highly productive biologically. It has large stocks of living resources, such as the krill population, that require understanding for effective use, protection, and management.

The Scientific Committee on Antarctic Research is an international, nongovernmental committee of the International Council for Science that provides advice on scientific research in the region. This well-established

BOX 3.3 EXPLORING ANTARCTIC CHANGE FROM SPACE

Recent moderate resolution imaging spectroradiometer satellite imagery analyzed at the University of Colorado's National Snow and Ice Data Center revealed that the northern section of the Larsen B ice shelf, a large floating ice mass on the eastern side of the Antarctic Peninsula, has shattered and separated from the continent. The shattered ice formed a plume of thousands of icebergs adrift in the Weddell Sea. A total of about 3,250 km^2 of shelf area disintegrated in a 35-day period beginning January 31, 2002. Over the past five years, the shelf has lost 5,700 km^2, and it is now about 40 percent the size of its previous minimum stable extent.

group could provide recommendations for coordinated programs in Antarctic research to the international advisory committee.

EXPLORING THE OCEAN THROUGH TIME

Sustained, large-scale, long-term observations are indispensable to all ocean science disciplines, and they often lead to discoveries of the processes that link the physics, chemistry, biology, and geology of the ocean. The ocean exploration program should be a partner in the establishment and use of observation systems, particularly in unexplored areas. An exploration-based ocean-observing system can and should provide information that will be useful for basic and applied research and for real-world applications. Processes that influence global climate, the continued development of accurate regional and global model-based forecasting capabilities, and the tracking of migrations of marine life are all areas for study. The benefits of observation systems to various economic sectors (as among them ocean transport and fisheries) and to the world's nations would add substantially to the value of the program.

The opportunity exists for a cooperative effort by all involved countries to work toward the placement and operation of multinational global and regional ocean observation systems. That goal will require the creation of new partnerships among scientists, government agencies, industry, and other potential users; extending financial relationships to include sharing of intellect, experience, data, instruments, facilities, and labor. Indeed, the multinational effort involved in installing and operating observation systems for ocean exploration, at coastal or open-ocean priority sites, might prove essential in creating the required synergies among interested nations to get a viable international ocean exploration program started and fully operational. Ocean-observing systems, shared within a multinational framework, should help provide answers to questions about regional priorities in fisheries, pollution, biodiversity, and ocean circulation to ocean exploration participants worldwide. It is unlikely that the central features of importance for ocean exploration—long-term sampling and observation—can be sustained by governments without such a broad range of supportive users.

MARINE ARCHAEOLOGY

One cannot imagine a history of our globe without watercraft. From the primitive floats and rafts that carried the first people to Australia 50,000 years ago to the giant oil tankers and aircraft carriers of today, boats and ships have allowed the discovery, colonization, supply, and defense of entire continents. Human history owes much to the contributions of Greek triremes, Roman grain carriers, Chinese junks, birchbark canoes, and Viking longboats. Many of the most famous explorers chose the sea as their highway: Columbus, da Gama, Magellan, and Cortes. Turning points in human history are associated with such names as *Mayflower*, Trafalgar, *Beagle*, Normandy, and Midway. And from earliest times until the advent of space vehicles, seagoing ships usually were the most technologically complex creations of their time. The study of the history of ships is therefore important in itself. But just as important is the study of objects made by humans. From tiny obsidian blades and bits of jewelry to huge marble elements of temples and churches, all have been transported at one time or another over water. Thus, the exploration of shipwrecks will write definitive histories of weapons, tools and other utensils, glass, ceramics, games, sculpture, weights and measures, metallurgy, and, especially in later times, instruments and machines of all kinds. Equally important is what shipwrecks can teach us about economic history. Then, too, there are inundated coastal habitation sites that can tell us about our early ancestors. Archaeological exploration of underwater sites will promote our understanding of global cultural heritage.

The public is fascinated by marine archaeology. Nielsen ratings showed that an ABC-TV "20/20" program on the exploration of a classical Greek ship was the second-most-watched program in America the week it was televised, and *National Geographic* magazine has found shipwrecks a favorite subject among readers of its various international editions. Such interest can lead to direct and indirect economic benefits through tourism. The museum that houses the seventeenth-century warship *Vasa* is the greatest tourist attraction in Sweden; the Bodrum Museum of Underwater Archaeology is the most visited archaeology museum in all of Turkey; and, when restored, La Salle's ship *Belle* will be the centerpiece of the new Bob Bullock State History Museum in Austin.

Although there are national programs of marine archaeology in France, Greece, Portugal, Israel, Spain, and Australia, among others, federal support of global archaeology in the United States comes mainly from NSF, which no longer funds all aspects of marine archaeology, and from the National Endowment for the Humanities, which does not support essential exploratory surveys.

SUMMARY

To a large degree, the oceans remain one of the great mysteries of our world. So many discoveries likely remain that narrowing the possibilities to those highlighted here was the source of much discussion among the committee members. In all, the areas highlighted are likely not only to attract partners from many nations, but to provide important discoveries relatively rapidly. Should an ocean exploration program be initiated for a lengthy period of time, these areas of promise could be greatly expanded.

4

International Organization and Management of an Ocean Exploration Program

No nation owns the oceans, and no nation has the financial, intellectual, or technological capacity to undertake a truly global program of ocean exploration alone. The challenge of exploring such a vast and diverse environment will be met with the financial, human, and equipment resources of many partners. International collaboration is the best avenue to a global exploration program.

Nearly half of the people on Earth live within 100 km of an ocean (World Resources Institute, 2001), and demands on the ocean for resources and waste disposal are increasing as the population expands. Exploration in the coastal ocean requires the active participation of the coastal nations that control exclusive economic zones. Moreover, given the considerable economic investment and effort needed for global ocean exploration, the United States can not by itself explore the vast regions of the ocean yet unknown and beyond the control of any single nation.

To promote and sustain an effective ocean exploration program, it is important to involve scientists and governments from many nations in a truly global effort. Most nations of the world have an ocean frontier, but ocean processes affect all nations, and the benefits of an ocean exploration program are global. Capabilities for ocean exploration are widely distributed around the globe, and no single nation can afford the kind of broad effort of greatest benefit to all.

Managing a large-scale, international ocean exploration program will require an organizational model that is sufficiently flexible to attract a diverse array of national and international participants while still providing adequate structure to ensure consistency in direction, information dissemination and management, and funding.

As part of the work of the committee on Exploration of the Seas, the International Global Ocean Exploration (IGOE) Workshop was convened to examine the possibilities for establishing a program and to air the concerns of various nations in beginning an ocean exploration effort. Seventy-three representatives from 22 nations met in Paris in May 2002 to discuss their interests in ocean exploration. Appendix C is an agenda and a list of participants, and Appendix D summarizes the proceedings. Presentations and discussions at the workshop made it clear that only a few countries have the interest, funding, and ocean-going ability to justify participation in a truly global ocean exploration program.

Discussions and presentations at the Workshop suggested that a coordinated international organization for ocean exploration should be designed to accommodate the following goals:

- promote and support the highest quality science and technology;
- provide for the development and application of promising new technology by leveraging the capabilities of international partners;
- encourage the broadest possible participation to achieve a synergistic effect and worldwide implementation;
- develop an international voice for ocean exploration;
- encourage increased international funding for exploration;
- provide the most efficient access to and use of platforms and capabilities;
- support the broadest possible and most efficient methods for sharing information;
- reduce political barriers to exploration and research;
- include developing countries in partnership and capacity building; and
- emphasize and promote effective international education and public outreach.

INTERNATIONAL ORGANIZATIONAL STRUCTURES

International oceanographic programs (Table 4.1) use a variety of management and oversight structures and involve many nations, depending on the research topics addressed. Participation in existing oceanographic programs might be the most effective way to initially identify potential international partners for new exploration efforts.

As presented by Dr. Minster, Chair of the French Institute for Exploitation of the Sea, major barriers to international cooperation can arise when funds must be pooled from different nations to support a large, international research program. In order of decreasing complexity, and therefore decreasing need for extensive, often difficult, negotiations are:

TABLE 4.1 Selected International Oceanographic Programs

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
Baltic Sea Regional Project (BSRP)	BSRP develops ecosystem management tools for the Baltic Sea ecosystem.	International Council for Exploration of the Sea (ICES) Members: Belgium, Canada, Denmark, Estonia, Finland, France, Germany, Iceland, Ireland, Latvia, Netherlands, Norway, Poland, Portugal, Russia, Spain, Sweden, United Kingdom, United States	ICES Observers: Australia, Chile, Greece, New Zealand, Peru, South Africa
Census of Marine Life (CoML)	CoML conducts research to assess and explain the diversity, distribution, and abundance of marine organisms throughout the world's oceans.	Denmark, Japan, United States	Scientific Steering Committee: Intergovernmental Oceanographic Commission (IOC) Members[a]
Global Climate Observing System (GCOS)	GCOS is a long-term, user-driven operational system that provides comprehensive observations required for monitoring the climate system; detecting and attributing climate change; assessing the consequences of climate variability and change; and supporting research toward improved understanding, modeling, and prediction of the climate system. It addresses the total climate system, including physical, chemical, and biological properties and atmospheric, oceanic, hydrologic, cryospheric, and terrestrial processes.	Steering Committee: Canada, China, France, Germany, Japan, Kenya, Malaysia, Norway, Russia, United Kingdom, United States	

continued

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
Global Ecology and Oceanography of Harmful Algal Blooms (GEOHAB)	GEOHAB fosters international cooperative research on harmful algal blooms in similar ecosystem types by comparing the key species involved and the oceanographic processes that influence their population dynamics.	Scientific Steering Committee: Canada, Chile, China, Finland, France, Germany, Italy, Mexico, South Africa, Spain, United Kingdom, United States	IOC Members Scientific Committee on Oceanic Research (SCOR) Members[b]
Global Ocean Ecosystem Dynamics Program (GLOBEC)	GLOBEC will address how global ecosystem change influences the abundance, diversity, and productivity of marine populations—primarily zooplankton (the assemblage of herbivorous grazers on the phytoplankton and the primary carnivores that prey on them)—that constitute a major component of oceanic ecosystems.	Germany, Norway, United Kingdom, United States	Angola, Denmark, Faroe Islands (Denmark), France, Iceland, Namibia, South Africa
Global Sea Level Observing System (GLOSS)	GLOSS aims at the establishment of high-quality global and regional sea level networks for application to climate, oceanographic, and coastal sea level research.	IOC Executive Council IOC Members World Meteorological Organization (WMO) Members	
Global Ocean Observing System (GOOS)	GOOS is a permanent global system for observation, modeling, and analysis of marine and ocean variables to support operational ocean services worldwide. GOOS will provide accurate descriptions of the state of the oceans, including living resources; continuous forecasts of the conditions of the sea for as far ahead as possible; and the basis for predictions of climate change.	Steering Committee: Argentina, Australia, Bermuda, Brazil, Canada, China, France, Germany, India, Italy, Japan, Kenya, Netherlands, Norway, Philippines, South Africa, Switzerland, United Kingdom, United States	International Council of Scientific Unions (ICSU) Members[c] IOC Executive Council IOC Members United Nations Environment Programme Governing Council[d] WMO Members (IOC Members plus the following)[e]

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
Integrated Ocean Drilling Program (IODP)	IODP builds on the Ocean Drilling Program, is slated to begin October 1, 2003, as an international program of scientific research that uses multiple integrated platforms to drill, core, and log in oceanic settings to investigate Earth system processes.	International Working Group: Australia, Canada, China, European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom), France, Germany, Japan, Sweden, United States IODP Management International, Inc., with Board of Governors from the United States and Japan.	
International Ridge Inter-disciplinary Global Experiments Studies (Inter-RIDGE)	Inter-RIDGE is an international, interdisciplinary initiative concerned with all aspects of mid-ocean ridges. It is designed to encourage scientific and logistical coordination, with particular focus on problems that cannot be addressed as efficiently by nations acting alone or in limited partnerships. Its activities range from dissemination of information on existing, single-institution experiments to initiation of fully multinational projects.	France, Japan, United Kingdom, United States	Associate Members: Canada, Germany, India, Italy, Korea, Norway, Portugal Corresponding Members: Australia, Austria, Brazil, China, Denmark, Iceland, Mauritius, Mexico, Morocco, New Zealand, Philippines, Russia, South Pacific (American Samoa [Associate], Australia, Cook Islands, Fiji Islands, French Polynesia [Associate], Guam, Kiribati, Marshall Islands, Micronesia, Nauru, New Caledonia [Associate], New Zealand, Niue, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu), South Africa, Spain, Sweden, Switzerland

continued

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
Joint Global Ocean Flux Study (JGOFS)	JGOFS research is on the processes that control regional to global and seasonal to interannual fluxes of carbon between the atmosphere, surface ocean, and ocean interior, and their sensitivity to climate changes.	International Geosphere-Biosphere Programme (IGBP) Scientific Committee: Australia, Belgium, China, Denmark, France, Germany, India, Japan, Kenya, Netherlands, South Africa, United Kingdom, United States ICSU Members SCOR Members	IGBP National Committee: Argentina, Australia, Austria, Bangladesh, Belgium, Benin, Bolivia, Botswana, Brazil, Bulgaria, Cameroon, Canada, Caribbean, Chile, China, Colombia, Comoros, Congo, Cuba, Czech Republic, Denmark, Ecuador, Egypt, Estonia, Finland, France, Germany, Ghana, Greece, Hungary, Iceland, India, Indonesia, Ireland, Israel, Italy, Ivory Coast, Jamaica, Japan, Kenya, Korea, Lebanon, Malaysia, Mexico, Mongolia, Netherlands, New Zealand, Niger, Nigeria, Norway, Pakistan, Peru, Philippines, Poland, Portugal, Romania, Russia, Senegal, Sierra Leone, Slovakia, South Africa, Spain, Sri Lanka, Sweden, Switzerland, Syria, Tajikistan, Tanzania, Thailand, Togo, Tunisia, Turkey, Uganda, United Kingdom, United States, Venezuela, Vietnam, Zambia, Zimbabwe
Ocean Drilling Program (ODP)	ODP is an international partnership of scientists and research institutions organized to explore the evolution and structure of Earth. ODP provides researchers around the world access to a vast repository of geological and environmental information recorded far below the ocean surface in seafloor sediments and rocks.	European Consortium (Belgium, Denmark, Finland, Iceland, Ireland, Italy, Netherlands, Norway, Portugal, Spain, Sweden, Switzerland), Germany, Japan, United Kingdom, United States Pacific Rim Consortium: Australia, Canada, Chinese Taipei, South Korea	Associate Members: China, France

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
South Pacific Sea Level and Climate Monitoring Project	The objective is to provide an accurate long-term record of sea levels in the South Pacific for partner countries and the international scientific community that enables them to respond to and manage related effects.	Cook Islands, Fiji, Kiribati, Marshall Islands, Micronesia, Nauru, Niue, Palau, Papua New Guinea, Samoa, Solomon Islands, Tonga, Tuvalu, Vanuatu	
Surface Ocean-Lower Atmosphere Study (SOLAS)	The goal of SOLAS is to provide quantitative information about important biogeochemical-physical interactions and feedbacks between the ocean and the atmosphere and to explain how this coupled system affects and is affected by climate and environmental change.	National Planning Committees or Funded Research Programs: Australia, Belgium, Brazil, Canada, China, France, Germany, India, Japan, Netherlands, New Zealand, Norway, Taiwan, United Kingdom, United States Steering Committee: Brazil, Canada, Denmark, France, Germany, India, Japan, Netherlands, New Zealand, Norway, United Kingdom, United States	ICSU Members IGBP National Committee IGBP Scientific Committee SCOR Members World Climate Research Programme Scientific Committee: Australia, Canada, China, Ecuador, India, Iran, Japan, Kenya, Russia, United Kingdom, United States
Tropical Ocean Global Atmosphere/Coupled Ocean Atmosphere Response Experiment (TOGA/COARE)	TOGA/COARE is an international research program on the interaction or coupling of the ocean and atmosphere in the western Pacific warm pool region.	Australia, China, France, Indonesia, Japan, New Zealand, Papua New Guinea, Solomon Islands, South Korea, Taiwan, United Kingdom, United States	Canada, Germany, Malaysia, Micronesia, Nauru, New Caledonia, Philippines, Russia, Singapore
World Climate Research Program (WCRP)	WCRP's goal is to promote fundamental scientific understanding of the physical climate system and climate processes needed to determine to what extent climate can be predicted and the extent of human influence on climate.	Country participation depends on the WCRP program (see below).	

continued

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
Climate Variability and Predictability (CLIVAR)	CLIVAR studies physical processes responsible for seasonal, interannual, decadal, and centennial climate variability and predictability through collection and analysis of observations and the development and application of models of the coupled climate system, in cooperation with other relevant climate research programs.	Canada, European Union (Austria, Belgium, Denmark, Finland, France, Germany, Greece, Ireland, Italy, Luxembourg, Netherlands, Portugal, Spain, Sweden, United Kingdom), Germany, Netherlands, New Zealand, United States	
Global Energy and Water Cycle Experiment	This project studies the hydrological cycle and energy fluxes by means of global measurements of atmospheric and surface properties; models the global hydrological cycle and its influence on the atmosphere, oceans, and land surfaces; develops predictive models for the variations of global and regional hydrological processes and water resources and their response to environmental change; and advances development of observation techniques, data management, and assimilation systems for operational application to long-range weather forecasts, hydrology, and climate predictions.	Scientific Steering Group: Brazil, China, France, Germany, Japan, Norway, Russia, United Kingdom, United States	

TABLE 4.1 Continued

Title	Goals and Objectives	Principal Participating Countries	Additional Participating Countries
World Ocean Circulation Experiment (WOCE)	The object is to explain ocean circulation well enough to model its current state; predict its future state; predict feedback between climate change and ocean circulation; and develop and implement, in consultation with the CLIVAR Scientific Steering Group, an effective transition of remaining WOCE scientific activities and infrastructure to CLIVAR as WOCE approaches its end.	Intergovernmental Panel: Australia, Brazil, Canada, Chile, China, Colombia, France, Germany, Japan, Netherlands, New Zealand, Nordic Countries (Denmark, Finland, Iceland, Norway, Sweden), Portugal, Russia, Spain, United Kingdom, United States	Argentina, Congo, Costa Rica, Faroe Islands (Denmark), Indonesia, Korea, Peru, South Africa, Ukraine, Uruguay

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[a] IOC Executive Council members are italicized. Afghanistan, Albania, Algeria, Angola, *Argentina*, *Australia*, Austria, Azerbaijan, Bahamas, Bangladesh, Barbados, *Belgium*, Belize, Benin, *Brazil*, Bulgaria, Cameroon, *Canada*, Cape Verde, *Chile*, *China*, *Colombia*, Comoros, Congo, *Costa Rica*, Croatia, *Cuba*, Cyprus, Denmark, Dominica, Dominican Republic, Ecuador, *Egypt*, El Salvador, Eritrea, Estonia, Ethiopia, Fiji, Finland, *France*, Gabon, Gambia, Georgia, *Germany*, Ghana, *Greece*, Guatemala, Guinea, Guinea-Bissau, Guyana, Haiti, Iceland, *India*, *Indonesia*, Iran, Iraq, Ireland, Israel, *Italy*, Ivory Coast, *Jamaica*, *Japan*, Jordan, *Kenya*, *Korea*, Kuwait, Lebanon, Libya, Madagascar, Malaysia, Maldives, Malta, Mauritania, Mauritius, *Mexico*, Monaco, *Morocco*, Mozambique, Myanmar, Namibia, Netherlands, New Zealand, Nicaragua, *Nigeria*, Norway, Oman, Pakistan, Panama, *Peru*, *Philippines*, Poland, *Portugal*, Qatar, Romania, *Russia*, Saint Lucia, Samoa, Saudi Arabia, Senegal, Seychelles, Sierra Leone, Singapore, Slovenia, Solomon Islands, Somalia, *South Africa*, *Spain*, Sri Lanka, Sudan, Suriname, *Sweden*, Switzerland, Syria, Tanzania, *Thailand*, Togo, Tonga, Trinidad and Tobago, *Tunisia*, Turkey, *Ukraine*, United Arab Emirates, *United Kingdom*, *United States*, Uruguay, Venezuela, Vietnam, Yemen.

[b] Argentina, Australia, Bangladesh, Belgium, Brazil, Canada, Chile, China, Denmark, Ecuador, Egypt, Finland, France, Germany, India, Ireland, Israel, Italy, Japan, Korea, Mexico, Monaco, Netherlands, New Zealand, Norway, Pakistan, Peru, Philippines, Poland, Russia, South Africa, Spain, Sweden, Switzerland, Turkey, United Kingdom, United States.

[c] Argentina, Armenia, Australia, Austria, Azerbaijan, Bangladesh (Associate), Belarus, Belgium, Bolivia, Brazil, Bulgaria, Burkina Faso (Associate), Cameroon (Associate), Canada, Caribbean (Associate), Chile, China, Colombia, Costa Rica, Croatia, Cuba, Czech Republic, Denmark, Egypt, Estonia, Finland, France, Georgia (Associate), Germany, Ghana, Greece, Guatemala (Associate), Hungary, India, Indonesia (Observer), Iran (Observer), Iraq, Ireland, Israel, Italy, Ivory Coast (Associate), Jamaica (Observer), Japan, Jordan (Associate), Kazakhstan (Associate), Kenya, Korea (Observer), Latvia, Lebanon, Lithuania, (former Yugoslav Republic of) Macedonia, Madagascar (Associate), Malaysia, Mexico, Moldova (Observer), Monaco, Mongolia (Observer), Morocco, Mozambique (Associate), Nepal, Netherlands, New Zealand, Nigeria, Norway, Pakistan (Observer), Peru, Philippines, Poland, Portugal, Romania, Russia, Saudi Arabia, Senegal (Associate), Seychelles (Associate), Singapore, Slovakia, South Africa, Spain, Sri Lanka, Sudan (Observer), Swaziland (Observer), Sweden, Switzerland, Tajikistan, Thailand, Togo (Observer), Tunisia (Associate), Turkey, Uganda (Associate), Ukraine (Observer), United Kingdom, United States, Uruguay, Uzbekistan, Vatican City, Venezuela, Vietnam (Observer), Zimbabwe.

[d] Antigua and Barbuda, Argentina, Bahamas, Belgium, Benin, Brazil, Burkina Faso, Canada, Chad, China, Colombia, Congo, Cuba, Czech Republic, Denmark, Egypt, Equatorial Guinea, France, Gambia, Germany, Greece, India, Indonesia, Iran, Italy, Japan, Kenya, Korea, Libya, Marshall Islands, Mexico, Moldova, Myanmar, Namibia, Netherlands, New Zealand, Nicaragua, Nigeria, Pakistan, Poland, Romania, Russia, Samoa, Saudi Arabia, Senegal, Slovakia, Sudan, Suriname, Switzerland, Syria, Thailand, Turkey, Uganda, United Kingdom, United States, Uruguay, Zambia, Zimbabwe.

TABLE 4.1 Continued

[e]Antigua and Barbuda, Armenia, Bahrain, Belarus, Bolivia, Bosnia and Herzegovina, Botswana, Brunei Darussalam, Burkina Faso, Burundi, Cambodia, Central African Republic, Chad, Djibouti, Honduras, Hungary, Kazakstan, Kyrgyz Republic, Laos, Latvia, Lesotho, Liberia, Lithuania, Luxembourg, (former Yugoslav Republic of) Macedonia, Malawi, Mali, Micronesia, Moldova, Mongolia, Nepal, Niger, Niue, Papua New Guinea, Paraguay, Rwanda, Sao Tome and Principe, Slovakia, Solomon Islands, Swaziland, Tajikistan, Turkmenistan, Uganda, Uzbekistan, Vanuatu, Yugoslavia, Zambia, Zimbabwe.

- shared investments that require formal long-term agreements at the national level (e.g., the *Jason II* satellite involved the National Aeronautics and Space Administration, the Centre National d'Etudes Spatiales, the National Oceanic and Atmospheric Administration, and the European Organization for the Exploitation of Meteorological Satellites);
- shared operational costs, which only requires informal, ad hoc agreements at the agency level (e.g., the Ocean Drilling Program [ODP], the International Marine Global Change Study);
- coordinated international programs without money exchange, just the informal, good-will cooperation of partners (e.g., the International Geosphere-Biosphere Programme, the World Climate Research Programme), although insecurity of funding is a disadvantage and program flexibility is an advantage; and
- cooperative experiments that only need specific, short-term agreements between agencies (e.g., tectonics in the Gulf of Corinth or deep water formation in the North Atlantic).

Assuming that there is agreement on scientific objectives of a specific international program, formal agreements are preferred to allow the sharing of operation costs for infrastructure; negotiation of specific funding at the national level; and the pooling of funds for implementation of common objectives. In addition to lacking flexibility, it is important to include assessment and evaluation procedures in those agreements. Informal agreements are more tractable for program management, sharing existing tools and infrastructure, and maintaining flexibility.

Following a discussion of Dr. Minster's presentation, the general consensus of the participants was that informal agreements and contributions of national assets would be the most likely route for successfully implementing a large scale international ocean exploration program. Cooperating nations need the freedom to participate in topical and regional exploration that serves the best interest of their citizens, without maintaining financial responsibility for exploration that does not meet their national needs.

The greatest level of international involvement is likely to occur when collaboration is based on each nation targeting its resources to thematic or geographic areas of national interest (Appendix D). Ocean exploration has the potential to engage many nations, both through establishing national programs focused on their own territorial waters and through participation in international cooperative efforts centered in regions or on topics of particular interest. For example, a smaller number of nations would be able to contribute to Arctic exploration than to marine biodiversity studies. Joint projects should be approved by each nation, with cost-sharing opportunities developed as an incentive to move sound project plans forward. Those distinctly international programs would allow the most flexibility for participating nations.

A number of specific program management arrangements, past and present, were discussed at the IGOE Workshop. The most frequently referred to was ODP (Box 4.1). The advantage of ODP's organization is the ability to pool international funds to support one unique facility, the drill ship.

BOX 4.1 THE OCEAN DRILLING PROGRAM

ODP is an international partnership of researchers and academic institutions that collaborate on using deep ocean drilling and coring to explore the evolution and structure of the Earth. U.S. funding for ODP is provided by a single agency (the National Science Foundation), but it is administered by the Joint Oceanographic Institutions, a not-for-profit corporation that receives funding from 23 countries. Contractors for facilities and services are selected competitively. A science committee provides guidance, and peer panels develop program plans and select expeditions. Performance evaluation committees report regularly to a governing board on the performance of contractors and the corporation. This program model allows ample opportunity for, and relies on, community participation and buy-in. Such openness to public, academic, and private-sector participation would benefit an ocean exploration program. ODP has been accountable in its performance; the budget is transparent, and an audit is performed annually. International partners have been actively engaged since 1974, exemplifying the global participation that will be critical to an ocean exploration program. Bilateral agreements have effectively facilitated international collaboration and, as a result of the success of the Joint Oceanographic Institutions, a new international not-for-profit corporation has been formed for the new phase of ocean drilling, the Integrated Ocean Drilling Program.

International collaboration is robust in ODP—22 nations participate effectively under a collection of bilateral agreements. The model also allows for scientific review of proposals, open participation in the proposal process, and frequent dialogue among managers, science advisory, and facilities panels. While the example that ODP sets is useful for framing the management of an ocean exploration program, ODP itself would not be an appropriate program for operation of the program due to its emphasis on drilling, rather than more interdisciplinary efforts. Furthermore, the ODP model, designed to facilitate managing a single, large asset, does not encourage contributions of diverse, independently owned and operated assets, such as those necessary for exploration. While it might be possible for those nations to combine forces to mount an international ocean exploration program, either modeled after or included within the highly successful ODP, the IGOE Workshop participants did not find a compelling rationale for such a recommendation.

In fact, many more nations than the current ODP membership are interested in exploring their own territorial waters and neighboring ocean basins. Several of those countries are near largely unexplored areas of the global ocean, notably the Southern and Arctic Oceans. A single international program is of less interest to these nations than more targeted programs specifically addressing geographic or topical areas of national interest. As highlighted at the IGOE Workshop, the full range of topics and regions that could be incorporated into an exploration program is too broad to allow for effective international partnering and management.

Other nations might follow a U.S. example by forming national ocean exploration initiatives. Lead organizations for those national programs could be government agencies, such as that proposed by this report for the United States, or other relevant institutions. As such parallel programs are established it could become necessary to set up an informal umbrella organization to provide information sharing and coordination among national programs. An excellent template for this process is the U.S. Ridge Interdisciplinary Global Experiments (RIDGE) program, which prompted other nations to set up their own programs for interdisciplinary study of midocean ridges. InterRIDGE is the international coordinating organization.

INVITATION TO OCEAN EXPLORATION WITHIN THE ANNUAL UNITED NATIONS GENERAL ASSEMBLY OCEAN RESOLUTION

The importance of international ocean exploration should be discussed at high levels of international governance. It would be useful for the U.S.

Department of State to coordinate with the United Nations Law of the Sea Office and the Intergovernmental Oceanographic Commission (IOC) to propose a new statement about the importance of ocean exploration in the annual General Assembly ocean resolution (Box 4.2). For some years, the United Nations General Assembly has adopted a resolution with recommendations concerning ocean issues (e.g., *Law of the Sea of 1994*, 49th General Assembly, A/RES/49/28; *Oceans and Law of the Sea of 1998*, 53rd General Assembly, A/RES/53/32; *Oceans and Law of the Sea of 2002*, 57th General Assembly, A/RES/57/141). This proposed resolution calls attention to the promise of ocean exploration, and it would be a significant vehicle for stating the desirability of broad international participation.

VOLUNTARY INFORMATION SHARING

Broad information sharing about ocean exploration initiatives, whether undertaken by the United States or by other nations, should be encouraged. A proposed model for information sharing is detailed in Figure 4.1, and it would include information about current exploration programs; potentially available resources, including ships and scientists; and proposals for exploration. IOC of the United Nations Educational, Scientific, and Cultural

BOX 4.2 PROPOSED GENERAL ASSEMBLY OCEAN RESOLUTION

Whereas basic knowledge about Earth's oceans is in the overall interest of humankind;

Recognizing there are large areas of the ocean in which we lack such basic knowledge; and

Convinced that cooperation in oceans exploration (seeking basic knowledge about the oceans and ocean processes) holds promise to enhance understanding of our planet.

The General Assembly:

Urges nations to seek to enhance basic understanding about the oceans through programs and activities of ocean exploration and to cooperate together to that end;

Calls upon IOC to consider establishing a voluntary information-sharing program for the cooperative sharing of information about ocean exploration, including planned programs and proposals, institutional and national interests, scientific and technical expertise, capacity building capabilities, available oceanographic ships, and other national or institutional resources available for such exploration; and

Nothing in this resolution is intended to affect the legal regime for the oceans as set out in the United Nations Convention on the Law of the Sea.

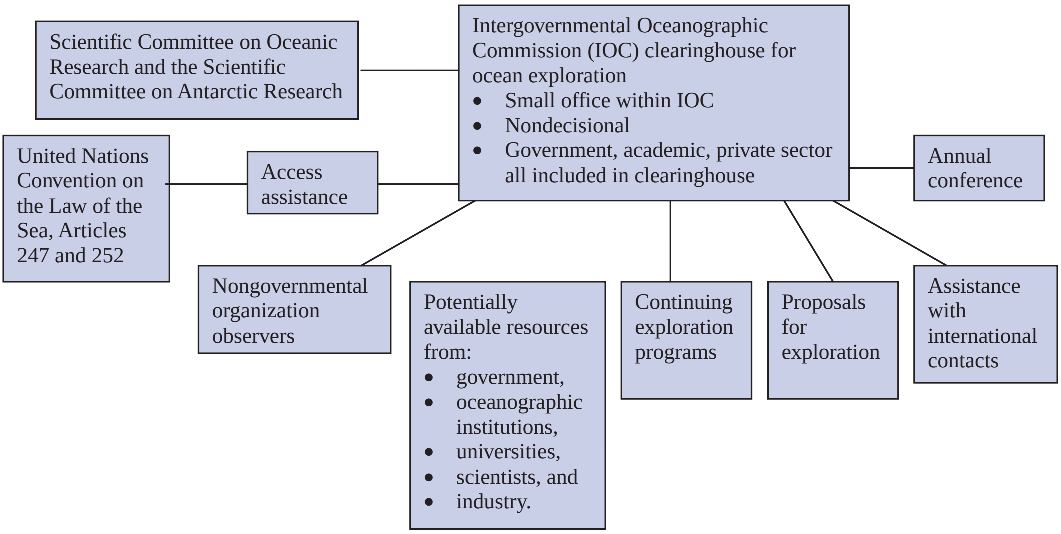

FIGURE 4.1 IOC voluntary information-sharing process for ocean exploration.

Organization is well positioned to execute such a function and might also be able to assist in communicating with governments the importance of cooperative ocean exploration. IOC also might consider sponsoring an annual conference on ocean exploration at IOC headquarters to solicit input for existing programs and discuss potential new collaborations, while seeking advice from the Scientific Committee on Oceanic Research and other interested entities as appropriate. The IGOE Workshop hosted by IOC demonstrated great international interest, as well as capabilities, in ocean exploration from developed and developing countries from many regions and for many disciplines.

CONSIDERATIONS FOR INTERNATIONAL PROGRAMS

A host of factors must be considered prior to establishing any international exploration program. At a minimum, each participating nation must agree to data standards and access policies. Several issues must be resolved before international collaborative programs become commonplace. Mechanisms must be established for sharing data, equipment, and costs; for use prioritization; for safety; and for access to areas within each country's exclusive economic zone.

Agreements also must include consideration of asset sharing. In the simplest agreements, each nation would maintain financial responsibility for its participants and equipment in any joint projects. Costs for participants from nonpartner nations, such as those from developing nations in the region being explored, should be considered and shared by the partners.

Cooperative oceanographic research relies on the availability of specialized, often customized and expensive, equipment. Because most oceanographic equipment is not insured, one challenge to sharing equipment is whether the borrower can guarantee to replace or repair lost or damaged equipment. Sharing equipment also presents the problem of use prioritization. Planning is critical for oceanographic work, and equipment must be available for loading, use, restoration, and repair, if necessary. If a promised piece of equipment becomes unavailable because of poor planning or unforeseen complications, time, resources, and sometimes even the entire project can be wasted or jeopardized. Those problems can be addressed in bilateral agreements and through strict enforcement of contracts.

Safe practices are required to ensure personal safety and equipment integrity. Some countries have rigorous safety programs—such as the University-National Oceanographic Laboratory System within the United States—that are strictly enforced and followed. Many countries, however, do not have such rigorous standards. Researchers who use oceanographic assets operated by countries with less rigorous safety standards than those of the United States assume their own risk—some unknowingly. To ameliorate this situation, and to protect the unknowing, each participant nation in an international program should develop and publish safety standards with verifiable check points to ensure that a legitimate program is in place and used effectively.

Finding: A single, all-encompassing international program is not feasible at the initial stages of program development. A single international global ocean exploration effort would likely be overcome by the bureaucratic structure under which it operated. Building cooperative agreements for shared projects should be a more effective approach to program development.

Recommendation: Given the considerations presented, it is prudent to begin an exploration effort with a model for a U.S. national program that will encourage collaboration and capacity building and that would be likely to lead to the development of similar programs in other

countries. Once other national programs are established, consortia of nations can voluntarily collaborate on program plans and pool resources using multilateral international agreements to undertake regional exploration or to pursue themes of shared interest. By developing distinct exploration programs for international cooperation to seek discoveries of specific resources or investigate regional features, the burden of international policy and agreements will be greatly reduced.

5

Domestic Organization and Management of an Ocean Exploration Program

Incorporating a new ocean exploration program into the U.S. marine science field presents numerous challenges. The large scale of the program, the interdisciplinary nature of the research, and the need for participation by a number of agencies must be taken into consideration. The United States maintains the world's largest national commitment to national and international ocean research. Progress in the ocean sciences is largely attributable to support given to individual, independent projects and to large-scale, multiple-investigator programs. Support of U.S. ocean research programs comes primarily from the National Science Foundation (NSF), the Office of Naval Research, the National Oceanic and Atmospheric Administration (NOAA), the National Aeronautics and Space Administration (NASA), and the U.S. Geological Survey, with additional support from many other government and private sources. The large scale of the program, the interdisciplinary nature of the research, and the need for participation by a number of agencies must be taken into consideration.

In a review of processes for selecting regional marine research, the National Research Council described four approaches: community plans, scientists' plans, agency plans, and legislative mandates (National Research Council, 2000b). Briefly, community plans are developed using a broad range of input from stakeholders, planners, and researchers; scientists' plans are developed generally through a series of scientific fora; agency plans seek to meet mission requirements; and legislative mandates are direct congressional requests.

Of the four types of approaches, both the scientists' and agency plans are the most commonly used for project selection, and could be appropriate for ocean exploration. NOAA funds research more readily using the agency plan model, while NSF uses the scientist plan model (National Research Council, 2000b). Within NOAA, this agency-driven research agenda serves to assist the agency with meeting its mission, which in the case of NOAA, includes such diverse needs as support for regulations protecting living resources (fisheries and protected species), navigational charts, and weather forecasting. Most NSF ocean research is motivated by scientists' plans and conducted under individual, competitively funded grants. Panels of peer reviewers judge proposals according to a host of criteria including investigators' track records, the importance of problems to be addressed, and the adequacy of investigative techniques. Broader criteria also are considered—educational benefits, outreach, and whether contributions are possible that will benefit society. This process has worked well for short-term (two- to three-year) projects with clear, testable hypotheses. Larger programs, such as the World Ocean Circulation Experiment, the Integrated Ocean Drilling Program, and the Ridge Interdisciplinary Global Experiments complement the smaller projects. The larger programs are developed with more integrated, interdisciplinary, and long-term goals that are too lengthy and intricate to be completed by a single investigator. Projects within those programs are selected not only for their scientific excellence, but also for their anticipated contributions to broader program goals.

Ocean exploration best fits within this last category of funding models: the program must be larger, better coordinated, longer term, and more interdisciplinary than individual investigator grants, while still being primarily science (rather than mission) driven. Individual exploration expeditions should be chosen based on their quality and their contribution to broader exploration goals. Even using this model as the basis for exploration, there are several choices for where this large-scale program would be placed within the federal government and how it would be structured. The National Research Council noted in its report *Global Ocean Science* that "[t]he effectiveness and to some degree, the character of these major programs can be greatly influenced by the program's structure" (National Research Council, 1999). For that reason, the committee invested substantial time and effort in debating the lead agency and administrative structure for ocean exploration so as to achieve a program that is:

1. goal and theme oriented;
2. scientifically excellent and creative;
3. international;
4. well funded in the long term;
5. reasonably independent from the missions of agencies involved;
6. provided with access to the highest-quality technical assets;
7. multisector, involving government, commercial, academic, private, and nongovernmental organizations;

8. highly visible to the public and involved in educational outreach;
9. efficiently managed; and
10. independently evaluated.

PLACEMENT OF OCEAN EXPLORATION WITHIN THE FEDERAL GOVERNMENT

The committee struggled with the difficulty of simultaneously satisfying goals 4 and 7 above. Consistent, adequate funding for a large-scale program requires a strong advocate and leader to guide the initiative through the federal budget process. This is a potential argument for housing exploration within a single agency, but only if the agency considers the program a high priority. If the agency does not have a vested interest in the success of the program, other efforts will be promoted instead, almost surely resulting in the program's demise. Placing an exploration program within a single agency, however, can dampen the interagency cooperation that is especially important in ocean research, which unlike space research, is scattered among a number of agencies including NSF, Navy, and NOAA. In recognition of the fact that many federal ocean science agencies bring capabilities and expertise to the table, the U.S. Congress created the National Ocean Partnership Program (NOPP) (Box 5.1).

A National Oceanographic Partnership Program Sponsored Exploration Program

NOPP is the government's best attempt to date at interagency cooperation. NOPP has embraced the task of implementing ocean observatories in an integrated, multi-agency manner. For example, through NOPP, there is not just one agency advocating ocean observing: there are many. Through NOPP's Ocean.US office, which is jointly supported by several NOPP member agencies, this inter-governmental organization is tackling major issues on the development, installation, and operation of ocean observatories that either cannot or should not be undertaken by one agency in isolation. NOPP is able to pool funds from the partner agencies and nonfederal sources to fund research proposals that respond to a broad interagency solicitation. The program has consistently encouraged proposals from teams that include academic, commercial, federal, and other not-for-profit partners. The leaders of the agencies meet twice annually to review program accomplishments and directions, and an Interagency Working Group is tasked with the day-to-day operation of the program. The program's independent advisory

BOX 5.1 NATIONAL OCEANOGRAPHIC PARTNERSHIP PROGRAM GOVERNANCE

NOPP is a collaboration of 14 federal agencies that seeks to lead and coordinate national oceanographic research and education programs. The National Ocean Research Leadership Council (NORLC), the decision-making body of NOPP, confirms NOPP activities and funding opportunities (Figure 5.1). NORLC is responsible for establishing NOPP policies and procedures. NORLC meets biannually to review and approve NOPP activities, reporting annually to Congress. NORLC membership is legislatively mandated to include the heads of the 14 federal agencies involved in conducting or funding ocean research or developing ocean research policy.

With membership that reflects NORLC's, the Interagency Working Group manages the day-to-day oversight and coordination functions of NOPP, such as formulation of recommendations to NORLC, implementation of NORLC decisions, routine interactions across agencies under NOPP, coordinating with the Ocean Research Advisory Panel, and oversight of the NOPP Office. The Interagency Working Group also makes funding recommendations to NORLC and oversees any interagency processes necessary to transmit funds for approved NOPP activities.

The Ocean Research Advisory Panel meets twice a year to provide scientific guidance to NORLC. It is composed of representatives from the National Academies, ocean industries, state governments, academia, and other appropriate organizations and communities.

The Federal Oceanographic Facilities Committee, composed of federal oceanographic facilities managers, advises NORLC on policies, procedures, and plans relating to oceanographic facility use, upgrades, and investments. The Committee also provides guidance on requirements and other matters relative to national oceanographic assets.

The NOPP Office was established by NORLC to assist in the management of NOPP and provide daily administrative support. Using competitive procedures, a contract for the operation of the NOPP Office was awarded to the Consortium for Oceanographic Research and Education in July 1997.

group, the Ocean Research Advisory Panel, has already recommended that NOPP embrace ocean exploration as an additional theme area to complement ocean observing and to better engage the public in ocean issues.

NOPP is an existing organization that would allow the major agencies with an interest in ocean exploration and the necessary assets, such as NOAA, NSF, and the Navy, to pursue a major program cooperatively, and assume leadership of various aspects as fits with the agency's ability. For example, NOAA might take on the task of systematic ocean mapping, with NSF piggybacking programs for assessing biodiversity in the midwater, while the Minerals Management Service adds the equipment and expertise to assess nonliving resources on those mapping expeditions. An additional

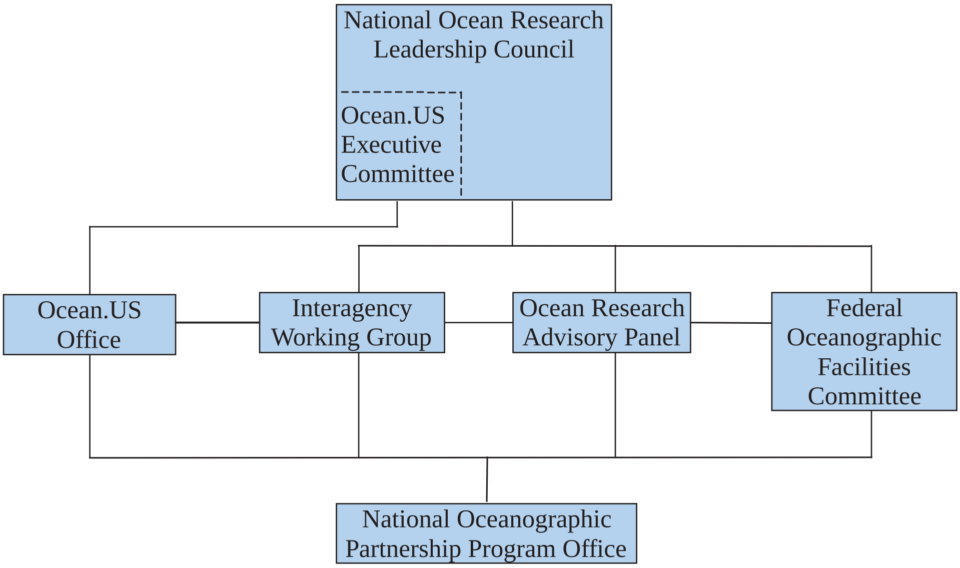

FIGURE 5.1 Current governance structure of the National Oceanographic Partnership Program (used with permission from the National Oceanographic Partnership Program Office).

advantage of placing an ocean exploration program under the auspices of NOPP is that it allows for other member agencies, such as the National Aeronautics and Space Administration (NASA), the U.S. Geological Survey, and the Environmental Protection Agency, to participate at any level without any additional bureaucracy.

Within NOPP, a new Ocean Exploration Interagency Task Force could integrate the initiative across the full range of governmental capabilities and encourage efficient use of funds. Task force membership should include representatives from all federal agencies with ocean interests, including the National Endowment for the Humanities, to ensure that relevant ocean exploration disciplines, such as marine archaeology, are included. The task force should be aware of and promote efficient leveraging of assets that could be achieved by conducting ocean exploration activities during the course of other oceanographic missions. The task force would convene to coordinate ocean exploration initiatives and opportunities at the government level worldwide. The group would encourage cooperative international use assets. Funding agencies should be engaged early through the task force to plan for collaborative exploration programs proposed by international groups of scientists.

The major drawback of a NOPP-sponsored ocean exploration program is that NOPP itself cannot directly receive funds appropriated by Congress. Garnering the financial resources for NOPP projects is dependent on the goodwill and cooperation of the member organizations. Interagency coordination is not unprecedented—the National Polar-orbiting Operational Environmental Satellite System combined the efforts of the Departments of Commerce (NOAA) and Defense to consolidate satellite needs for polar data gathering. NOAA leads the management, the Department of Defense leads acquisition efforts, and NASA provides technology developments to meet the systems' operational requirements. However, funding a major program through separate line items in many agency budgets is not a desirable situation. The committee believes that NOPP could be a nearly ideal home for ocean exploration if the difficulties in funding NOPP programs can be overcome. The tremendous disadvantage NOPP programs face in the federal funding process has received considerable attention from the U.S. Commission on Ocean Policy.

A National Oceanic and Atmospheric Administration Funded Exploration Program

In recognition of the need for a separate program for ocean exploration, and in response to the report of the President's Panel on Ocean Exploration (National Oceanic and Atmospheric Administration, 2000), NOAA created an Office of Ocean Exploration in 2001 and has received modest funding to support it. NOAA managers develop program plans and choose expeditions from solicited proposals after seeking advice from a panel of peer reviewers. Clearly, capitalizing on this existing NOAA program and office could assist in the establishment of a new, large-scale program. The office has leveraged agency assets efficiently, and NOAA has worked to seek adequate funding for the program. Since its establishment, the NOAA program has included an engaged and substantial outreach program, and it has shown commitment to elementary and secondary education. NOAA's experience in public affairs, education, and outreach would be an asset to an ocean exploration program.

There are specific elements of NOAA upon which a successful, truly global program can be built. They include NOAA's rapid response capability, the ocean and atmospheric modeling work done in conjunction with NASA, and problem solving demonstrated by targeted programs such as the Hydrothermal Vents Program and the Geophysical Fluid Dynamics Lab.

NOAA's current program has significant drawbacks, however. Outside the agency, the Ocean Exploration program is perceived as favoring internal NOAA agency topics and U.S. coastal regions, as opposed to exploring new frontiers in the least known oceans. The perception arises, in part, from the opaque budget and program selection processes. Program goals are vague, making it difficult to maintain exploration priorities independent of NOAA's mission. As a result, it could be difficult for the agency to maintain program direction true to its founding vision in times of fiscal hardship and in the face of pressure to focus on the agency mission.

Recurring problems, such as slow grant processing and a lack of responsiveness to researchers, undermine the program's reputation in the oceanographic community, and are likely to only get worse if the program grows in size. For instance, the academic research community is not engaged in the expedition-planning process. As a result, support from the community is not likely to increase as necessary for a premier program.

Although allowances should be made for this young program, the trends in management, funding, and involvement of the scientific community have been troubling. Congressional earmarks are already appearing in the program budget resulting in a limited programmatic flexibility; the highest priority areas and highest quality proposals often do not receive funding. The office appears to be somewhat of an orphan—ocean exploration is not included in the latest NOAA strategic plan (National Oceanic and Atmospheric Administration, 2003b). There also are no plans for a completely external, independent assessment of program success. If these problems were allowed to persist in the management or oversight of a larger program, the quality and effectiveness of the program would be seriously compromised.

For a large-scale ocean exploration program to be successfully led by NOAA, there must be a fundamental departure from the current NOAA Office of Ocean Exploration. At a minimum, the agency would need to demonstrate a high-level commitment to exploration, a more open forum for setting program goals, a more transparent decision-making process, more efficient program management, the willingness to involve major agency partners and undergo external review, and an improved ability to protect ocean exploration funds from redirection towards mission-oriented research. The U.S. Commission on Ocean Policy has recognized some of the structural problems that limit the effectiveness of NOAA as the nation's oceans agency.

A National Science Foundation Funded Exploration Program

The National Science Foundation already has experience in running a major ocean exploration program. The International Decade of Ocean Exploration (IDOE) was a large-scale ocean exploration effort that incorporated many separate projects from 1971 to 1980. Congress provided funding through NSF, a non-mission-oriented agency, and, although the program was directed by an NSF program manager, advice was provided by a steering group comprising of members of the academic community. The program was deemed a success and remained true to the founding vision.

A new program in ocean exploration that followed the examples of IDOE would benefit from NSF's reputation for excellence both nationally and internationally. Incorporating an exploration program into NSF would not create any new institutions, and it would take full advantage of University-National Oceanographic Laboratory System capabilities. NSF also has relatively low administrative overhead, leaving more funds available for research. NSF has successfully managed the U.S. Antarctic Program (National Science Foundation, 1997), which shares some elements of an ocean exploration program: high-tech infrastructure, multidisciplinary research, grants management, and logistical support. NSF management of other successful programs—the Ridge Interdisciplinary Global Experiments, the Ocean Drilling Program (ODP), and the World Ocean Circulation Experiment—is familiar to the oceanographic community and could result in strong research community involvement and support. Programs conducted under this model, especially IDOE, have boosted the international visibility and scientific output of the oceanographic community and produced data sets of lasting value.

Incorporating an ocean exploration program within NSF would not be without problems. During IDOE, NSF had difficulty engaging federal partners, such as NOAA, NASA, and the U.S. Navy, so assets were not effectively leveraged. Scientists from agencies with stated missions were at a disadvantage in academic peer review because of their unfamiliarity with the process and with the academic research community. Although siphoning of exploration funds to agency missions must be avoided, a successful exploration program should allow agency scientists to compete fairly in the proposal process. More importantly, an NSF model could result in a loss of commitment from NOAA, the agency that is most aggressively pursuing the program. Finally, although NSF has significant input into the scheduling of the University-National Oceanographic Laboratory System facilities for NSF-funded science, its experience in operating ships through ownership or lease is restricted to the Office of Polar Programs and ODP, and thus it has less control over the capabilities and operations than is necessary for an exploration program.

After weighing the issues involved in oversight and funding, perhaps the most appropriate placement for an ocean exploration program under the auspices of NOPP, provided that the problems with routing funds to NOPP-sponsored projects is solved. This solution has the best chance of leading to major involvement by NOAA, NSF, and other appropriate organizations such as the Office of Naval Research. The committee is not prepared to support an ocean exploration program within NOAA unless the major shortcomings of NOAA as a lead agency, as described above, can be effectively and demonstrably overcome. A majority of the committee members felt that the structural problems limiting the effectiveness of NOAA's current ocean exploration program are insurmountable. A minority of the committee members felt that the problems could be corrected. If there is no change to the status quo for NOPP or NOAA, the committee recommends that NSF be encouraged to take on an ocean exploration program. Although a program within NSF would face the same difficulties of the existing NOAA program in attracting other federal (and nonfederal) partners, NSF has proven successful at managing international research programs as well as a highly-regarded ocean exploration program that remained true to its founding vision.

> **Finding: After exhaustive deliberation, the committee found that an ocean exploration program could be sponsored through NOPP, or through one of the two major supporters of civilian ocean research in the nation: NOAA or NSF.**
>
> **Recommendation: NOPP is the most appropriate placement for an ocean exploration program, provided the program is revised to accept direct appropriations of federal funds. If those funding issues are not resolved, NOAA (with consideration to the comments above) or NSF would be appropriate alternatives.**

MANAGEMENT OF AN OCEAN EXPLORATION PROGRAM

An ocean exploration program could be managed within the sponsoring agency or through a contract to an independent entity. In the past, it was common for major programs to be managed from within the sponsoring agency, even at NSF, which maintains a lean administrative structure and no in-house research or facilities. The advantages of retaining the management for major programs within the sponsoring agency are that the agency retains ownership of the program, connections to other internal agency programs are tight, and those within the agency who have nurtured the program are rewarded by assuming leadership. In fact, this is the route that NOAA has adopted for its current ocean exploration program.

In recent years, agencies are increasingly turning to nongovernmental groups to take on the day-to-day operations of large programs. The advantages of this approach are several. First, the process of competitive bidding for the management of the program leads to creativity in program design, cost savings, and incentives for excellent performance. Second, as programs build up and close down, there is no need to accommodate the personnel requirements through agency headcount. NSF chose the independent contractor route in selecting the Joint Oceanographic Institutions (JOI) (Box 5.2) to run ODP (Box 4.1), and has recently issued a request for proposals for management of the Ocean Observing Initiative. NASA will be selecting an independent contractor to manage the International Space Station (ISS) (Box 5.3).

The advantages of an external contractor are potentially even greater for an ocean exploration program. For example, if NOPP were to lead the effort, management by an independent contractor would provide a neutral third party to balance the interests of the various agency partners and accept contributions from a variety of public and private sources. If NOAA were to lead the program, management by an external group could mitigate some of the perceived inadequacies in the present, internal-NOAA program. For example, the program would be an "arm's length" away from the pressures of the agency mission and subjected to regular external review. Depending on the choice of the external managing organization, grant processing, priority-setting, connection to the external community, and transparency of decision making could be improved. If NSF were asked to lead the program, the agency would almost surely choose this route rather than build internally the infrastructure to manage the exploration-specific assets and data system.

BOX 5.2 JOINT OCEANOGRAPHIC INSTITUTIONS

JOI is a private, nonprofit organization that brings to bear the collective capabilities of individual oceanographic institutions on research planning and management in the ocean sciences. Membership is by invitation only, and currently stands at 18 institutional members. Members pay annual dues, which support some basic administration. JOI has successfully bid on the management of several major programs, such as NSF's ODP and the U.S. Science Support Program. The size of JOI's organization can expand or contract to meet the needs of its current contracts. Agencies with interests in marine research have also found JOI a useful organization for convening meetings and workshops given its responsiveness and connection to the academic community.

The central controlling body of JOI is the JOI Board of Governors, whose members are representatives of U.S. oceanographic and marine research institutions, or other organizations, that are partners in ODP (Figure 5.2, refer to figure for acronym definitions). EXCOM comprises U.S. and non-U.S. members and is a subcommittee of JOI. EXCOM approves scientific and operational plans developed by SCICOM, and sets policies for the achievement of the program's objectives. Actions of EXCOM are subject to approval by the Board of Governors and JOI manages the program including international co-mingled funds. EXCOM also evaluates and assesses ODP accomplishments in the context of the established goals and objectives of the Long Range Plan. BCOM oversees and reviews ODP's program plans and budgets. The Joint Oceanographic Institutions for Deep Earth Sampling's science advisory structure is directed by SCICOM, which consists of two Science Steering and Evaluation Panels, several planning groups, TEDCOM, OPCOM, and three service panels. Each of these units follows the guidelines and mandates of SCICOM that are EXCOM approved. SCICOM's responsibilities include: supervision of ODP's Long Range Plan; prioritizing drilling proposals that address the scientific goals of the Long Range Plan; approval of OPCOM's annual drilling schedule; long-term science development; organizing Program Planning Groups; internal and public communication; assigning advisory panels proposals to review; and suggesting prospective Co-Chief Scientists for each drilling leg. ESSEP and ISSEP evaluate drilling proposal quality and foster ocean drilling proposals that concentrate on issues that are best solved by drilling. These panels recommend proposals for external comment so that SCICOM can better rank them. TEDCOM recommends the appropriate drilling tools and techniques required to meet scientific objectives, and recognizes tools and techniques that need to be improved and supervises this progress. OPCOM deals with operational issues, such as ship scheduling, technological development, and scientific measurements and advises SCICOM on scientific implementation and technological development needed to achieve ODP's goals (Ocean Drilling Program, 2001a, 2001b).

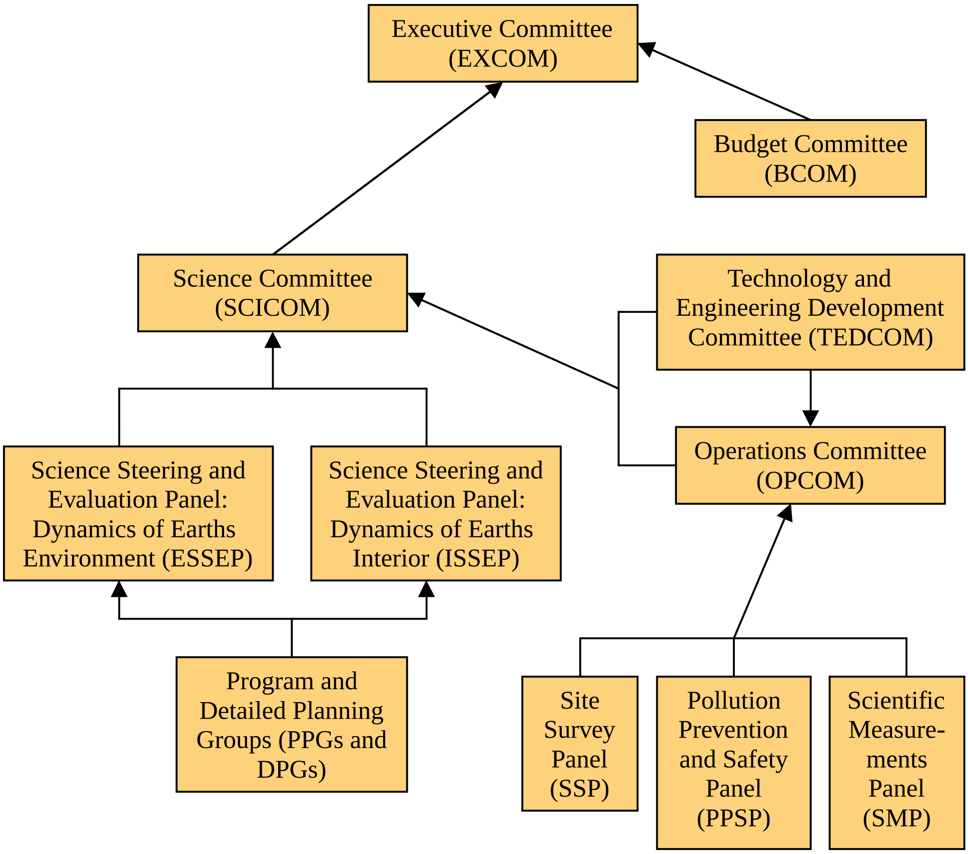

FIGURE 5.2 The advisory structure for Joint Oceanographic Institutions for Deep Earth Sampling (modified from Ocean Drilling Program, 2000).

BOX 5.3 THE INTERNATIONAL SPACE STATION

Perhaps the best-known international scientific collaboration is ISS. This innovative program seeks to construct human habitat in outer space, to allow humans to learn how to live and work in space, and to develop a world-class research facility. Research will be conducted on the effects of long periods of weightlessness on human health—a prerequisite for human exploration of Mars. NASA began the space station program in 1984, and a memorandum of understanding was signed by Canada, Japan, the European Space Agency, and the United States in 1989. Russia joined in 1993, and as of 1998, it had received about $800 million from NASA for U.S. portions of the space station that were contracted to Russia—the only exchange of money between partners. Currently, Belgium, Canada, Denmark, France, Germany, Italy, Japan, the Netherlands, Norway, Russia, Spain, Sweden, Switzerland, the United Kingdom, and the United States are ISS partners (Smith, 2002). Financial and equipment contributions determine each nation's share in the research program.

In 1998, NASA proposed that a nongovernmental organization, which would report to NASA, should oversee space station research by managing and operating ISS. In February 2003, "Congress gave NASA a green light to create a private institute for research aboard the orbiting laboratory" (Lawler, 2003). The arrangement will be modeled on NASA's Space Telescope Science Institute at Johns Hopkins University, in Baltimore, Maryland, which directs the Hubble Space Telescope (Smith, 2002). The nongovernmental organization, which should be selected by the end of 2004, initially will manage a few aspects of the space station pertaining to science, technology, and commercial research. Once competence is established, NASA will hand over increasingly more duties (Smith, 2002). By deferring ISS management to another organization, NASA hopes to better assist research, increase research opportunities, and enhance ISS's long-range efficiency in science, technology, and commercial research and development (National Aeronautics and Space Administration, 2002a).

The decision to establish a private overseer was in response to FY2001 and FY2002 Appropriations Acts (P.L 106-377; P.L. 107-73), directing NASA to complete an assessment of ISS management options. NASA analyzed a range of options, from the agency's continued supervision of ISS to establishing an independent government entity that would completely assume direction of the space station. A thorough qualitative and quantitative analysis of each option led NASA to propose that a nonprofit institute could optimize ISS management. This institute would "perform research leadership functions for ISS, which will maximize return of science results, advanced technologies, and commercial applications" (National Aeronautics and Space Administration, 2002a).

The implementation of a nonprofit institute is expected to lead to a more effective and efficient space station program. NASA seeks to reduce the research community's detachment from ISS, and dedicate itself to making ISS a world-class international research resource, with appropriate science guidance and opportunities for experimentation. Although not yet implemented, the use of a nonprofit organization appears to have advantages that would benefit a large-scale, international engineering and science program.

Finding: Management of large-scale ocean research programs can be effectively and efficiently operated through the use of independent contractors. Nonfederal operators can receive support from multiple government agencies and receive financial support from private sponsors. Independent audits of program performance can be used to ensure the program is achieving the desired outcomes.

Recommendation: A nonfederal contractor should be used to operate the proposed U.S. ocean exploration program. The original contract should be awarded following a competitive bidding process. The program should be reviewed periodically and should seek to leverage federal resources for additional private contributions.

SUGGESTIONS FOR THE OPERATION OF AN EXPLORATION OFFICE

The committee believes that the arguments in favor of managing ocean exploration through a nonfederal contractor are compelling, regardless of which organization sponsors the program. The management of an independent Exploration Program for the Oceans (ExPO) office should be competitively awarded. ExPO would establish science committees to formulate program plans, manage program assets, award competitive grants for exploration proposals consistent with planning, and award other grants and contracts. The contracts could include support for important infrastructure, such as data management. International expertise in the form of an International Global Ocean Exploration (IGOE) committee would provide the national program with advice from respected ocean explorers worldwide. Because ExPO would be chosen competitively and evaluated periodically, it would be subject to rigorous scrutiny and held to a high standard of accountability. The oversight of ExPO would be critical to ensure proper management and should include a board of governors, science committees, and an IGOE committee. Participants from the private sector, the academic community, and government would participate in those groups with the exception of the Board of Governors (Figure 5.3).

The proposed ExPO structure offers a process for project selection that follows most closely the ODP model for review, ranking, and selection of proposals. Selection of projects would begin in the subcommittees of ExPO's Science Committee. Subcommittees could be geographic or thematic (e.g., biodiversity and Arctic exploration). Each subcommittee would first design program plans based on broad questions using the scientific method. The subcommittees might convene community workshops to

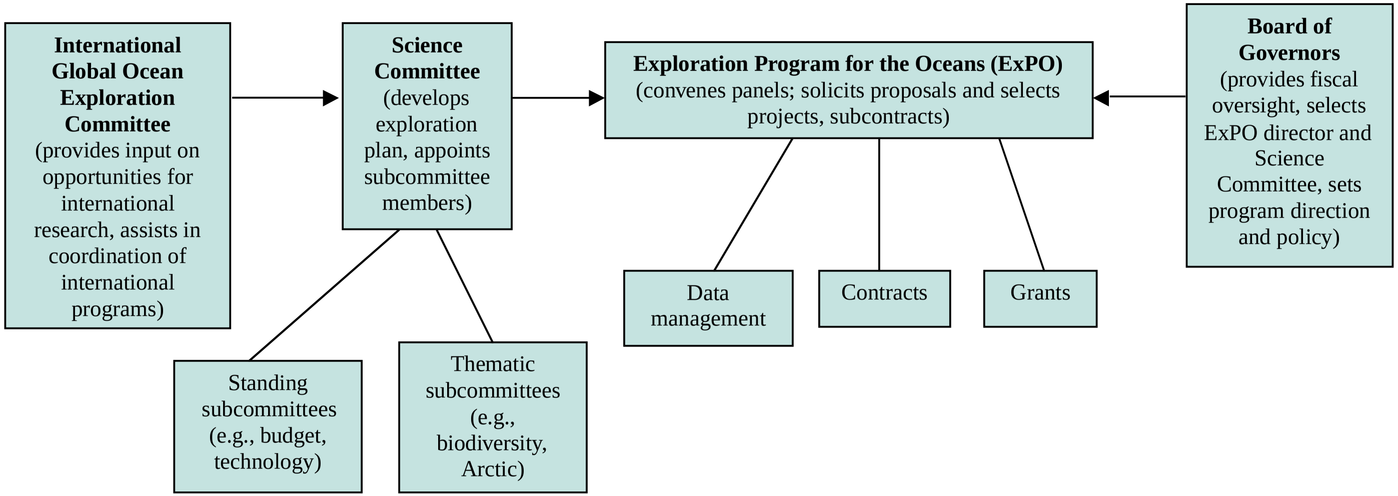

FIGURE 5.3 Possible structure of the ExPO office, based on the advisory structure for the Joint Oceanographic Institutions for Deep Earth Sampling (Figure 5.2).

formulate the exploration plans, which ultimately would be approved by the Science Committee and shared with other subcommittees to identify areas of common interest and overlap. If overlapping areas are anticipated, subcommittee liaisons would be appointed.

Teams of investigators would submit proposals that respond to elements of the program plan for one or more of the theme or priority areas. Proposal teams would have members from several disciplines, including, for instance, biology, geochemistry, marine chemistry, and physical oceanography, as necessary. Examples of appropriate proposals are presented in Boxes 5.4 and 5.5. Proposals would be distributed to the most appropriate subcommittee for review, with input from other appropriate subcommittees as needed. Each subcommittee would present its top-ranked proposals to the Science Committee each year, and superior but unfunded proposals for which there is continued interest would be considered again. The Science

BOX 5.4 BIODIVERSITY PROPOSAL

A team of investigators proposes to conduct autonomous underwater vehicle (AUV) video surveys along a transect in the Atlantic Ocean between the Grand Banks and the Sargasso Sea to determine the identity, abundance, and diversity of mesopelagic fauna associated with surface productivity. Six AUVs will be equipped with conductivity, temperature, and depth counters; plankton counters; red lights; and low-light video cameras. AUVs will porpoise up and down through the water column in swath formation along the track, automatically homing in on the support ship periodically for fresh batteries and to download data. The surface ship is equipped with a remotely operated vehicle and a human occupied vehicle to collect for physiological and genetic analysis some of the more unusual, fragile, and undescribed species encountered along the transect. While the submersibles are serviced, the ship collects water samples via a rosette to measure carbon export from the surface waters via ^{234}Th. The results are combined with satellite observations of chlorophyll appropriate to the season of the year and altimetry for real-time geostrophic oceanography data on the distribution of water masses. The transects are run four times: spring, summer, fall, and winter. A computer program makes a first cut through the videos to determine which frames show macroorganisms. A video analyst then identifies the organisms in the flagged frames, providing statistics on the absolute numbers of organisms and their diversity. The transect data are used to place the results from the submersible sampling within a broader framework of marine biomass and biodiversity. The ExPO office would be responsible for coordinating with other research programs, such as the Census of Marine Life, to integrate the new exploration data and relate the findings to the public.

BOX 5.5 ARCTIC PROPOSAL

A team of investigators, consisting of physical oceanographers, marine chemists, and microbiologists, proposes to install an array of deep moorings under the Arctic ice to monitor the intrusion of warm, saline Atlantic seawater under the ice cap. The moorings are installed from an ice-breaker, with some sites in the array accessed by the ship's helicopter, which deploys a small drilling rig. The ship conducts multibeam mapping and other measurements along its course to contribute to other themes of the Arctic Science Committee. The deployed moorings are equipped with conductivity, temperature, and depth counters, nitrate analyzers, osmotic water samplers, and molecular probes that identify microorganisms by genetic code. The moorings have sufficient battery life to operate unattended for one year, during which time they monitor the waxing and waning of the intrusion of Atlantic water under the ice and the associated transport of heat, chemical compounds, and microorganisms into the Arctic environment. Weekly data "messengers" are deployed to melt through the ice and transmit data to ExPO via satellite link. If a major under-ice event is observed, the program has the flexibility to deploy AUVs from any platforms ExPO is currently operating in the region to sample the intrusion front precisely and to collect supplemental data. Those data will be important in collecting the first year-round measurements of this dynamic environment—important to our understanding of global climate patterns and change.

Committee would then produce an exploration plan for the following year by selecting from the subcommittee-endorsed proposals and considering geography, program balance, and best likelihood of fundamental discovery. The Science Committee also would establish a mechanism for responding to unexpected opportunities that require quick action.

INTERNATIONAL GLOBAL OCEAN EXPLORATION COMMITTEE WITHIN THE U.S. OCEAN EXPLORATION PROGRAM

Opportunities for international cooperation and collaboration should be sought by the United States. An IGOE committee could be created within the proposed ExPO with membership drawn from those nations likely to engage in ocean exploration. Representatives from current member nations of the Scientific Committee on Oceanic Research might be appropriate for initial participation. Membership could be further adjusted as new international participants emerge. The IGOE committee would provide its international perspective on ocean exploration to a U.S. program. This advisory committee would encourage other national programs by example, through facilitating asset leveraging, and by clearly communicating the value of exploration. The IGOE committee also would assist in coordinating those new efforts, and it could play a key role in overcoming barriers to data sharing.

6

Ocean Research Technologies

Dramatic advances in our ability to explore the deep sea are attributable to research and development done by academic and private organizations. High-quality, long-term, multinational research programs have greatly increased our understanding of the processes that govern our planet. The Joint Global Ocean Flux Study (JGOFS), the Ocean Drilling Program (ODP), and the Global Ocean Observing System use tools, technology, and human resources developed and provided by a variety of nations. A new exploration effort should use existing equipment and technology whenever possible, but it will require new methods and systems that will adjust and improve to meet emerging needs. A global ocean exploration system should include observations from existing satellites, moored open-ocean sensors, data voluntarily contributed from various ships, and the global sea level network, as well as other observations that are not yet defined or routinely collected (Figure 6.1). Resources should be available for the development of innovative tools to support selected exploration voyages or investigations. The infrastructure for an ocean exploration program must provide for postcruise sample and data analysis and interpretation, rapid dissemination of results, and data management that will promote effective integration and analysis of multidisciplinary data sets.

The science and technology results from several continuing large-scale research programs—the Tropical Ocean and Global Atmosphere program, the Ridge Interdisciplinary Global Experiment, and JGOFS—provide important information and experience that can be applied when designing operational ocean exploration system that is effective, affordable, and consistent with our knowledge of the scales of ocean biology, chemistry, and physics (National Research Council, 1993).

Recommendation: An ocean exploration program should seek to access and encourage new developments in ocean technology.

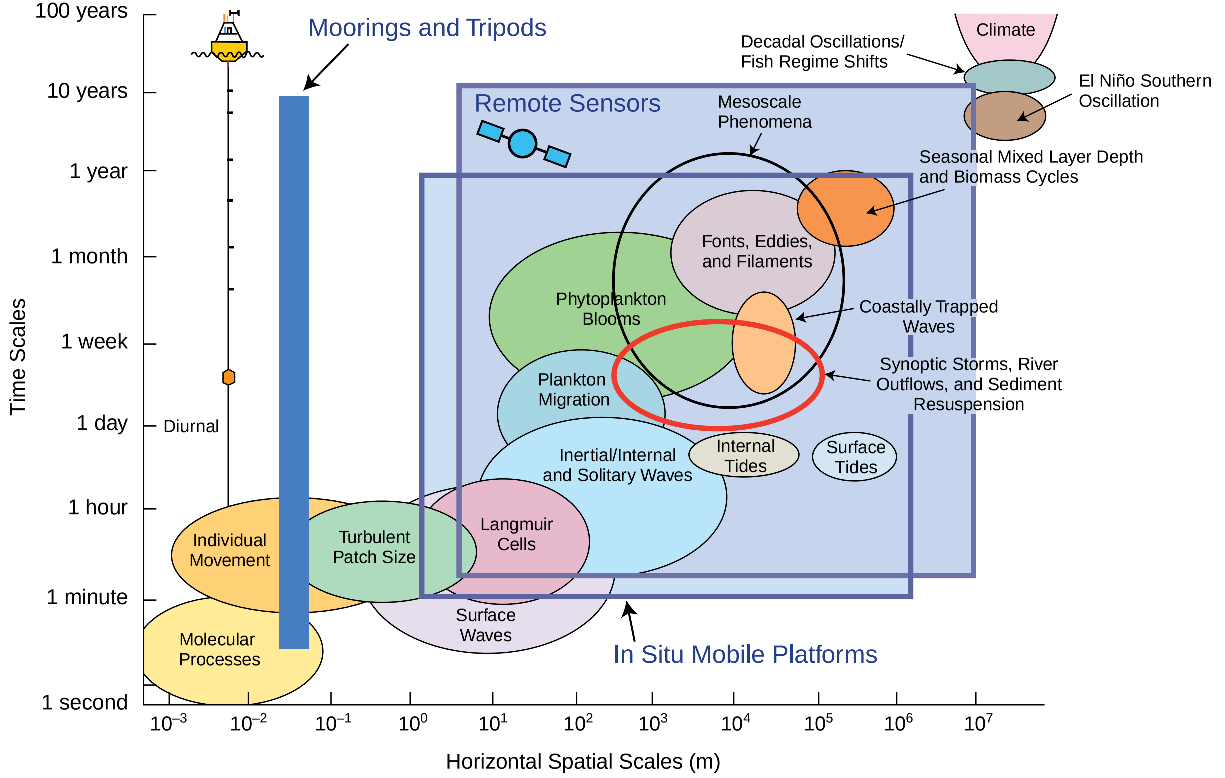

FIGURE 6.1 Time and horizontal space diagram. Ovals illustrate several physical and biological processes. Rectangles indicate the current approximate spatial and temporal sampling abilities of several platforms (modified from Dickey, 2003).

OCEAN TECHNOLOGY

This section briefly reviews the considerable technology available to the ocean exploration program. It also discusses the need for new technology in an ocean exploration program.

Platforms

Oceanographic research is conducted from a variety of platforms. Ships are the most recognizable, but there are many other types of research platforms: stationary observation systems (moorings and bottom-supported platforms), mobile observation systems (submersibles, remotely operated vehicles [ROVs], autonomous underwater vehicles [AUVs], drifters, gliders), and satellites with remote-sensing capabilities. An ocean exploration program that includes archaeology will further diversify the platforms needed.

Ships

Virtually all oceanographic research is conducted from vessels that are owned by agencies or private organizations within individual nations; there are no truly international research vessels, with the possible exception of the vessels used by ODP and the Integrated Ocean Drilling Program (IODP). Many nations maintain research vessels of various sizes that operate in most of the world's oceans, and the global research fleet consists of nearly 500 vessels from 53 nations (Appendix E). The information presented here was gathered through a voluntary database, and the current condition of the vessels is not known. Commercial vessels are sometimes used, for example, to take advantage of their particular capabilities or for short-term charters. The size of the global oceanographic research fleet suggests great potential for international cooperation.

Within the United States, the Academic Research Fleet provides essential support to basic research in oceanography. For more than 40 years, the National Science Foundation (NSF) and other federal agencies have worked cooperatively with universities and academic research institutions to provide the broadest possible access to the sea for the nation's oceanographic research community. Ship-based research operations are coordinated by the University-National Oceanographic Laboratory System (UNOLS), an excellent model for managing a research fleet (National Science Foundation, 1999). UNOLS is a consortium of 57 institutions, 20 of which currently operate 28 ships. UNOLS ensures communitywide ship access, cooperative ship scheduling, standards for operations and safety, and uniform funding and cost-accounting procedures. The ships are privately, state, or federally owned and are operated by academic institutions. The fleet includes large ships for oceanwide investigations, intermediate-sized ships for regional investigations, small ships for coastal and estuarine work, ships specifically designed for unique environments, and platforms with special capabilities such as the submersible *Alvin* and the Floating Instrument Platform. NSF provides the majority of support for fleet operation, maintenance, and upgrades, while the U.S. Navy has historically provided most of the larger ships.

Other federal agencies also operate research ships. The National Oceanic and Atmospheric Administration (NOAA) operates 15 ships to support its oceanographic research program (National Oceanic and Atmospheric Administration, 2003c). The Oceanographer of the Navy maintains a fleet of ships that operate around the world, although their activities are limited to operational mapping and sampling in areas of specific interest to the Navy.

ODP and the new IODP control drill ships. ODP supports the riserless drill ship, the Joint Oceanographic Institutions for Deep Earth Sampling (JOIDES) Resolution, through a program administered by the Joint Oceanographic Institutions, Inc. Texas A&M University receives much of the funding to operate JOIDES Resolution, administer field research, provide technical and scientific services, assist with technology development and report production, develop and administer the program's database, and serve as a repository for the recovered cores. IODP is scheduled to begin in October 2003 with the decommissioning of the JOIDES Resolution. The United States will supply a riserless drill ship, and the Japanese are constructing a riser[1] drill ship, the *Chikyu*. The consortium of European countries may be responsible for managing other types of platforms, such as geotechnical drill ships, jack-up rigs, and polar drilling platforms.

Submersibles

The most familiar oceanographic tools to the general public are submersibles, which provide oceanographic researchers with a unique and

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[1] A drilling riser is a pipe that connects a drilling rig on a drill ship to a seabed blow-out preventer. Within the riser, a drill pipe is used to advance the hole. Drilling fluid is carried down the inside of the drill pipe, and cuttings and drilling fluid are carried in the annular spacing between the drill pipe and riser back to the rig on the vessel.

dynamic perspective of the ocean and its processes. Submersible technology allows human presence in much of the world's oceans, but, perhaps even more promising to the oceanographic community, remotely operated and autonomous underwater vehicle technology has advanced rapidly in the past 20 years, making the systems more widely available and capable of many more tasks than in the past. The current NSF funding structure for supporting such vessels for marine research does not encourage use of commercially available ROVs nor encourage competition within the oceanographic community. An international ocean exploration program would be greatly enhanced if commercial assets could be accessed and used by the scientific community.

Technology costs must be weighed against vehicle utility in choosing which submersible to use. Submersible costs are driven in large part by the depth capability of the vehicle. The costs for development of technologies necessary for a submersible to withstand pressures of the deep ocean increase nearly logarithmically below 6,500 m; one percent of the ocean floor lies below that depth. Human occupied vehicles (HOVs) have the additional substantial requirements for life support and complex safety systems. As an example, the *Jason II* ROV cost an estimated $4 million to construct, but Japan's full-ocean-depth ROV, now lost at sea, cost an estimated $60 million.

Human Occupied Submersible Vehicles

Many significant discoveries during the past three decades of marine research have resulted from observations and samples taken from HOVs (Table 6.1). HOVs provided the first detailed view of the structure and nature of volcanism along a midocean spreading ridge (e.g., Ballard and Van Andel, 1977) and the first comprehensive maps of the variation in composition of lavas within a ridge crest (e.g., Bryan and Moore, 1977). HOVs have been used extensively for observing and sampling hydrothermal vents and their associated exotic communities of organisms. HOVs also have been used extensively as effective tools for public outreach, and they have been the subject of broadcast and cable television programs.

In October 1999, the UNOLS Developing Submergence Science for the Next Decade workshop (Developing Submergence Science for the Next Decade, 1999) stressed the continued need for increased power and lift capabilities of HOVs, tether-free maneuverability, and the continued human presence provided by HOVs (Box 6.1). Although rapid progress is being made in videography and photography to develop capabilities that match

TABLE 6.1 Human Occupied Vehicles (HOV) for Scientific Research and Exploration

HOV	Operator	Maximum Operating Depth (m)
Shinkai 6500	JAMSTEC, Japan	6,500
MIR I and *II*	P.P. Shirshov Institute of Oceanology, Russia	6,000
Nautile	IFREMER, France	6,000
Alvin	National Deep Submergence Facility, Woods Hole Oceanographic Institution, United States	4,500
Cyana	IFREMER, France	3,000
Shinkai 2000	JAMSTEC, Japan	2,000
Pisces IV	HURL, United States	2,170
Pisces V	HURL, United States	2,090
Johnson-Sea-Link I and *II*	HBOI, United States	1,000
Deep Rover 1002	James Cameron	1,000
Deep Rover	Nuytco Research Ltd., Canada	900
JAGO	Max Planck Institute, Germany	400
Remora 2000	Comex, France	610
DeepWorker 2000	Deep Ocean Expeditions	600
Delta	Delta Oceanographics, United States	370
Clelia	HBOI, United States	300
Thetis	Greek National Centre of Marine Research	300

NOTE: JAMSTEC, Japan Marine Science and Technology Center; IFREMER, French Research Institute for Exploitation of the Sea; HURL, Hawaii Undersea Research Laboratory; HBOI, Harbor Branch Oceanographic Institution.

those of the human eye, there will be a need for in situ human presence in the sea for the predictable future. U.S. programs need to replace the 35-year-old *Alvin* to continue oceanographic research. Planning is under way, including a review by the National Academies, for an HOV that can go to 6,500 m, which would allow researchers to explore 99 percent of the ocean floor in studies that require a human presence. Relatively inexpensive HOVs of lesser depth capability can provide sufficient access to the ocean floor for such things as shallow searches for shipwrecks at diving depths (Figure 6.2), and research in coastal habitats, for example.

Remotely Operated Underwater Vehicles

Over the past 10 years, the marine scientific community has begun to use ROVs routinely to collect deep-sea data and samples. For instance, in 1995 the *Magellan 725* ROV was used to locate, collect data on, and leave a memorial plaque at the R/V *Derbyshire*, which sank in 1980 during a

BOX 6.1 DISCOVERING THE OCEANS: DEVELOPING SUBMERGENCE SCIENCE FOR THE NEXT DECADE

Key Findings

- The oceans remain a scientific frontier for the twenty-first century with broad societal and academic relevance to issues such as the role of the oceans in global climate change and the limits of life processes in extreme environments on Earth and other planets.
- Dramatic advances in submergence vehicle technologies and instruments now provide unprecedented access to the oceans and seafloor. Those technologies and vehicles will foster a revolution in our ability to synoptically measure the ocean chemical, biological and physical processes.
- New mechanisms are required to improve scientific research access to all types of submergence vehicles and tools. They should be developed to address issues relating to scheduling existing assets, conducting field work outside traditional operating areas, and responding to time-sensitive processes at the seafloor or in the water column. The broadest range of vehicle capabilities should be provided to U.S. investigators while preserving the existing capabilities of the National Deep Submergence Facility.
- Long-standing U.S. leadership in submergence science and technology is being challenged by other countries (France, Germany, Japan) that have greater funding for submergence science and vehicle facilities.

Key Recommendations

- Accelerate development of AUVs.
- Construct a new, state-of-the-art, deep-diving (>6,000 m), occupied submersible.
- Plan for a new, robust deep-diving (>7,000 m) ROV.
- Develop new sensors and tools.
- Increase access to submergence vehicles and tools. This implies increased funding for submergence facilities, support and technology to ensure the access, facilities infrastructure, and technology required to meet the needs of U.S. deep-submergence science.

Critical Technology Needs

- Design AUVs for a variety of applications (coastal, polar, event response) and with a variety of interchangeable sensors. These could be used independently or as part of underwater observatory systems.
- Develop better manipulative capabilities; chemical, biological, and physical properties sensors for submersibles and ROVs; and the ability to maintain in situ conditions during experiments and sample recovery.
- Improve imaging, both high-resolution digital video and still photographs.
- Design new protocols and equipment to facilitate data telemetry to the surface and to transfer data to and from seafloor sensors.
- Improve seafloor mapping at various scales using ROV and tethered systems in a nested survey approach.
- Integrate in situ experiments to fully characterize the ocean chemical, physical, and biological processes. The transfer of knowledge and instrument design from public and private engineering groups to the broad oceanographic community will be crucial.

FIGURE 6.2 The human occupied vehicle *Carolyn* visits a medieval shipwreck whose cargo consisted of millstones (used with permission from Tufan Turanli, Institute of Nautical Archaeology).

typhoon—all forty-four aboard were lost; no distress call was ever placed. The ROV was able to provide sonar and video footage to confirm the sudden and catastrophic event, suggesting that structural elements contributed to the loss. The most obvious advantage of using ROVs is their ability to remain underwater almost indefinitely. They also remove the human risk factor, and they have excellent power and lift capabilities. ROV development has been extensive: the size, work capacity, depth capabilities, and payload all have increased in recent years. The Japanese research ROV *Kaiko* has been to the Mariana Trench (10,911 m). Recent advances in satellite communications and the burgeoning of the Internet now allow information to be transmitted from ROVs in real time almost anywhere in the world at reasonable cost.

Introduced into the world's oceans as a part of military technology for remote observation, ROVs were quickly adapted by the offshore energy industry to support deep-water operations. Evolution of those systems has led to the current generation of vehicles, which provide a highly capable proxy for human eyes, hands, and other senses in the deep sea. Although early-generation vehicles were equipped with low-quality video cameras, the latest generation's high-quality cameras transmit high-definition video images and data by fiber optic cable.

Commercially available ROVs range from small, portable units used for shallow-water inspection to the heavy, work-class, deep-water ROVs used by the offshore oil and gas industry and the military. The small ROV systems, such as the *VideoRay*, *Phantom*, and *MiniRover*, usually are powered by electric-motor-driven thrusters of less than 20 horsepower that operate in depths of less than 300 m. Those ROVs are relatively inexpensive—in the range of $10,000 to $100,000—and they are used for marine science, civil facility inspections, recreation, archaeology, and similar observational tasks.

Medium-class ROV systems, such as the *Scorpio* and *Viper*, cost millions of dollars. They weigh a metric ton or more, and with their overboard-handling systems, winches, generators, and control systems are not readily portable. They are typically semi-permanent installations on support vessels. Operating depths are 1,000-2,000 m. They carry a variety of payloads, which could include one or two manipulators and a variety of special tools, such as water jets and cutting tools. They also can be outfitted with sensors for gathering scientific data and with still and video cameras. Sidescan sonars for object location and obstacle avoidance are also common. Researchers use the systems for exploration video and photographic document support, instrument placement, and oceanographic data and sample gathering.

Heavy, work-class ROVs, such as *Innovator* and *Millennium*, provide maximum underwater power. They are capable of up to 500 horsepower and could potentially reach 5,000 m depths with significant modifications. They carry significant payloads and a variety of tools. The large ROV systems cost upward of $2.5 million and are seldom used outside of the international offshore oil and gas industry.

Only a limited number of ROVs are accessible to the international scientific community (National Research Council, 1996) (Table 6.2). In the United States, there is one facility at the Woods Hole Oceanographic Institution's National Deep Submergence Facility that provides a variety of ROVs (a towed sidescan sonar system, a towed imaging and acoustic system, and ROV capable of sampling) to the U.S. scientific community. The new ROV *Jason II* uses fiber optics to provide the bandwidth necessary to accommodate the wide variety of oceanographic sensors and imaging tools available today and has a maximum depth rating of 6,500 m. *Jason II* can

TABLE 6.2 Remotely Operated Vehicles (ROVs) for Scientific Research and Exploration

ROV	Operator	Maximum Operating Depth (m)
Kaiko[a]	JAMSTEC, Japan	10,000
Jason II	Woods Hole Oceanographic Institution, United States	6,500
ATV	Scripps Institution of Oceanography	6,090
VICTOR 6000	French Research Institute for Exploitation of the Sea	6,000
Tiburon	MBARI, United States	4,000
HYSUB 75-3000 Hyper Dolphin	JAMSTEC, Japan	3,000
Ventana	MBARI, United States	1,850
Homer/Rover	Harbor Branch Oceanographic Institution, United States	300

NOTE: JAMSTEC, Japan Marine Science and Technology Center; MBARI, Monterey Bay Aquarium Research Institute.
[a] *Kaiko* was reported lost at sea in the spring of 2003.

support nine video channels, high-definition video and electronic still cameras, a multibeam sonar, and a closed-loop control via a 1,200 kHz Doppler that enhances the quality of every sensor on board. It is reasonable to expect a *Jason II* submersion to last up 100 hours.

Autonomous Underwater Vehicles

In scientific and commercial work another type of underwater vehicle has emerged that will become more commonplace. Some 43 institutions and companies around the world are operating AUVs (Appendix F)—several operate more than one. AUVs are untethered submersibles with onboard power supplies and computers programmed to cover a specific route and gather information through sensors, video, and still cameras (Figure 6.3). AUVs are not new; the concept was demonstrated in 1898 by Nikola Tesla using a remotely controlled, submersible boat.

AUVs have been developed for specialized research applications, and the Office of Naval Research has initiated a partnership program with several universities to develop AUVs. Some are designed for water column research, including one used by the Monterey Bay Aquarium Research Institute to observe the way Atlantic Ocean water changes as it enters the Arctic Ocean. Another experiment used AUVs to track the evolution of biological communities across nutrient-rich upwelling fronts. Developed at the Woods Hole Oceanographic Institution, the remote environmental monitoring unit system is a low-cost AUV for coastal monitoring and multiple vehicle survey operations. Although it is small, the remote environmental monitoring unit system is configured to support a variety of sensor packages. It has a conductivity, temperature, and depth sensor and optical backscatter sensors. Telemetry data provide time of day, depth, heading, and a geographic position for the data. A larger model, with an acoustic Doppler current profiler (ADCP) and global positioning system, is being tested.

AUVs also can be designed specifically for near-bottom work. With a gross weight of 680 kg and a maximum operating depth of 5,000 m, the *Autonomous Benthic Explorer* has performed a variety of fully autonomous, precisely navigated surveys in rugged seafloor terrain. The measurements have included fine-scale magnetic and bathymetric surveys, development of photo mosaics, and quantitative surveys of hydrothermal plumes. A multibeam sonar (SM2000) was added recently. Typical dives last from 16 to 34 hours, depending on the instrument payload and the bottom terrain. The *Autonomous Benthic Explorer* often operates independently of the surface vessel, allowing the ship to perform other tasks beyond the acoustic range of an AUV.

The offshore oil and gas industry uses AUVs for geologic hazard surveys and pipeline inspection. Today, AUVs are used in high-resolution geophysics, water column physical measurements, and missions for the military. There is no universal vehicle and AUV attributes are mission driven. Some AUVs have been shown to be superior and more efficient than surface-ship-towed systems for deep-water, high-resolution geophysical studies. The *Hugin 3000* AUV, which is rated to 3,000 m, became fully operational in January 2001, for conducting geological hazard and archaeological surveys in the Gulf of Mexico. Its sensors include a multibeam echo sounder for swath bathymetry and imagery, a chirp sidescan sonar, a chirp sub-bottom profiler, the conductivity, temperature, and depth scanner, and a cesium magnetometer.

AUV technology is developing rapidly, and some research and development is being done at universities. The Massachusetts Institute of Technology AUV Laboratory designs, builds, and tests small robotic submarines. As their technological capabilities improve, AUVs will continue to provide an effective alternative to other types of oceanographic platforms in an international ocean exploration program.

Fixed and Floating Offshore Oil and Gas Structures

Several thousand structures have been installed in oceans around the world for oil and gas extraction. Those fixed platforms could be used routinely to acquire oceanographic data. Hundreds of structures are situated throughout the Texas and Louisiana shelf of the Gulf of Mexico; several structures are in water deeper than 1,000 m. Although commercially owned and operated, many could serve as fixed stations for oceanographic observations. Several industry-sponsored projects have collected long-term data on waves, currents, and atmospheric conditions for use in industrial design models. Incorporating oil and gas platforms into planned observation efforts could provide an important mechanism for collaboration with private industry.

FIGURE 6.3 Autonomous underwater vehicles use programmed routes and sampling protocols to collect oceanographic data. (A) *Xanthos*, designed at the Massachusetts Institute of Technology, can dive to 3,000 m (used with permission from the Massachusetts Institute of Technology Sea Grant). (B) The *Autonomous Benthic Explorer* (ABE) can dive to 5,000 m. It is 2 m long and can cruise at 2 knots. On-board equipment includes a conductivity, temperature, and depth device; sonar; video cameras; and a magnetometer (used with permission from the Woods Hole Oceanographic Institution).

Space-Based Remote Sensing

The National Aeronautics and Space Administration (NASA) conducts ocean exploration in missions that rely on new technologies (satellites and sensors) and techniques for ocean observation (Box 6.2). The resulting data are enhanced through efforts to model physical, chemical, and biological ocean patterns as well as seafloor morphology, and there is ready access to the data. Currently, 31 satellites, operated either for or by NASA, are being used to investigate the Earth's physical, chemical, and biological properties.

BOX 6.2 THE NATIONAL AERONAUTICS AND SPACE ADMINISTRATION'S MODERATE RESOLUTION IMAGING SPECTRORADIOMETER

One example of instrumentation for satellite deployment is the moderate resolution imaging spectroradiometer (MODIS) currently deployed on the *Terra* and *Aqua* satellites, part of NASA's Earth-observing system. MODIS captures the most detailed measurements yet of the sea's surface temperature (Figure 6.4). Data are collected daily around the globe, providing daylight reflection and 24-hour emission spectral imaging at any point on the Earth at least every 2 days.

MODIS measures the thermal infrared energy, or heat, radiated from the sea's surface. The data are processed to remove artifacts from the atmosphere, including variations caused by clouds, dust, and smoke. The result is a measurement of sea surface temperature that is accurate to within 0.25 °C. Oceanographic data collected using MODIS include:

- surface temperature with 1-km resolution, day and night, with absolute accuracy of 0.3-0.5 °K for oceans;
- water-leaving radiance to within 0.2 percent from 415 to 653 nm;
- chlorophyll fluorescence within 50 percent at surface concentrations of 0.5 mg/m^3;
- concentration of chlorophyll a within 35 percent, net ocean primary productivity, other optical properties;
- net primary productivity and intercepted photosynthetically active radiation;
- cloud mask containing confidence of clear sky (or, alternatively, the probability of cloud), shadow, fire, and heavy aerosol at 1-km resolution;
- cloud properties characterized by cloud phase, optical thickness, droplet size, cloud-top pressure, and temperature;
- aerosol properties, defined as optical thickness, particle size, and mass loading; and
- global distribution of total precipitable water.

Many of the data-gathering efforts are the result of strong international participation; the *Jason I* project is a collaboration with France, and the Advanced Earth Observing Satellite-II is in conjunction with Japan.

NASA has provided data that have already been incorporated into the scientific and public debates of the oceans' role in climate change. Among the best-known NASA missions is Topex/Poseidon, conducted with France, which revolutionized our understanding of the El Niño climate patterns by providing the first global data on sea level. Another endeavor, the Sea-Viewing Wide Field-of-View Sensor project, has collected global sea sur-

With the primary mission of integrating the Earth sciences, instruments such as MODIS not only improve our understanding of the linkages between the oceans and climate, but they allow spatial and time series exploration unlike that of any previous generation of instruments (National Aeronautics and Space Administration, 2003).

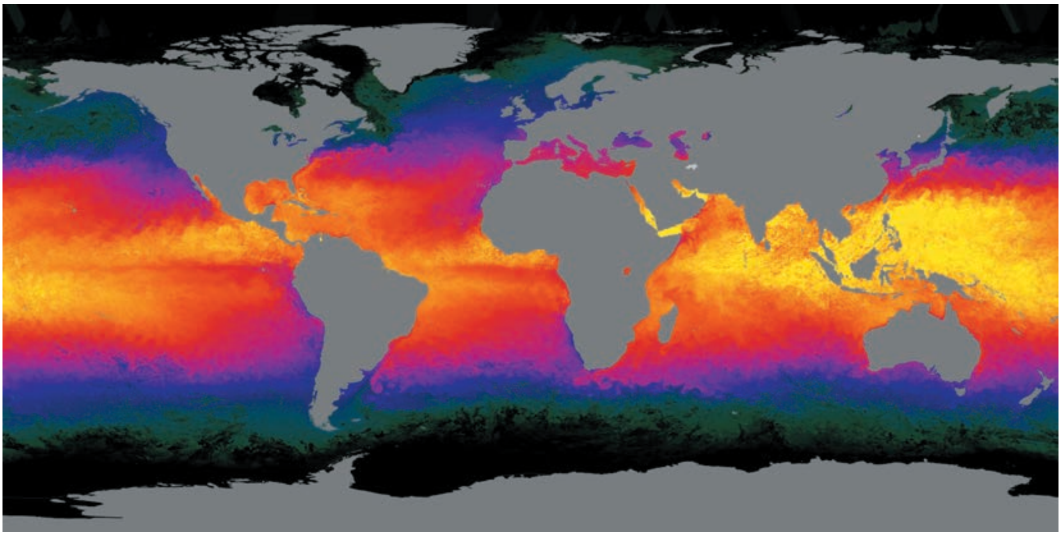


FIGURE 6.4 Sea surface temperatures, June 2-9, 2001, measured by the Moderate Resolution Imaging Spectroradiometer. Cold waters are black and dark green. Blue, purple, red, yellow, and white represent progressively warmer water (National Aeronautics and Space Administration, 2002a).

face bio-optical data since 1997. This surface collection of chlorophyll data has allowed researchers to view seasonal and annual large-scale patterns in chlorophyll concentrations (Davenport et al., 2002; McClain et al., 2002; Figure 6.5). The chlorophyll data reveal the biological productivity of the waters and highlight the importance of physical transport patterns (Moore and Abbott, 2002). Many of the satellite data sets are readily available through a variety of innovative interfaces on the Internet. Some of the observation satellites use technologies that can track the oceans' geophysical conditions—sea surface temperature, ocean surface wind, ocean surface topography, ocean color, sea surface salinity, mixed layer depth, gravity gradiometry, laser and radar altimetry, and synthetic aperture radar and reflectivity. Remote-sensing technology, coupled with data gathered in concurrent oceanographic expeditions, will be an important component of a global exploration program.

Instrumentation Requirements

Ocean exploration requires observations of the state of the oceans and the forces that act on it. Because observations are made in a corrosive, turbulent environment with high pressures at depth, they are difficult and expensive to obtain. And because of the size and variability of the ocean, observations are always incomplete. Space-based remote-sensing, acoustics, and automatic measurements taken during routine voyages could all be applied to global ocean exploration.

Any ocean exploration program should emphasize making novel, multidisciplinary observations in new undersea environments. Ocean explorers of most disciplines will need ships to collect data and samples of seawater, rocks, sediments, and organisms. There are well-proven systems for large-scale surveying that could to be used in remote, unexplored areas. Characterization of important biological, chemical, and biogeochemical processes is hindered by a lack of samples and observations at fine scales over most ocean surfaces.

One important function of an ocean exploration program would be to expedite the use of the new technology for ocean exploration. The program must seek scientists and engineers who are designing instruments that observe or sample the ocean in original ways. The transition of promising prototypes to more mature, widely available systems could be promoted. The program could expedite development of new technology by matching inventors and commercial organizations interested in licensing technology for mass production and wider distribution. If commercial interest is unlikely

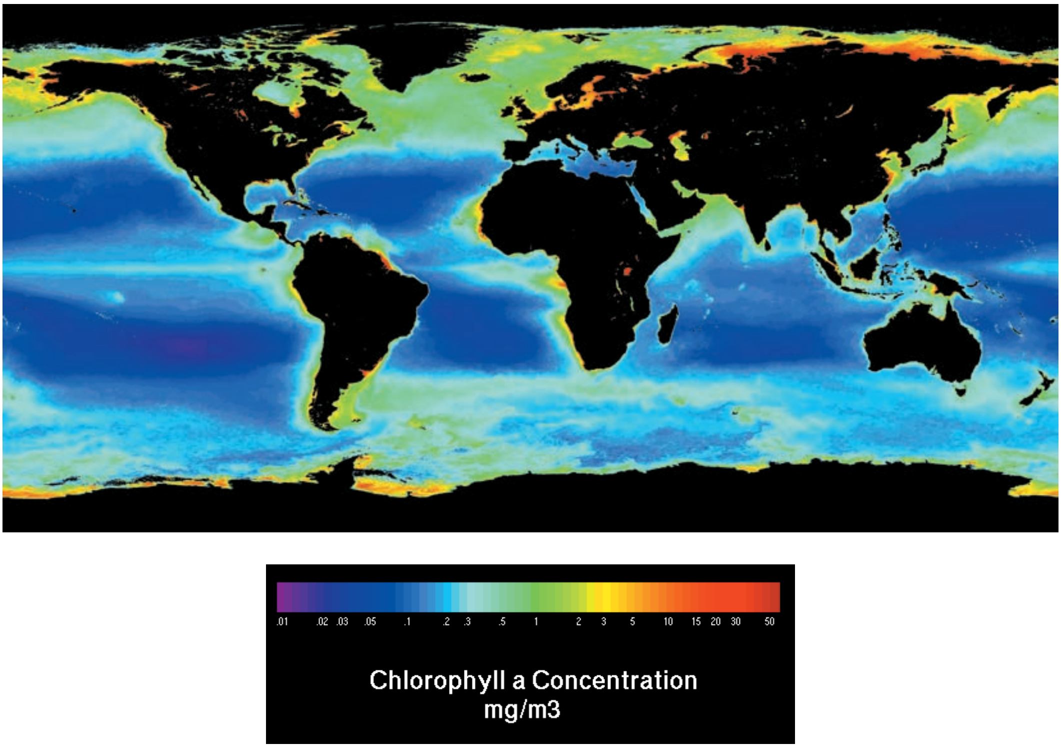


FIGURE 6.5 Average chlorophyll a concentration (National Aeronautics and Space Administration, 2002b). Time series of global distribution of chlorophyll a can be used to estimate annual primary production in surface ocean waters.

in the near term because of the specificity of the technology, a cadre of trained technicians could receive partial support from the ocean exploration program to maintain and operate novel, but essential, technology.

It is important that a global ocean exploration program use standardized, or at least compatible, sampling techniques. For example, hydrographic standards should be compatible with those established by WOCE, because those are the standards that have been adopted by other researchers interested in obtaining highly accurate ocean observations. Similarly, JGOFS standardization methods for measuring productivity, nutrients, and dissolved organic carbon should be adopted by the ocean exploration measurement program because they have been reviewed and accepted by the international oceanographic research community.

Exploration of the Water Column

Physical and chemical oceanographic observations and modeling are becoming global, but the resources required to deploy and sustain large-scale observations of the world's oceans are enormous. In general, seagoing equipment to measure the physics of the oceans is more mature than are the biological and chemical counterparts. Current meters, the conductivity, temperature, and depth sensors, and ADCPs, which are widely available, are routinely mounted on or deployed from oceanographic vessels.

In some cases remote-sensing equipment, such as optical plankton counters and bioluminescence detectors, can provide proxies for marine biology. Satellite-borne sensors that receive energy radiated across the electromagnetic spectrum have provided a synoptic, big-picture view of upper-ocean parameters of interest. Ocean color, for example, is used as a proxy for the abundance of chlorophyll. Unfortunately, the satellite data are dominated by the signal from the uppermost tenths of centimeters of the ocean, and most of the water column goes unsampled.

Traditionally, research in ocean chemistry and biology has relied on laboratory analysis of water and microscopic examination of living specimens. Recently in situ instrumentation has been deployed from ships, ROVs, moorings, AUVs, and other platforms to obtain information remotely, without the delay or expense of sample recovery. Most such systems are in development, although many are becoming commercially available. For example, the Digi-scanner chemical analysis system automatically applies reagents to filtered seawater to perform in situ colorimetric analyses. The results of the analysis are returned to shore, but the samples are not. The in situ ultraviolet spectrometer detects the presence and abundance of chemical species of interest, such as nitrate, by measuring the ultraviolet absorption of the molecules. The instruments require no reagents, only power, and thus conceivably could be deployed unattended for long periods.

With the advent of new and more sophisticated remote-sensing techniques, it is likely that the demand for sampling also will increase. The range of remotely sensed data will require in situ sampling for calibration, identification, interpretation, and analysis. As coverage of the ocean surface improves, a concomitant need for improved subsurface acoustic coverage (by ADCPs, acoustic thermometry, and inverted-echo sounders) is inevitable. Modern sensor packages are needed that can be dropped and retrieved along a ship's route to measure salinity, oxygen, and fluorescence (primarily from phytoplankton). Disposable, free-falling sensor packages have been developed that either transmit their data from great depths via acoustic signals or return to the surface to broadcast to satellites.

Fluorometers, transmissometers, and spectroradiometers measure phytoplankton populations, the turbidity of the water column, and the amount and wavelength of the light that penetrates the ocean surface at a given site. Flow cytometry is another optically based technology that is extremely useful for characterizing the size and color of phytoplankton and bacteria and for sorting populations based on those and other criteria (National Research Council, 1993). Correlating site data with measurements from satellite ocean-color sensors provides the means to extrapolate phytoplankton measurements, and their associated productivity, to regional or even global scales (e.g., Harding et al., 2002). Mooring optical instruments together with current meters and temperature and salinity sensors provides a technique for collecting long (months) and highly resolved (minutes to hours) time series measurements, and permits biological oceanographers to study the physical factors that control phytoplankton populations. Moorings contribute time- and depth-variable data; satellite sensors provide information on variation over the global ocean surface.

In situ sampling of zooplankton populations began with simple nets, but now optical and acoustic sensors collect data and transmit images almost instantly (Wiebe and Benfield, 2003). Three-dimensional analyses of individual organisms and their spatial relationships will be possible on scales small enough to elucidate the behavior of individual organisms (National Research Council, 1993). General application of acoustic technology will require development of inexpensive equipment and techniques to use and analyze the large volumes of data generated.

A new suite of elegant and sophisticated technologies and instruments for molecular biology has been developed in the past two decades that could greatly facilitate marine studies. The technologies of molecular genetics are now applicable to ocean science. DNA microarray probes for specific genes promise the full power of using marine organisms' genetic codes to identify species present in the water column, count them, and determine their biogeochemical processes. The technologies allow researchers to manipulate and probe the most fundamental life processes in new ways, and they will revolutionize our knowledge of the processes and mechanisms that regulate population, species, and community structure in ocean ecosystems. Development of novel probes and sensors for in situ sampling and molecular analyses is a priority for biological sampling and for identification of novel organisms and processes.

Exploration of the Seafloor and Below

Well-proven systems exist for large-scale surveying that should be deployed in remote, unexplored areas. The systems include multibeam sonar and bathymetry systems and magnetometers and gravimeters routinely used on research vessels. The academic oceanographic community has two multichannel seismic systems available for exploring below the ocean floor. Lamont-Doherty Earth Observatory maintains a 6-km-long multichannel seismic streamer that records acoustic energy reflected off deep horizons from a 20-airgun array on the R/V *Maurice Ewing*. The Scripps Institution of Oceanography has a "chirp" sonar that provides less depth penetration but higher resolution (<1 m) in the upper sediment column at ocean depths to 4,000 m (Driscoll, 1999; Gutierrez et al., 2003). The system is portable and can be installed on ships temporarily. The petroleum industry operates multichannel seismic systems that provide three-dimensional images of structures below the bottom of the ocean. The facilities are expensive. They also require a high degree of expertise for operation and a dedicated, special-purpose ship. At the time of writing, the replacement of *Ewing* by a substantially more capable ship is being investigated.

Exploratory investigations of marine biology, geomorphology, and archaeology will require seafloor imaging at higher resolution than is possible with acoustic systems. For those fields, visual data are becoming an increasingly valuable tool for ocean research and will be a cornerstone of ocean exploration. Still, video, and high-definition television cameras have been mounted on HOVs and ROVs. Still cameras with strobe lights are routinely deployed from AUVs, and light detection and ranging technology is now well developed. This latter platform, in particular, provides an inexpensive avenue for high-resolution visual exploration of the ocean bottom as well as the water column.

Coring and dredging devices are used to collect geological samples and specialized equipment for sampling in extreme environments, such as at hydrothermal vents, has been developed to collect fluids and micro- and macrofauna. Physical and chemical sensors are being developed for continuous recording at seafloor observatories placed near hydrothermal vents.

Exploration in the Fourth Dimension

The concept of acquiring long time series data for fundamental oceanic processes and key ecosystem variables at important locations in the global ocean is not new. Yet with the exception of tide gauge stations, routine collection of temperature data by commercial ships, and local physical measurements, time series measurement programs are rare. A notable exception is the Continuous Plankton Recorder Surveys in the North Atlantic Ocean, which began in 1931 (Hardy, 1926; Planque and Batten, 2000). Other continuing programs that measure biological variables include the California Cooperative Oceanic Fisheries Investigation. But they are generally poorly funded, and funding must be secured on nearly a year-to-year basis. Virtually all recent planning reports stress the importance of long time series to investigate the variability of fundamental Earth processes, identify global changes, and describe the fundamental attributes of marine ecosystem dynamics. Satellite sensors and moorings provide one level of information, but more in situ observation is needed. Federal agencies recently have recognized the importance of supporting long-term measurement programs. For example, NSF supports time series stations near Bermuda and Hawaii, and is sponsoring the Ocean Observatories Initiative and Major Research Equipment and Facilities Construction projects; NOAA supports an observatory on Axial Seamount on the Juan de Fuca Ridge in the northeastern section of the Pacific Ocean, off the North American coast, as well as the Tropical Atmosphere Ocean array in the equatorial Pacific for monitoring El Niño. The National Ocean Partnership Program has initiated the National Office for Integrated and Sustained Ocean Observations to coordinate the development of an operational, integrated, sustained ocean observation system (Ocean.US, 2003). All of these projects could be considered the beginning of time series measurements within a global ocean exploration program.

Marine Archaeology

Undersea archaeology often requires equipment that is similar to that used in oceanography, although adaptations generally are necessary for specific studies. Most shipwrecks happen when vessels run aground, so the sites are within human diving depths. True archaeological excavation, as opposed to commercial salvage, can be conducted best and often only by the human hands of divers. Shipwreck and inundated-site exploration relies on equipment designed for relatively shallow work, down to around 70 m, and generally not deeper than 90 m.

Although most archaeological sites are in shallow waters, Robert Ballard's discoveries of well-preserved wrecks below 200 m in the Black Sea and the U.S. Navy's serendipitous discovery of two Phoenician wrecks deep in the eastern Mediterranean show that extraordinarily well-preserved and important ancient wrecks also can be found in much deeper water. Ballard's deep-water discoveries of the *Titanic* and various modern warships demonstrate our ability to locate wrecks at almost any depth, even when their precise locations are not known. The successful search for and careful salvage of artifacts from the nineteenth-century steamship *Central America*, more than a mile below the ocean's surface, is another example. However, the great expense of such deep-water excavations cannot yet justify the year-round operation of vessels large enough to carry the necessary equipment and must depend on access to vessels designed for deep oceanographic research.

Almost all ancient wrecks currently known were found visually. The most effective method of searching for ancient wrecks is by divers or, better, by human-occupied submersibles with good visibility. In just one month in 2001, for example, the two-person *Carolyn* (Bass, 2002) allowed the discovery of 14 ancient wrecks and 10 possible wrecks off the coast of Turkey while at the same time the archaeologists there were revisiting 12 wrecks identified in earlier surveys. More modern wrecks, with iron anchors, armaments, and sometimes—as is the case with the ironclad *Monitor* and the submarine *Hunley*—iron plating or iron hulls, are more easily found by magnetometers or sonar. To be located by side-scan sonar a portion of the wreck must protrude above the seafloor. Once a wreck is recognized by sonar it can be visually inspected and recorded with ROVs. Manipulator arms on ROVs can even be used to pick up small objects for sampling purposes. Mud-penetrating sonar has also been used to locate wrecks completely embedded in bottom sediments and invisible to the eye.

Once an underwater site has been chosen for detailed study, it can be excavated either by airlifts (nearly vertical suction pipes of various sizes that act much like vacuum cleaners), or by underwater dredges that suck up sediment and discharge it away from the site more horizontally. In either case, the actual digging is best done by hand, with the airlift or dredge used to clear the area of hand-disturbed sand or silt. The site can be mapped three dimensionally at each stage of the excavation by a number of photogrammetric techniques, including those that use the Eos Systems program PhotoModeler Pro; the Virtual Mapper; and Rhinoceros, a NURBS 3D modeling program (Green et al., 2002). They allow a single diver with a digital camera to accomplish on the sea bed what once required the presence of several divers with meter tapes, plane tables, or various pioneering photogrammetric mapping methods (Rosencrantz, 1975; Bass and van Doorninck, 1982). Marine archaeologists often lift heavy artifacts with air-filled balloons, whose ascent is easily controlled (Fagan, 1985). Actual excavation, of course, requires only a small fraction of the time necessary to study a site scientifically; a rule of thumb is that for every month of diving, two years of post-excavation laboratory conservation are required, not only to preserve the finds from disintegration, but in order to learn the maximum possible from each artifact (Hamilton, 1996). Better techniques of preserving waterlogged wood than by polyethylene glycol or freeze drying are needed; however, although the use of silicone oils shows promise (Smith, 2003), and replication of iron artifacts by pouring liquid epoxy into the natural molds created by the growth of seabed concretion on oxidizing iron has a still unknown shelf life. Conservation of iron artifacts (Hamilton, 1976) as large as the entire Confederate submarine *Hunley* (Friends of the *Hunley*, Inc, 2003) or the 150-ton turret of the U.S.S. *Monitor* (National Oceanic and Atmospheric Administration, 2002b) requires not only large space and skill, but large financial resources.

Technology Development

A global ocean exploration program should promote and enhance the development of new oceanographic technology. Major oceanographic programs are frequently users or enhancers of existing technology, and in many instances they have contributed to the development of important advances in technology (Table 6.3). ADCPs, Lagrangian drifters and floats, the autonomous Lagrangian circulation explorer, and improved meteorological packages were developed in conjunction with WOCE and the Tropical Ocean and Global Atmosphere program. The Coastal Ocean Processes program developed in situ plankton pumps, inner-shelf mooring techniques, and instruments to measure gas flux. A global ocean exploration program will no doubt stimulate new technologies, and resources should be available for the development of new tools to support selected exploration voyages or investigations.

> **Finding: An ocean exploration program will require technology and facilities selected to suit the needs of specific program plans. Access to standard and new technology, including commercially available equipment and technology that is not used for and by research institutions, is necessary for an ocean exploration program to succeed.**

TABLE 6.3 Advancements Attributed to Major Oceanographic Programs

Program	Advancement
World Ocean Circulation Experiment	Profiling autonomous Lagrangian circulation explorer floats Accelerator mass spectrometer for radiocarbon measurement Satellite altimetry Successful open-ocean use of passive tracer technology Improved data assembly and availability
Joint Global Ocean Flux Study	Standardized methods for nutrient chemistry Certified reference material programs (carbon dioxide reference materials, dissolved organic carbon workshop, particulate organic carbon sediment comparison) Dissolved organic carbon methodology
Ridge Interdisciplinary Global Experiments	Radioactive dating of young basalts In situ logging temperatures Seafloor geodetic techniques
United States Science Support Program	Scripps Institution of Oceanography's wireline reentry systems
Coastal Ocean Processes	In situ plankton pumps Inner-shelf mooring Instruments to measure gas flux
Tropical Ocean and Global Atmosphere	Atlas moorings Real-time subsurface data Distribution of data via Internet Distribution of graphics via Internet Distribution of predictions via Internet

SOURCE: National Research Council, 1999.

Access to commercially available assets, such as HOVs, ROVs, and AUVs, would increase flexibility and allow researchers more access to new environments, and thus promote the development of even more new technology. Both new and existing technologies will be required; the development of novel probes and sensors for in situ sampling and molecular analysis will be particularly important for biological sampling and discovery of organisms and processes. A global ocean exploration program will no doubt stimulate such new technologies, and resources should be available for the development of new and innovative tools to support selected exploration voyages or investigations.

Recommendation: The list of equipment for an ocean exploration program should be tailored to meet the scientific program's plans. The exploration program should seek to expedite the development and use of the new technology in new undersea environments.

DATA MANAGEMENT

Oceanographers must improve their use and integration of data from the ocean sciences, mine those data for new knowledge, and convey new insights to decision makers and the general public. Our knowledge of the natural world is limited not just by the complexity of the natural entities and processes but also by the complexity of the data that describe them. Although an exploration program cannot be the sole driver for advanced data systems in the ocean sciences, discovery will depend as much on being able to make use of multidisciplinary data in federated repositories as it will on collecting the data in the first place. The importance of data management has been receiving increased attention with new computing and technology capabilities (e.g., Woods Hole Oceanographic Institution, 2001).

Technology no longer limits data management. Network speeds double every nine months; computer speed doubles every 18 months (Moore, 1965; Intel, 2003). Bandwidth and storage also have grown exponentially. We can afford to "waste" storage and networks while we conserve "scarce" computing as these exponentials cross—a complete reversal of the situation that gave rise to small numbers of isolated data archives. Mass storage systems must be treated as large, distributed data repositories, fed by instruments on ships, moorings, cables, and satellites operating nearly in real time. A program in ocean exploration should take on key challenges for the oceanographic sciences by modeling, designing, and implementing the data discovery, integration, and visualization components for a semantic web in environmental science—essentially an Internet for environmental data and information. This will involve developing and testing the use of formal ontologies to facilitate scientific analysis by discovery and automated integration of relevant, but heterogeneous data. In this context, "ontology" is a fairly new concept that is emerging from various semantic-web initiatives. Ontology is a formal representation of all the major concepts in a discipline; it is a semantic system that contains key terms, definitions of those terms, and specification of relationships among those terms. Today much of this information is exchanged through the use of extensible markup language. There are ongoing efforts to build ontologies for various professional fields.

An early example from ODP was the development of a relational database with a Web interface to present information, much of it metadata, about the cores recovered. The schema, or standards, developed to describe recovered sediments and rocks are very helpful in the next step of establishing a useful ontology. The resultant ontology could be readily extended to physical samples of Earth materials no matter the source.

Archiving and annotation of video and other photographic data could require a significant investment. There are few standards for video archiving, and there is no easy access to archived information. One system that shows promise is the Monterey Bay Aquarium Research Institute's Video Information Management System, a relational database used to archive information from cameras deployed from its ROVs. The Video Information Management System creates files that tag events seen in video to environmental parameters recorded by other systems on the vehicle. It provides the raw material for establishing ontology usefulness outside of this particular application. The files are created through a graphical user interface connected to a knowledge base that is tied to thousands of biological and geological observations that could be observed in the video frames. The video analyst can access windows on the computer touch screen for various oceanic environments (midwater, shallow-water benthic, deep-water benthic) with an array of buttons that represent what is likely to be encountered. If the analyst were to push the button for a species of squid, a file can be created to link the observation of the squid with date, time, latitude, longitude, depth, temperature, pressure, salinity, oxygen concentration, video tape, and frame number. That file can be incorporated into a relational database that extends for more than 10 years and includes data from more than 2,500 dives. The relational database allows researchers to test hypotheses that require the integration of results from many years of data. Thus this system fulfills a principal requirement for ocean exploration: it permits later generations of researchers to address questions that might not have even been posed originally.

The development of intelligent analytical tools and an infrastructure for semantic integration of diverse, distributed data sources will remove barriers to knowledge discovery that now plague oceanography. The development of readily applicable engineering methods will ensure that the resulting knowledge environment supports the needs not only of scientists, but of decision makers and the public as well. Perhaps no discipline stands to gain more from these advances than oceanography, where researchers are grappling with questions that range over extremes of spatial and temporal scales, and where investigations encompass all of the physical and life sciences. The requirements for centralized data archives have largely disappeared in preference to a federated collection of data sources generally maintained by those closest to the data.

The "grid" is a term used for defining a variety of notions linking computational resources such as people, computers, and data (Foster and Kesselman, 1999). A "data grid" is a network of storage resources—from archival systems, to caches, to databases—that are linked by common interfaces across a distributed network. Data grids can be found in physics research (Grid Physics Network, 2001; Hoschek et al, 2000), in biomedical applications (Biomedical Informatics Research Network, 2001), and in the ecological sciences (Knowledge Network for Biocomplexity, 1999). Other data grids are developing for astronomy, earthquake research, and multi-sensor systems. "Real-time data grids" manage and provide access to real-time data from distributed sensors and sensor networks.

Real-time data management is faced with the problems of disseminating large collections of data to users and applications; providing a collaborative environment for analyzing and performing data-intensive computing; and managing, curating, storing, and moving large quantities of information. The data grid provides solutions to these problems through software that integrates multiple data resources and provides a uniform method for accessing data across a virtual network space. For example, the Real-Time Observatories, Applications, and Data Management Network (2002) is developing infrastructure for:

- Internet-Internet provider-wireless Internet protocol connectivity to diverse sensors for multiple disciplines, including off-shore on moorings and ships;
- seamless access to real-time data from heterogeneous sensor networks;
- integration of sensor input across disciplines with real-time integration triggered by events; and
- metadata attribute-based discovery for real-time data to achieve the goals above requires an architecture that is flexible, scalable, and distributed, which deals with diverse formats of real-time and stored data and provides dynamic metadata discovery.

These approaches are being pursued aggressively in other fields, and oceanography must depart from the technology-bound, older systems of subject-matter archives (or none) to develop a more flexible system that encourages discovery.

Linking to Existing Archives

Many oceanographic data archives already exist, such as NOAA's National Environmental Satellite, Data, and Information Service, which consists of the National Oceanographic Data Center (NODC), the National Geophysical Data Center (NGDC), and the National Climatic Data Center (NCDC). Those centers acquire and preserve the nation's atmospheric, climatic, geophysical, and oceanographic data, and their mission is to preserve quality, consistency, and continuity for the public interest, policy development, economic good of the nation, and the progress of science. They share responsibility for operating the World Data Centers to facilitate the international exchange of scientific data.

NODC data holdings include physical, chemical, and biological oceanographic data for estuaries, coastal seas, and the deep oceans; NOAA marine environmental buoy data, sea level, and ocean current data; NOAA CoastWatch data and images; and satellite altimetry. NODC collects data from federal agencies, universities, research institutions, and private industry and through bilateral exchanges with other countries. Users can access NODC data many ways—through online searches, direct downloads, and as archived material on diverse media.

NGDC has been the primary repository for many years for geophysical data collected aboard vessels in transit (depth, magnetic field, gravity) including U.S. and foreign research vessels. Oceanographic holdings include solid-earth geophysics data with information on magnetics, gravity, and natural hazards; marine geology and geophysics data, including seafloor samples, bathymetry, gravity, magnetics, and sub-bottom profiles; and paleoclimatological ice cores. NGDC gathers data from NOAA observation programs, universities, other government agencies, non-U.S. organizations, and satellites. Its products include software and systems that enhance the use of environmental data. Unfortunately, NGDC is little more than an archive; it does not maintain comprehensive holdings, and retrieval of data can be difficult. The data it receives are not subject to quality control, and there is no straightforward way to retrieve readily-specific data from the archive it provides.

NCDC is the principal repository for atmospheric and climate data archives. Its holdings include national and global environmental climate, satellite, and radar data from NOAA and National Weather Service agencies and laboratories, and it provided access to U.S. Air Force and U.S. Navy databases and products from non-Department of Defense users. NCDC data sources include satellites, radar, remote-sensing systems; National

Weather Service cooperative observers; aircraft and ships; radiosonde, wind profiler, rocketsonde; solar radiation networks; and National Weather Service forecasts, warnings, and analyses. NCDC products include user-defined climatological graphs and storm event data; near-real-time and archived radar and satellite images; hourly, daily, and monthly climate summaries; and national and global analyses and technical reports.

Other oceanographic data archives contain information on global ocean circulation, geochemistry, and geology. NASA's Earth Observing System-Data Interface System is the primary U.S. repository for satellite observations of Earth. Under the National Ocean Partnership Program's auspices, the United States is preparing data archives and standards for operational ocean observatory systems. ODP maintains its own archives of results from core and borehole logs and a relational database with a World Wide Web interface that describes the cores. Several large international science programs, among them WOCE and JGOFS, have created archives for physical and chemical oceanographic data. Those databases have continued to grow even though their research programs have ended.

Finding: In the past, the lack of standardized data collection efforts hampered long-term utility of very large data sets (e.g., the International Decade of Ocean Exploration). Crucial to the long-term success of the programs is its ability to provide useful archives for access long after the original exploration efforts end.

Recommendation: Data collection and reporting must be standardized to allow data sets from a variety of explorations to be integrated. The sampling techniques and reporting formats should be designed to be acceptable to the worldwide oceanographic community.

The proposed ocean exploration program should be committed to contributing its own relevant data to the existing archives through its Web presence. In some cases, it will be necessary to provide software patches to the existing databases that will allow users to interface with the databases, regardless of the type of data accessed. Ideally, users of the exploration program's portal should be able to download data and have access to graphic presentations of the data and collection locations.

Finding: The Internet is a phenomenal new tool for disseminating the results of oceanographic work to a wide variety of audiences. The excitement and unique information gathered by the proposed exploration program is very well suited to Internet dissemination.

Recommendation: The Internet should be embraced by an ocean exploration program as one place to describe and enhance exploration activities. A program in ocean exploration should work to address some of the key challenges to the oceanographic sciences by modeling, designing, and implementing the data discovery, integration, and visualization components for a semantic web in environmental science.

Data Access Policies

The data management system of the proposed Office of Ocean Exploration should establish data access policies before the first observations are collected. Restrictions on publication or distribution of data from existing databases must be respected when those data are accessed. For example, some industrial data might be made available through an exploration Web site, but with restrictions such as the inability to access individual data points. Users could locate relational graphs, but not the data used to generate them. In this way the data would be available and useful for expedition planning, but not for quantitative analysis.

A default policy could provide for immediate availability through the Internet for any new data generated or acquired through the ocean exploration program, although the traditional rules of research would allow investigators some proprietary time before the public access is allowed. Proper calibration or data validation should be expedient but still ensure the quality of the data. It must be recognized, however, that in many cases unrestricted dissemination of data is not desirable: for example, it would not be useful to reveal the location of an archaeological site that could be plundered if that information were readily available to the public. Data access policies must be flexible to allow for withholding specific information when explorers can adequately justify the need to do so. Alternatively, a “copyleft” policy could be developed. Copyleft, in the popular usage, means “a copyright notice that permits unrestricted redistribution and modification, provided that all copies and derivatives retain the same permissions” (Design Science License, 2002). Certainly, some mechanism must be developed to balance investigators’ proprietary time against the expeditions’ public dissemination of results and data. An exploration program’s ability to react to events or transients is severely degraded when data are not immediately available. Furthermore, the effective archiving of data and metadata becomes more expensive if arbitrary delays are introduced.

Finding: Despite the efforts of federal agencies and other parties, data sharing remains problematic across the ocean sciences. The success of an ocean exploration program will be greatly enhanced by allowing data to be shared soon after collection. Real-time data access is also a possibility that should be considered in the early stages of the program.

Recommendation: Data access and management policies must be established before exploration begins. In particular, any exploration program should encourage oceanographers to improve their capacity to access and integrate data from many ocean sciences, extract new information from those data sets, and convey new insights to decision makers and the public. The proposed Exploration Program for the Oceans office should seek ways to contribute to or link exploration data to existing oceanographic and archaeological data archives.

POSTCRUISE SAMPLE AND DATA ANALYSIS

Considerable shore-based data and sample analysis is often required after a cruise, but funds for postcruise support have been lacking in some major national and international programs, such as NOAA's Office of Ocean Exploration and ODP. The obvious result has been to limit the ability of the scientific community to make the best use of information extracted from data. Support for postcruise science should be a major component of a global ocean exploration program.

Finding: Often only preliminary investigations can be conducted while oceanographic cruises are under way. Additional materials and equipment for sample processing on land must be accessed in order to uncover critical information. Discoveries by an ocean exploration program are very likely to occur as a result of additional, postcruise sample processing.

Recommendation: Support of postcruise science should be a major component of a global ocean exploration program. Researchers should be supported for activities that will enhance their shipboard work, such as sample analysis and data interpretation and presentation. Without direct support, many discoveries might not come to fruition.

7

Outreach, Education, and Capacity Building

Ocean exploration provides rich content that easily captures the imagination of people of all ages. Any ocean exploration effort should seek to:

- bring new discoveries to the public in ways that infuse exploration into their daily lives and capture the inherent human interest in the ocean;
- enfranchise the global community in ocean exploration; and
- develop and foster collaborations among scientists and educators in ocean exploration.

Strong education and outreach programs with global applications should be incorporated into the exploration program. Capacity building—not only to multiply the program's usefulness, but also to develop and conduct international ocean exploration—must be integral to national and international ocean exploration programs.

Because educational systems and cultures differ from one country to another, the responsibility for education and outreach must lie in the ocean exploration programs of each nation. National efforts also should build on each country's expertise through international exchange programs, training, and workshops to ensure broad dissemination of results. Documentaries and other media products are effective tools for educating people everywhere, and they could be used to highlight scientific and archaeological exploration of the oceans within each nation's program.

The exploration program should be recognized globally to enfranchise the global community. An international public awareness campaign on ocean exploration, including an international treaty or declaration for cooperation on ocean exploration, a high-profile and visually exciting kick-off expedition, and the attendant media activities and presentations, should be considered to highlight the fledgling program. Private-sector participation should be sought.

A dedicated exploration flagship, with a name that becomes a household term, much like Jacques Cousteau's *Calypso*, permanently outfitted for education and outreach activities would greatly facilitate achievement of this goal. Near-real-time communications between research vessels and students, educators, and the general public could be accomplished through satellite links and Internet broadcasts (Box 7.1).

Informing government officials about program plans and accomplishments is critical to any large, federally funded program, and it will be important for all countries involved. This will require additional activities beyond those designed to reach the general public. Those activities will differ between countries, but might include inviting government officials and policy makers to visit national centers of exploration and seeking their participation on short portions of cruises, producing fact sheets on recent discoveries and their implications for the research community and society, and inviting decision makers to observe and participate in ocean exploration educational and outreach activities in their own regions.

The proposed focus on the Arctic should be of particular interest to resource managers and policy makers concerned about global climate change. The terrestrial environments in the far north are already showing signs of distress, and latitudinal shifts in ecosystems amplify the more subtle signs discerned in more temperate locations. There is every reason to believe that the marine environment is affected similarly. The drivers for change are not just global warming, but pollution, disease, and human predation in as-yet-unknown proportions. Outreach efforts connected to Arctic exploration would help inform worldwide policy on greenhouse gas emissions, fishing quotas, natural resource extraction, and clean water standards.

> **Finding: The way an ocean exploration program is organized—both nationally and internationally—can make a difference in the effectiveness of public outreach and education efforts. To be successful, educators must learn the science necessary to effectively use the curricula and scientists must understand teachers' needs. Those collaborations cannot be an afterthought; they must be fully integrated throughout the process of ocean exploration. By fostering collaborations among scientists and educators, an exploration program can ensure that educators are an integral part of the planning and conduct of the exploration activity, whether at sea or on land.**

BOX 7.1 CURRENT OUTREACH POSSIBILITIES

Advances in telecommunications technology, including commercially available Earth-orbiting satellites, inexpensive stabilized antennas, high-bandwidth fiber-optic vehicle systems, high-definition video technology, and Internet2, allow real-time access to remote locations around the world and create a cost-efficient means for sharing expensive resources.

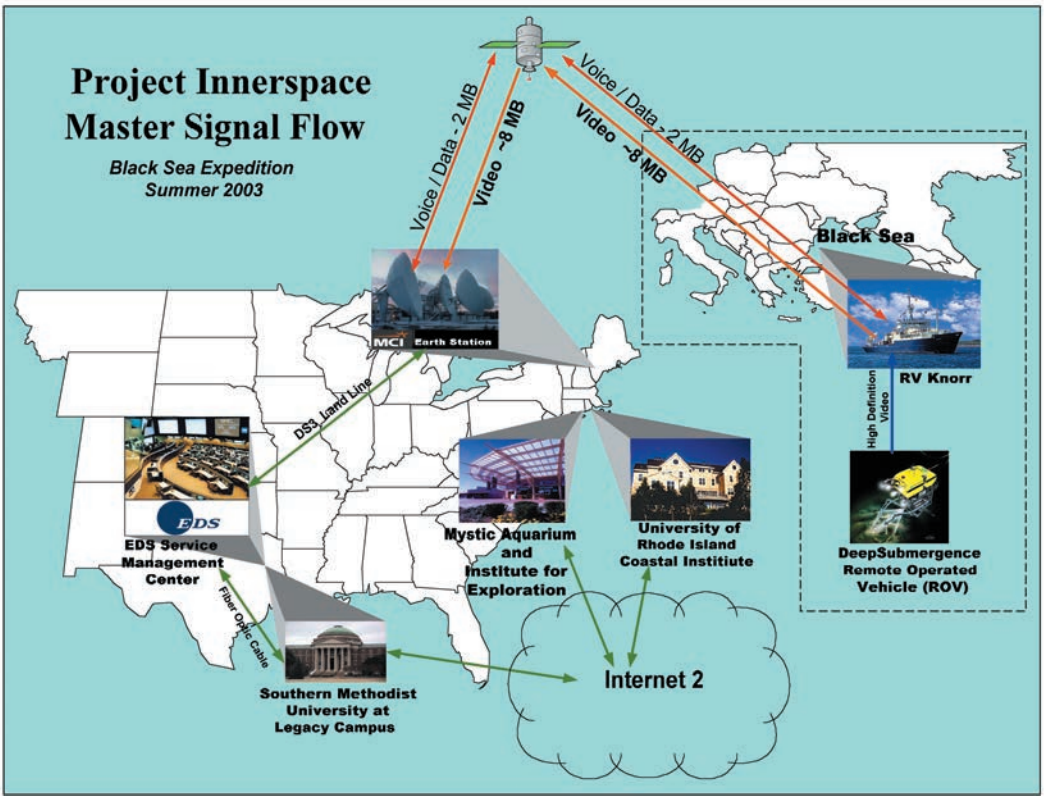
Piggy-backing on a research expedition taking place in the Black Sea and the eastern Mediterranean Sea in July and August 2003, the Sea Research Foundation's Institute for Exploration, in collaboration with the Electronic Data Systems Corporation and the University of Rhode Island, plans to create live video and data streams and produced programming from the University-National Oceanographic Laboratory System R/V *Knorr* to the University of Rhode Island and the Mystic Aquarium and Institute for Exploration so that scientists, students, and the general public can participate in a deep-water archaeological and geological field research program (Figure 7.1). The Institute for Exploration plans to develop a satellite telecommunications system it believes will revolutionize the way scientists, students, and the public participate in field research and exploration. The system will be portable and available for use on cruises beginning in 2004.

FIGURE 7.1 Telecommunications system aboard the R/V *Knorr* (used with permission from the Institute for Exploration). Data from a remotely operated vehicle will be displayed within the shipboard telecommunication and control center and transmitted back to the University of Rhode Island. A replica of the R/V *Knorr's* control center will allow scientists to participate in the expedition from the University of Rhode Island on a 24-hour basis. The Mystic Aquarium and Institute for Exploration will develop a telecommunication production facility connected to the University of Rhode Island via Internet2. In the facility, production staff will adapt the University of Rhode Island and R/V *Knorr* activities into an educational outreach program for distribution to a network of educational organizations that will participate via the public Internet and Internet2. National Geographic Television also will provide live broadcasts of research activities.

Recommendation: Strong education and outreach programs with global applications should be incorporated into any exploration program to bring new discoveries to the public, enfranchise the global community in ocean exploration, and develop and foster collaborations among scientists and educators in ocean exploration.

INFORMAL EDUCATION

Aquariums and other informal education centers are invaluable to ocean education because they attract a large number and variety of people. Many also offer hands-on activities that allow patrons to experience oceans and



oceanic ecosystems. Informal education centers often can bring ocean exploration to the general public in real time on a daily basis with docents and interpreters explaining the science in engaging ways. Such centers increase public support for marine science, and they expose diverse groups of young people to science as a potential career.

FORMAL EDUCATION

Ocean-related curriculum materials can improve ocean literacy, increase future generations' stewardship of the oceans, and encourage more students from diverse cultural backgrounds to pursue ocean-related careers. In particular, the multidisciplinary nature of ocean exploration offers captivating natural examples that can be used to teach basic science—physics, chemistry, biology, mathematics, and geology—in ways that show science is both engaging and relevant to our lives. Unique and dynamic tools and programs should be developed to capitalize on the excitement of exploration (Box 7.2). Data and observations from cruises or from seafloor observatories can be used as the foundations for instructional materials and hands-on activities that teach basic scientific concepts while increasing an understanding of the oceans. Of course, all curriculum development must be done to ensure alignment of materials with academic standards.

Use of ocean-exploration-based materials in national and international classrooms as part of standard curricula will require workshops or study groups to focus on how educators can learn the science necessary to use new curricula effectively, how teachers should conduct the activities, and how the new material can be incorporated into classrooms. A teacher-in-residence program within each nation's exploration program would be particularly effective in the preparation and production of the materials for such workshops and study groups. Participants could then extend their professional development to others in their regions, enabling the use of new exploration educational materials. As the program continues educator networks could offer professional development and information dissemination. The Bridge program is one example of a successful development effort (Virginia Institute of Marine Science, 2003).

BOX 7.2 OUTREACH MECHANISMS

An ocean exploration program should incorporate unique, dynamic outreach programs that capture public attention and provide information about the importance of the oceans. Programs for journalists and science writers could take the form of journalist-in-residence programs within each nation's ocean exploration program or short, intensive, international workshops to focus attention on specific expeditions or discoveries. Informal education centers throughout the world could sponsor "ocean exploration ambassador" programs to bring the latest in ocean exploration discoveries to the public. A core group of ambassadors would be trained within individual nation's exploration programs, either at home or abroad, to work with other educators and the news media within their own regions and countries to disseminate information on ocean exploration. An Ocean Explorer Corps could be established for students in each nation's ocean exploration program. The corps would provide a means of communication, participation, and regular contact with explorers and other people who work in the field.

Partnership development must be the responsibility of each nation participating in the exploration program, and it could be accomplished through professional organizations (examples in the United States include the National Science Teachers Association, the National Marine Educators Association, and the American Geophysical Union) or through other model programs, such as the Centers for Ocean Science Education Excellence created through the National Science Foundation, and the Bridge program (Virginia Institute of Marine Science, 2003) of the National Oceanographic Partnership Program. Professional development opportunities that immerse teachers in the world of scientific investigation can support the development of inquiry-based, standards-based educational materials and products. Educators and students, where appropriate, and science writers, artists, journalists, and others could participate in expeditions or shore-based activities, and post-project lesson plans should be developed by scientists and educators from the data collected.

TRAINING AND CAPACITY BUILDING

"Capacity building" occurs when the potential for further learning and skills development is increased by a multiplier effect. For example, one person trained in ocean exploration increases capacity by training others. Capacity also can be built through institutional development and restructuring, and it must be supported by human, technical, and financial resources.

Capacity building should be an important component of an international exploration program, and many tools can be used: independent, informal learning; more formal training; government-sponsored research (with the legislative support needed to create the necessary institutions). Individual capacity building should involve ways to inform citizens about the importance of the oceans in their daily lives and to promote careers in science, technology, exploration, and allied fields. Agency capacity building to undertake ocean exploration and to manage and analyze data can occur through appropriate technology transfer and training. National capacity can be built to establish ocean exploration programs that achieve national research priorities and to promote one nation's full participation in international exploration efforts.

Building capacity involves outreach, education, and training. Whether the target of such efforts is one student or the staff of an agency or ministry, a variety of educational tools, such as standard curricula, apprenticeships, exchange programs, and other initiatives described in Box 7.2, can be used. Education spawns capacity building when those who have been trained promote ocean exploration in their own agencies, institutions, or countries. Principal investigators for projects from the United States could team with foreign investigators to build mutual capacity. Training of scientists in ocean exploration techniques should target existing gaps in local capacity, especially those gaps that become impediments to reaching stated national, regional, or international goals and priorities.

Financial and technical support are important too, but an international exploration program can do much to build capacity even without huge outlays of money. One way is to leverage funds by raising the profile of exploration efforts in the eyes of the philanthropic community, by providing linkages to a network of donors, and by offering to match funds as necessary. Another way to strengthen institutional capacity through an international exploration program is for the institution to act as a model of how to plan and coordinate exploration efforts, either nationally or regionally. As the international exploration program grows, it will serve as an important catalyst for building needed capacity in other nations.

The proposed theme area of marine biodiversity has great potential to contribute to capacity building: the loss of biodiversity before a baseline can even be quantified is of concern for developed and developing nations alike. And some studies in that area will require only low-technology tools (fishing boats with nets, simple towed camera systems, divers with cameras) as well as sophisticated submersibles. There are excellent examples of terrestrial research programs that preserve critical habitat and protect valuable or endangered species by educating the local populace on the long-term economic gains to be derived from healthy and diverse ecosystems. There is every reason to believe that similar models can be replicated in the marine environments.

Long-term support for an ocean exploration effort will only be possible if government officials are kept fully informed of program plans and accomplishments. In addition, mechanisms for building capacity—to multiply the program's effect and to develop and conduct international ocean exploration—will be integral to national and international ocean exploration programs. It will be important to promote global recognition of the ocean exploration program and to build the ocean exploration capacity of each country's citizens and government.

> **Finding: In a large scale, international ocean exploration program capacity building can serve to enlist additional countries in the efforts, increase the resources (e.g., trained personnel) available for future work, and aid partner nations in good stewardship of our shared oceans.**

Recommendation: National exploration programs should strengthen participation in international exploration through exchange programs for scientists and educators from different countries and through training programs for educators who are preparing to set up exploration-based programs in their own countries. All materials and resources developed or collected through the ocean exploration program should be collected in a repository to document the history of collaborations among scientists and educators involved in ocean exploration.

8

Supporting an Ocean Exploration Program

MOVING BEYOND THE EXISTING PROGRAM

The National Oceanic and Atmospheric Administration's (NOAA) Office of Ocean Exploration, which was established in 2000, does not have the wherewithal to undertake the interdisciplinary, global ocean exploration program proposed in this report. Significantly higher allocations are needed to support a more comprehensive program. More money is needed to increase the program's scope, its flexibility, and researchers' access to equipment—all of which will serve to increase its chances for success.

The budget for NOAA's Office of Ocean Exploration is indicative of current limitations on U.S. ocean exploration. Initially funded at $4 million in 2001, during ensuing years the program has been funded for $13.2 million and $14.2 million annually. The budget for fiscal year 2004 is in the same range although at the time of publication Congressional support is uncertain. This initial effort has been worthwhile, and it serves as a basis for evaluating what can be accomplished. The effort has been partially proposal driven and partially driven by agency mission, without significant thematic direction or input from the scientific community. That aside, some regional workshops have been held to engage more members of the scientific community in the office's efforts.

Fiscal limitations have constrained NOAA's ability to carry out a comprehensive exploration program. Critical elements, such as the following, have been compromised by a lack of money:

- Postcruise science is not funded. Not all discoveries are made during an actual offshore effort, and some discoveries could be missed if specialized onshore tests cannot be performed. Few significant discoveries have been announced or exploited.

- Data management is not funded, so the oceanographic research community has little access to information.
- Only limited technology development is funded. New sensors, for example, to investigate novel sites or measure unsampled properties of the ocean, are not being developed.
- Ship costs are usually leveraged with other planned programs. The resulting ad hoc efforts do not allow complete freedom to explore a particular site or to venture out of relatively well-studied areas to explore the entire world's oceans.
- Project planning is often for the short term because of the nature of government budgeting and within-agency appropriations.
- International cooperative efforts are not supported.
- The scientific community does not see the program as a significant resource of funding for sustained exploration programs.

The NOAA effort is not large enough to generate significant discoveries in the ocean sciences nor is it likely to advance the new technologies that could initiate commercial opportunities. Despite its small budget; however, the NOAA program has demonstrated that there is substantial interest from the U.S. ocean research community. The NOAA exploration program has received many proposals that it was unable to fund.

EXISTING U.S. ASSETS: MECHANISMS TO INCREASE AVAILABILITY

The University-National Oceanographic Laboratory System (UNOLS) allocates ships and other research platforms using proposals submitted to the oceanographic research agencies, primarily the National Science Foundation (NSF), the Office of Naval Research, and NOAA. If the exploration program is to use existing U.S. assets, an accommodation must be explicitly incorporated into the UNOLS allocation system. Because exploration programs will be additions to the current research expedition schedules, additional ship time must be allocated. Since demand fully occupies available UNOLS global class ship time, exploration programs will have to compete for available ships. The proposed fleet capitalization effort should encompass exploration-related programs and the special requirements that might be associated with them (Federal Oceanographic Facilities Committee, 2001). Exploration also could be hampered by UNOLS inability to respond rapidly to a discovery because of the lack of availability. Long-term planning and agency commitment, more than a year in advance, is essential to the efficient operation of an oceanographic fleet. Historically, only NSF and the Office of Naval Research have been able to accommodate such planning. The current UNOLS system cannot generally accommodate short-term, short-notice charters. A specially designed ship for exploration programs or the ability to use short-term commercial charters could help alleviate this problem.

Issues of cost and safety also must be addressed to ensure that short-term commercial charters are efficient and safe. Use of some specialized commercial equipment such as remotely operated vehicles (ROVs), autonomous underwater vehicles (AUVs), human occupied vehicle (HOV), and some laboratory equipment could be made possible by establishing agreements in advance of the need for deployment. This is especially true for portable equipment that can be deployed rapidly to sites anywhere in the world.

COST OF OPERATIONS

Operational and capitalization costs for three funding scenarios are described in Table 8.1. The minimal program (about $30 million for the first year, including capitalization costs; $30 million for subsequent years' operation) would target just one or two priority themes to be truly successful. It might be able to support a long-term program focused on a particular theme, but only if the funding were constant. Capitalization costs would be minimal—there would be limited education and outreach and little opportunity to explore extremely remote or hostile locations. All assets would be rented or leased, so advanced scheduling would be essential and there would be only limited opportunity to respond to specific events.

Three priority theme areas could be addressed by a program funded according to the middle plan (about $125 million for the first year, including capitalization costs; about $70 million for subsequent years' operation costs). The program would use two years' ship time with varying capabilities, depending on the environment and the themes addressed. Capitalization would enable the purchase of a dedicated HOV, three dedicated ROVs, and five dedicated AUVs and leasing or renting additional submersible facilities and other equipment. Data management would be state of the art. International efforts could include joint projects. Outreach could occur from shipboard operations and include film and television. Education would include curriculum development and teacher training. The geographic range of operations would be extended to all oceans, but there would still be limited opportunity to respond to rare events.

The fully capitalized program (about $270 million for the first year, including capitalization costs; about $110 million for subsequent years'

TABLE 8.1 Operational Funding Estimates: Program Features

Funding	Minimal Program	Competitive Program	Fully Capitalized Program
Annual funding	About $30 million	About $70 million	About $110 million
Equivalent class 1 ship time[a]	One year	Three years	Two years plus one year on a dedicated purpose-built ship
Number of exploration themes addressed concurrently	One	Three	Several
Environmental conditions	Nonhostile	Some hostile	All oceans
Locations	Mostly U.S. territories	All oceans	All oceans
International participation	Collaborative efforts	Cooperative efforts	Acceptance of in-kind contributions[b]
Long-term programs	Limited	Moderate	Moderate
Capitalization	Minimal	Moderate	Large
Remotely operated vehicles	One leased for a full year	Three owned and operated	Five owned and operated (state of the art)
Human occupied vehicles (HOV)[c]	One leased for a full year	One leased for full year; one owned and operated	Two leased plus one owned and operated
Autonomous underwater vehicles (AUV)	One leased for a full year	Five owned and operated[d]	Ten owned (state of the art)[d]
Outreach	At sea	Long-term capacity building	Long-term capacity building
Development of future program visions (as a percentage of a budget)[e]	Limited	Moderate	Full
Data management	Yes	Yes and investigate new methodologies	Yes and investigate new methodologies

[a] Equivalent class 1 (greater than 250 feet long) ship time/year could be for a single vessel or for several vessels concurrently for a total of one ship-year on a vessel classified by the University-National Oceanography Laboratory System as class 1.

[b] In-kind contributions could include contributed ship time, professional assistance, technical support, and satellite access.

[c] HOV leases refer to possible leasing of existing assets as listed in Table 6.1.

[d] Commercial AUVs could be leased, if appropriate.

[e] Dynamic new exploration plans will require dedicated resources, feasible only with greater funding.

operation) would focus on several priority themes simultaneously. That program would include year-round use of several exploration platforms and flexibility in scheduling those platforms to best meet program goals. The program-owned fleet would consist of a ship, three HOVs, five ROVs, and ten AUVs. The fully capitalized program's HOVs, ROVs, and AUVs would have a range of water depth capabilities. HOVs would be purchased for shallow-water research ($200,000-$300,000) and for work at depths of 6,500 m ($20 million). ROVs would range in water depth and manipulator capabilities from the relatively inexpensive "observation" types to heavy-work, deep-water units. The costs for those vehicles are discussed later. The program also would have the resources to lease other platforms in specialized environments as needed. With less funding, the program would likely need to schedule the use of different platforms, and it would not have complete control over the scheduling of platforms for exploration projects. Technology development would include sensors and platforms, and outreach would extend to international capacity building.

Annual operating expense estimates were generated using estimates for various costs associated with maintaining the Exploration Program for the Oceans (ExPO) office, supporting the oversight framework, and conducting exploration (Table 8.2). The estimates in Table 8.2 are derived from committee members' experience, the operational costs of comparable programs, and a review of several reports and Web sites. Ship costs, for example, are based on 300-day-per-year use at $20,000 per day—approximated from costs for UNOLS for large and global class ships. For 2001, the R/V *Revelle*, R/V *Melville*, R/V *Thompson*, R/V *Knorr*, and R/V *Atlantis* averaged $5.5 million each (National Science Foundation, 2000). One ship-year equivalent is projected for the minimal program level. For the competitive program, two ship-years are proposed. At the fully capitalized level, costs are estimated for the operation of two leased vessels and one owned vessel fully dedicated to ocean exploration. The ExPO office budget figures were estimated based on three successive annual budgets (2000-2002) for the Joint Oceanographic Institutions. The expenses include personnel, rent and equipment, miscellaneous office expenses, and hiring outside contractors (including legal assistance for developing international agreements).

The budget for submersible equipment and operations (HOVs, ROVs, AUVs) is based on input from the operators of major U.S. oceanographic facilities for submersible science (Monterey Bay Aquarium Research Institute, Woods Hole Oceanographic Institution, Harbor Branch Oceanographic Institution). For example, a $4.5 million annual budget presented by Richard Pittenger (personal communication) for the National Deep Submergence

TABLE 8.2 Yearly Cost Estimates[a]

Item	Minimal Program ($ million)	Competitive Program ($ million)	Fully Capitalized Program ($ million)
Ship time	6.0	12.0	18.0
Exploration Program for the Oceans Office			
Personnel	1.3	2.6	3.9
Rent and equipment	0.2	0.4	0.6
Office expenses	0.2	0.4	0.6
Outside contractors	0.5	1.0	1.5
Human Occupied Vehicle (HOV), Remotely Operated Vehicle (ROV), and Autonomous Underwater Vehicle (AUV) operations	6.0	20.0	36.0
Other shipboard equipment	2.0	3.0	4.0
Data management			
Information services (10% of budget)	3.0	7.0	11.0
Science support			
Meetings	0.5	1.0	1.5
Travel	0.5	1.0	1.5
Scientist support	3.5	7.0	10.5
Technology development (10% of budget)	3.0	7.0	11.0
Education and outreach (10% of budget)	3.0	7.0	11.0
Total Operations	**29.7**	**69.4**	**111**
Capitalization			
Ship	0.0	0.0	70.0
HOV	0.0	25.0	25.0
ROV	0.0	12.0	20.0
AUV	0.0	15.0	30.0
Other equipment	1.0	3.0	15.0
Total capitalization	**1.0**	**55.0**	**160**
Total program	**30.7**	**124**	**271**

[a] These budget values are based upon the committee's best current estimates for technology development of the major infrastructure items, and for operations.

Facility includes the deep submergence vehicle *Alvin*, the ROV system *Jason II/Medea*, DSL 120 (towed sonar vehicle), and *Argo II* (towed imaging and mapping vehicle). The operation day varies by platform. HOVs generally have a 12-hour operation day; ROVs and AUVs can operate for 18-24 hours. At the minimal program level, the annual cost of $6 million is based on $2 million each for one HOV, one ROV, and one AUV. This would enable the operation of each system—an HOV, an ROV, or an AUV—deployed on one or several vessels for the equivalent of one ship-year. For the competitive program, the budget includes sufficient assets to be deployed on two ships or their equivalent (Table 8.1, note a): two HOVs, three ROVs, and five AUVs. For the fully capitalized program, at least three complete systems (HOV, ROV, AUV) or "fleets" of AUVs, plus some combination of HOVs and ROVs as dictated by science, would be funded.

The cost for other shipboard equipment includes leasing instrumentation and equipment as dictated by a given mission. Data management is estimated at 10 percent of the total operating budget. For comparison, the Ocean Drilling Program spends about 3.4 percent of its budget on data management—a figure the committee believes is too low—and the Incorporated Research Institutions for Seismology spend about 33 percent on data management—which would be too large a proportion of the total ExPO budget. The committee proposes 10 percent of the budget as a realistic figure. The budget includes the costs of sending scientists to and from sea and to meetings to present findings. It also includes salaries for scientists while at sea as well as for some follow-up time after cruises. It includes costs for sample and data analysis. Neither ExPO nor the Ocean Drilling Program is designed to do the science associated with collecting samples and data at sea; they would collect, catalog, and describe the samples. Sufficient funding must be allowed for data archival and for publishing results. Some funding should be made available for postcruise scientific studies to facilitate and develop hypotheses for the discoveries made during ocean cruises.

It is assumed that an ocean exploration program will require regular, extensive technical development to ensure program success. Ten percent of the annual budget is allocated for technology development. For comparison, NSF budgets about $10 million annually for technology development in ocean sciences (A. Isern, personal communication).

The education and outreach budget is 10 percent of the annual appropriation, following NOAA's Office of Ocean Exploration's current budget profile. The committee believes this is appropriate, particularly for the competitive and fully capitalized programs.

INITIAL CAPITALIZATION

The success of the exploration program will depend on the capital assets available (Table 8.2). The most obvious question is whether the program will own (or contract for a long-term charter) a flagship and, if it does, what its specifications should be. Other assets should include submersibles of various types—ROVs, AUVs, and HOVs—and specialized laboratory equipment that will allow shipboard processing of data. The advantages of ownership are obvious: it is better to have a fleet that is available on short notice and to have access to equipment that is suitable for use in a particular area or environment.

An exploration flagship is recommended to maximize program capabilities; ensure access and scheduling flexibility; and allow for well-integrated, ship-based education programs. Although the initial expense can be daunting, at least one government report has shown that purchasing a vessel is more cost effective than is long-term leasing (U.S. General Accounting Office, 1999). The ocean exploration vessel should be equipped with a state-of-the-art ROV, a state-of-the-art HOV, and at least one state-of-the-art AUV. The estimated cost for such a flagship would be $70 million to $80 million. Ship capitalization assumes that a UNOLS large or global class ship will be required to sail in all oceans. Limited ice strengthening of the vessel also is assumed. The cost estimates were obtained from the Federal Oceanographic Facilities Committee (2001) ($70 million). The flagship should be capable of:

- state-of-the-art navigation and broadband communications for all oceans;
- Class 2 dynamic positioning;
- simultaneous ROV and HOV activities;
- HOV capabilities to 6,500 m;
- ROV and AUV capabilities to 6,500 m; and
- state-of-the-art sampling.

More specific equipment requirements should be determined by a select interdisciplinary committee. To ensure a competitive, cost-effective vessel selection process, the ExPO office should consider issuing a request for proposals for vessel procurement and the ship should be operated by UNOLS. Bids would likely include new and retrofit vessels, and cost-effectiveness would be considered in selecting the final contract. Therefore, those equipment capital costs are not estimated in this report. Capitalization requirements also would depend on the assets reliably available from UNOLS.

Any project need to investigate below 6,500 m water depth is not expected to represent a significant portion of the exploration effort. Until recently, full-ocean-depth requirements for an ROV could have been met by existing equipment (Japan Marine Science and Technology Center, 2003). Recently, the full-ocean-depth *Kaiko* was lost. At a development cost estimated at $60 million (National Research Council, 1996), a *Kaiko*-equivalent would represent a considerable proportion of the proposal capital budget. This one piece of equipment might not be used a significant amount of time during the program. The cost of building a full-ocean-depth HOV capable of reaching the approximately one percent of ocean floor below 6,500 m are estimated to be three to five times that for a 6,500 m HOV and are not included here.

Capitalization costs for ROVs depend on several factors, and they can vary dramatically from one system to another, even among ROVs of the same class (Box 8.1). The most important considerations for estimating costs for those systems involve the variables of mission requirement, operating depth, and support vessel, which should result in detailed specifications (Table 8.3). The cost to build a 6,500 m ROV was estimated at $4 million, which was based on the cost ($3.7 million) of the *Jason II* (R. Pittenger, personal communication).

Where possible, AUVs for exploration purposes should use commercial capabilities (on short- or long-term charters) because considerable experience is required to achieve reliable mission success. For example, the *Hugin 3000* AUV, manufactured by Kongsberg-Simrad and operated by C & C Technologies, Inc., is successfully used for high-resolution geophysical surveys. Significant costs are associated with the capitalization and development of AUVs with sophisticated or deep-water capabilities. The cost of the *Hugin 3000* is $3.5 million (C. Hancock, personal communication) with an expected additional $2 million (T. Chance, personal communication) in added costs to fully outfit the system. It costs about $3 million more each year to maintain the *Hugin 3000*. Other AUVs with less sophisticated requirements, such as the *Bluefin* and the *Autonomous Benthic Explorer*, require less initial capital (about $2 million) and are suggested as sufficient for water column and limited benthic studies.

HOV use in an exploration program is expected to vary from shallow water to deep water. Many archaeological studies use shallow-water HOVs such as Seamagine's *Seamobile* (Seamagine Hydrospace Corporation, 2001; Bass, 2002), which costs $200,000 to $300,000. Programs that focus on a continental shelf or slope could use mid-depth-range submersibles, such as the Hawaii Underwater Research Laboratory's *Pisces* and the Harbor Branch

BOX 8.1 VEHICLE COSTS

Mission requirements determine the amount of power that must be transmitted to an ROV as well as the specialized tooling, video, navigation, and sensor and sampling equipment required (Table 8.3). This in turn determines the number and size of power conductors, fiber-optic cables, and armoring, which affect the complexity, overall diameter, and weight of the umbilical. Manipulators run, for example, the full range—from simple joystick-controlled grabbers to more costly, complex, and sophisticated systems that use master-slave control functions for great dexterity and multiple tool options. Consideration must be given to the amount of spares to be carried onboard. For an ROV system with worldwide operational capability far from shore-based support, the amount of spares and test and repair equipment could be a significant cost factor. The operating-depth requirement determines the length and characteristics of the umbilical and the surface handling system, including the winch used to store, launch, and recover ROVs. It also will determine the packaging of instrumentation and ROV components, such as buoyancy, electronics housings, and other pressure-resistant components the cost of which is affected by depth. The support vessels must be considered in the cost analysis. Costs to mobilize and permanently install large ROV or HOV systems with very deep capabilities can be significant and are part of the overall capitalization. Placement of the system, including the launch and recovery equipment and control centers, can require expensive vessel modifications. Special consideration also might need to go to building over-boarding systems to allow for launch and recovery in rough seas. For smaller, lighter, and less-depth-capable portable "flyaway" systems designed for opportunistic use aboard a range of vessels, there will be an operating (noncapital) cost each time the system is mobilized and installed and then deinstalled, demobilized, and refurbished. The support vessel options and geographic flexibility attributed to this type of system must trade off against the lesser capability, but they certainly are appropriate for a significant number of applications.

TABLE 8.3 Capitalization of Commercial Remotely Operated Vehicles (ROVs)

ROV Class	Task	Depth (m)	Horsepower	Approximate cost ($ million)
Observation	Observation	300	1-20	0.01-0.10
Medium	Observation, medium work	2,000	25-50	1-2
Heavy	Heavy work	3,000	75-150	2.5-3.5

Oceanographic Institution's Johnson-Sea-Link submersibles. For deeper HOV applications, the United States can only reach a depth of 4,500 m. Russia, Japan, and France have better capabilities (Table 6.1). Plans are being discussed to enhance the deep-submergence fleet. Currently, the National Research Council's Committee on Future Needs in Deep Submergence Science is reviewing deep-submergence needs for NSF; the final report is expected in 2003. The cost of a 6,500 m water depth HOV is estimated at $20 million (R. Pittenger, personal communication).

Finding: Access and flexibility are necessary to implement an ocean exploration program. Although assets for oceanographic research exist, a new ocean exploration program that seeks to enhance the current efforts, as proposed in this report, will require substantial assets. New oceanographic assets would increase the effectiveness of the program, while minimizing interference with current research endeavors.

Recommendation: To undertake a truly large-scale, ocean exploration program that would incorporate the disciplines discussed in this report, a specialized, dedicated flagship, and a modest fleet of underwater vehicles should be provided. Such a program would require first-year funding of approximately $270 million. Thereafter, annual operating costs would be about $110 million. A more moderate program, operating fewer assets, could be operated for approximately $70 million annually.

Finding: The scope of the proposed ExPO office will depend on annual funding. An important new ocean exploration program can be undertaken at various levels, and estimates of the return on that investment should be made accordingly. If funds are limited, the theme areas the program seeks to address should be scaled back. This apportionment of program initiatives will help ensure support for postcruise data analysis and data bank maintenance and support. In any such initiative, the input of the research community should be sought to assist in identifying necessary trade-offs. The ExPO office should be responsible for implementing program activities and operations—congressional earmarking can obstruct program integrity and success. With broad, interdisciplinary involvement, open forums for discussion of program goals and choices, and accountable management of the program, a large-scale, international ocean exploration initiative is likely

to succeed in providing economic, scientific, and environmental benefits for all.

Recommendation: Especially at the lower levels of funding presented in this report, the efficient, effective use of resources must be ensured and should involve the following:

- **decision-making should be informed by the research community, program managers and administrators, and legislators; and**
- **a clear statement of program goals must be used to drive the choices of capitalization.**

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Appendixes

A

Committee and Staff Biographies

COMMITTEE

John Orcutt (Chair) is a Professor of geophysics and Deputy Director at Scripps Institution of Oceanography and Interim Dean of Marine Sciences at the University of California, San Diego. Dr. Orcutt earned his undergraduate degree in mathematics and physics at the U.S. Naval Academy, a M.Sc. in physical chemistry as a Fulbright Scholar at the University of Liverpool, and a Ph.D. in geophysics from the University of California, San Diego-Scripps Institution of Oceanography. His research focuses on the internal structure of ocean spreading centers, the use of information technology in integrating real-time data from a wide variety of sensors using wireless networks, and ocean seismo-acoustics including rough seafloor scattering and the use of small arrays. Dr. Orcutt is the President-Elect of the American Geophysical Union and is a Secretary of the Navy/Chief of Naval Operations Oceanography Chair. He is a member of the American Philosophical Society and served briefly as Interim President of the Ocean Drilling Program in 2000. Dr. Orcutt is a former member of the Ocean Studies Board and has served on numerous NRC committees.

Shirley Pomponi (Vice-Chair) is the Vice President and Director of Research at Harbor Branch Oceanographic Institution. Dr. Pomponi earned a Ph.D. in biological oceanography from the University of Miami. Her research focuses on the development of methods for sustainable use of marine resources for drug discovery and development, and in particular, on developing cell lines of bioactive marine invertebrates and determining the role of associated microorganisms in the production of bioactive secondary metabolites. Dr. Pomponi is a member of the Society for In Vitro Biology, the Society for Biomolecular Screening, the American Society for Cell Biology, and the American Geophysical Union. Dr. Pomponi served on the

President's Panel on Ocean Exploration and the NRC's Committee on Marine Biotechnology: Development of Marine Natural Products.

Tundi Agardy is the Founder and Executive Director of Sound Seas, which works to promote effective marine conservation by utilizing both science and sociology, and works as the interface between public policy and community-based conservation efforts. Dr. Agardy earned a Ph.D. in biological sciences in 1987 from the University of Rhode Island. She was a Senior Scientist at the World Wildlife Fund and Senior Director of the Global Marine Program for Conservation International. Dr. Agardy has been a member of numerous organizations, such as the International Union for Conservation of Nature and Natural Resources Commission on National Parks and Protected Areas and Species Survival Commission.

George Bass is a Distinguished Professor Emeritus of Anthropology at Texas A&M University. Dr. Bass earned a Ph.D. in classical archaeology in 1964 from the University of Pennsylvania. His research focuses on classical and nautical archaeology. Dr. Bass has received many honors, including the Archaeological Institute of America's Gold Medal for Distinguished Archaeological Achievement, a National Geographic Society Centennial Award, and the National Medal of Science.

Earl Doyle is presently a consultant who retired from Shell Oil where he was a Senior Staff Civil Engineer working in the area of ocean engineering. Mr. Doyle earned a M.S. in ocean engineering in 1968 from the University of Rhode Island. He is a current member of the Ocean Studies Board.

Terry Garcia is Executive Vice President of the National Geographic Society. Mr. Garcia earned a J.D. in 1980 from George Washington University. He is responsible for the Society's core mission programs and is a member of the Society's Executive Management Council and Committee for Research and Exploration and a trustee of the Society's Education Foundation. Prior to joining the Society in 1999, Mr. Garcia was the Assistant Secretary of Commerce for Oceans and Atmosphere, U.S. Department of Commerce, and Deputy Administrator of the National Oceanic and Atmospheric Administration. In his role he directed and coordinated all domestic and international coastal and ocean programs of the National Oceanic and Atmospheric Administration. From 1994 to 1996, Mr. Garcia was the National Oceanic and Atmospheric Administration's general counsel. Prior to entering government service, Mr. Garcia was a Partner in the law firm of Manatt, Phelps & Phillips in Los Angeles.

Bruce Gilman is retired from Sonsub Inc. where he worked in the areas of engineering, operations and management of programs, projects and organizations dealing with the offshore and marine environment including manned diving, manned submersibles and unmanned remotely operated vehicles. Mr. Gilman earned a B.S. in aeronautical engineering from Polytechnic University. He is a registered Professional Engineer, Marine Technology Society Fellow, member of the American Society of Mechanical Engineers and Society of Petroleum Engineers, serves on the Texas Sea Grant College Program Advisory Committee, and holds several patents relating to the offshore industry.

Susan Humphris is a Senior Scientist in the Department of Geology and Geophysics and Director of the Earth-Ocean Exploration Institute at Woods Hole Oceanographic Institution. Dr. Humphris earned a Ph.D. in chemical oceanography in 1977 from the Massachusetts Institute of Technology and Woods Hole Oceanographic Institution Joint Program. She taught undergraduates and served as Dean at the Sea Education Association for 13 years before returning to Woods Hole Oceanographic Institution. Her research focuses on volcanic and tectonic controls on the distribution and characteristics of hydrothermal activity at mid-ocean ridges, the geochemistry of rock-water interactions, and the role of the associated hydrothermal fluxes in global geochemical mass balances. From 1996 to 1998, Dr. Humphris was Chair of the Science Committee for the Ocean Drilling Program. She has also served on some NRC committees.

Isao Koike is the Director of the Ocean Research Institute of the University of Tokyo. Dr. Koike earned a Ph.D. in microbiology in 1975 from the University of Tokyo. His research focuses on marine biogeochemistry, especially dynamics of dissolved and colloidal organic matter in the ocean, microbial nitrogen and carbon transformation, and nutrient dynamics in tropical lagoon. Dr. Koike joined many cruises to the Western Pacific Ocean and the Bering Sea as Principal Investigator, and also performed field surveys in the Pacific Islands and Southeast Asia. He is the Secretary of the Japanese National Scientific Committee for the International Geosphere-Biosphere Programme and the Treasurer for the Executive Board of the International Council for Science of the International Geosphere-Biosphere Programme.

Richard Lutz is the Director of the Center for Deep-Sea Ecology and Biotechnology at Rutgers University. Dr. Lutz earned a Ph.D. in 1975 from the University of Maine. His research focuses on shellfish ecology and biology of deep sea hydrothermal vents. Dr. Lutz participated in the first biological expedition to the Galapagos Rift vents in 1979. He served on the Steering Committee for the Workshop on the Mid-Oceanic Ridge: A Dynamic Global System.

Marcia McNutt is the President and Chief Executive Officer of the Monterey Bay Aquarium Research Institute, which is privately funded by the David and Lucile Packard Foundation to develop better technology for ocean research and apply it to outstanding problems through teamwork between scientists and engineers. Dr. McNutt earned her Ph.D. in earth sciences in 1978 from Scripps Institution of Oceanography. Her own research focuses on the use of marine geophysical data to study the physical properties of the Earth beneath the ocean. Dr. McNutt has received the Macelwane Award from the American Geophysical Union and fellowship in the American Academy of Arts and Sciences. She is a past President of the American Geophysical Union and served as Chair of the President's Panel on Ocean Exploration.

John Norton Moore is the Walter L. Brown Professor of Law at the University of Virginia School of Law and Director of the University's Center for Oceans Law and Policy. In addition to his scholarly career, Professor Moore has a distinguished record of public service. Among seven presidential appointments, he served as Chairman of the National Security Council Interagency Task Force on the Law of the Sea, Ambassador and Deputy Special Representative of the President to the Law of the Sea Conference, and as a member of the National Advisory Committee on Oceans and Atmosphere. Professor Moore has served as Chairman of the Marine Education and Policy Division of the Marine Technology Society (MTS) since 1979, was an MTS Fellow in 1983, and received the MTS-sponsored "Compass Distinguished Achievement Award" for 1994. He is also a co-founder of the international Rhodes Academy of Oceans Law and Policy.

Walter Pitman, III is a Special Research Scientist at Lamont-Doherty Earth Observatory at Columbia University. Dr. Pitman earned a Ph.D. from Lamont-Doherty Earth Observatory at Columbia University. His research focuses on past sea-level changes, both short- and long-term, their causes and effects on the sedimentary record, climate change, and human history. He is a member of the National Academy of Sciences.

Jörn Thiede is the Director of the Alfred Wegener Institute for Polar and Marine Research. Dr. Thiede earned a Ph.D. in geology in 1971 from Kiel University. His research focuses on marine sediments and arctic geology. In 1998, Dr. Thiede received the Murchison Medal from the United Kingdom Geological Society and is the current Chairman of the European Polar Board. He served on the NRC Committee on Arctic Solid-Earth Geosciences and was recently elected as a foreign member of the Russian Academy of Sciences.

Victor Vicente-Vidal Lorandi is Professor and Head of the Oceanography Studies Group at the Centro de Investigación en Ciencia Aplicada y Tecnología Avanzada of the Instituto Politécnico Nacional. Dr. Vicente-Vidal Lorandi earned a Ph.D. in oceanography in 1978 from the University of California, San Diego-Scripps Institution of Oceanography. His research focuses on coastal circulation, modeling of coastal discharges, mesoscale circulation phenomena associated with Loop Current ring interactions with topography, and water mass distribution within the Intra-Americas Sea. Dr. Vicente-Vidal Lorandi served on the OSB's Academia Mexicana de Ciencias-National Research Council Joint Working Group on Ocean Sciences.

STAFF

Jennifer Merrill earned a Ph.D. in marine and estuarine environmental science from the University of Maryland Center for Environmental Science. Dr. Merrill is a Senior Program Officer for the Ocean Studies Board and staffs a broad range of topical studies. Studies completed at the NRC include *Ocean Noise and Marine Mammals* (2003), *Oil in the Sea III* (2003), and *Marine Biotechnology in the Twenty-First Century: Problems, Promise, and Products* (2002). Her research interests include watershed and wetland management, geochemistry, and nutrient cycling in coastal systems.

Jodi Bachim serves as a Senior Project Assistant for the Ocean Studies Board. She received a B.S. in zoology from the University of Wisconsin-Madison in 1998. Since starting with the Ocean Studies Board in May 1999, Ms. Bachim has worked on several studies regarding fisheries, geology, nutrient over-enrichment, and marine mammals.

B

Acronyms

ADCP	acoustic Doppler current profiler
AUV	autonomous underwater vehicle
BCOM	JOIDES's Budget Committee
BSRP	Baltic Sea Regional Project
C	carbon
C-SCOUT	Canadian Self-Contained Off-the-shelf Underwater Testbed
CLIVAR	Climate Variability and Predictability
COARE	Coupled Ocean Atmosphere Response Experiment
CoML	Census of Marine Life
EEZ	exclusive economic zone
ESSEP	JOIDES's Science Steering and Evaluation Panel: Dynamics of Earth's Environment
EXCOM	JOIDES's Executive Committee
ExPO	Exploration Program for the Oceans
GCOS	Global Climate Observing System
GEOHAB	Global Energy and Oceanography of Harmful Algal Blooms
GLOBEC	Global Ocean Ecosystem Dynamics
GLOSS	Global Sea Level Observing System
HBOI	Harbor Branch Oceanographic Institution
HOV	human occupied vehicle
HURL	Hawaii Undersea Research Laboratory
IASC	International Arctic Science Committee
ICES	International Council for Exploration of the Seas

ICSU	International Council for Science
IDOE	International Decade of Ocean Exploration
IFREMER	Institut Français de Recherche pour l'Exploitation de la Mer
IGBP	International Geosphere-Biosphere Programme
IGOE	International Global Ocean Exploration
IGY	International Geophysical Year
IOC	Intergovernmental Oceanographic Commission
IODP	Integrated Ocean Drilling Program
IPY	International Polar Year
ISS	International Space Station
ISSEP	JOIDES's Science Steering and Evaluation Panel: Dynamics of Earth's Interior
JAMSTEC	Japan Marine Science and Technology Center
JGOFS	Joint Global Ocean Flux Study
JOI	Joint Oceanographic Institutions
JOIDES	Joint Oceanographic Institutions for Deep Earth Sampling
LOS	Law of the Sea
LOSC	Law of the Sea Convention
MBARI	Monterey Bay Aquarium Research Institute
MODIS	Moderate Resolution Imaging Spectroradiometer
NADW	North Atlantic Deep Water
NASA	National Aeronautics and Space Administration
NCDC	National Climatic Data Center
NGDC	National Geophysical Data Center
NOAA	National Oceanic and Atmospheric Administration
NODC	National Oceanographic Data Center
NOPP	National Ocean Partnership Program
NORLC	National Ocean Research Leadership Council
NRC	National Research Council
NSF	National Science Foundation
ODP	Ocean Drilling Program
OPCOM	JOIDES's Operations Committee
POGO	Partnership for Observation of the Global Ocean

RIDGE	Ridge Interdisciplinary Global Experiments
ROV	remotely operated vehicle
SCICOM	JOIDES's Science Committee
SCOR	Scientific Committee on Oceanic Research
SOIREE	Southern Ocean Iron Enrichment Experiment
SOLAS	Surface Ocean-Lower Atmosphere Study
TEDCOM	JOIDES's Technology and Engineering Development Committee
TOGA	Tropical Ocean and Global Atmosphere
UNOLS	University-National Oceanographic Laboratory System
WCRP	World Climate Research Program
WHOI	Woods Hole Oceanographic Institution
WMO	World Meteorological Organization
WOCE	World Ocean Circulation Experiment

C
International Global Ocean Exploration Workshop: Agenda and Participants

AGENDA

May 13-15, 2002
Intergovernmental Oceanographic Commission
Paris, France

Monday, May 13

9:00 a.m. Welcome: Morgan Gopnik, Director, Ocean Studies Board, U.S. National Academies, Washington, D.C.

9:15 a.m. John Orcutt, Professor, Scripps Institution of Oceanography, California (Chair, NRC Exploration of the Seas Committee)

9:30 a.m. Patricio A. Bernal, Executive Secretary, Intergovernmental Oceanographic Commission; Assistant Director-General, United Nations Educational, Scientific, and Cultural Organization, France

9:45 a.m. U.S. Congressman James C. Greenwood

10:00 a.m. Plenary session
Chair: Shirley Pomponi, Vice President and Director of Research, Harbor Branch Oceanographic Institution, Florida (Vice-Chair, NRC Exploration of the Seas Committee)

- *Charge to speakers: Why/what is ocean exploration: value of exploration in general, and of a coordinated international exploration program in particular?*

10:10 a.m. Marcia McNutt, Director, Monterey Bay Aquarium Research Institute, California (Member, NRC Exploration of the Seas Committee)

10:30 a.m. Break

10:50 a.m. Joe Baker, Chief Scientist and Commissioner for the Environment, Department of Primary Industries, Queensland Government, Australia
11:10 a.m. Victor Smetacek, Head, Division on Pelagic Ecosystems, Alfred Wegener Institute, Foundation for Polar and Marine Research, Germany
11:30 a.m. Panel discussion

12:00 p.m. Lunch

2:00 p.m. Existing programs
Chair: Susan Humphris, Senior Scientist, Woods Hole Oceanographic Institution, Massachusetts
(Member, NRC Exploration of the Seas Committee)

- *Charge to speakers: Please detail current or prior oceanographic explorations (including international programs), and their objectives that have occurred in your nation/organization. What have been the significant discoveries/results?*

2:00 p.m. Keynote: Captain Craig McLean, Director, Office of Ocean Exploration, U.S. National Oceanic and Atmospheric Administration, Maryland
2:20 p.m. John Field, Professor, University of Cape Town, South Africa
2:40 p.m. Jeremy Green, Head, Department of Maritime Archaeology, Western Australia Maritime Museum
3:00 p.m. Shubha Sathyendranath, Executive Director, Partnership for Observation of the Global Oceans, Canada

3:20 p.m. Break

3:40 p.m. Jilan Su, Physical Oceanographer, Second Institute of Oceanography, State Oceanic Administration, China; and Chair, Intergovernmental Oceanographic Commission, France

4:00 p.m. Sunil Murlidhar Shastri, Lecturer, Scarborough Centre for Coastal Studies, University of Hull, United Kingdom

4:20 p.m. Rene Drucker-Colin, President, Mexican Academy of Sciences

4:40 p.m. Rob Murdoch, Director, Research Development, National Institute for Water and Atmospheric Research, New Zealand

5:00 p.m. Panel discussion

6:00 p.m. Reception

Tuesday, May 14, 2002

9:00 a.m. Priority areas for a coordinated international exploration program
Chair: Victor Vicente-Vidal Lorandi, Director, Oceanography Department, Instituto Politecnico Nacional, Mexico (Member, NRC Exploration of the Seas Committee)

- *Charge to speakers: What distinctive features of ocean exploration would make it a priority area for your country/organization to participate? What benefits would your nation/organization foresee in an international ocean exploration program? Based on studies that have been conducted to date by your nation/organization, what would you rate as the top 3-5 exploration goals to be undertaken, with a brief discussion of your reasons for your assessment and priority ranking?*

9:00 a.m. Keynote: Fred Grassle, Chair, Scientific Steering Committee for the Census of Marine Life, Rutgers University, New Jersey

9:20 a.m. Michael P. Meredith, Senior Scientific Officer, British Antarctic Survey, United Kingdom

9:40 a.m. Harry Breidahl, Educational Consultant, Nautilus Educational Pty Ltd., Australia
10:00 a.m. Bryndis Brandsdottir, Research Professor, Science Institute, University of Iceland

10:20 a.m. Break

10:40 a.m. James A. Yoder, Director, Ocean Sciences Division, U.S. National Science Foundation, Virginia
11:00 a.m. Annelies Pierrot-Bults, Science Policy Officer, Institute for Biodiversity and Ecosystem Dynamics, University of Amsterdam, Netherlands
11:20 a.m. Muthukamatchi Ravindran, Director, National Institute of Ocean Technology, India
11:40 p.m. Stephen R. Hammond, Chief Scientist, Ocean Exploration Program, U.S. National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory, Oregon
12:00 p.m. Panel discussion

12:20 p.m. Lunch

2:00 p.m. Technology and infrastructure capabilities and needs
Co-Chairs: Earl Doyle, Shell Oil (retired), Texas
(Member, NRC Exploration of the Seas Committee)

- *Charge to speakers: What assets currently exist, and what technologies/assets are needed to facilitate a coordinated international exploration program?*

2:00 p.m. Keynote: Alain Morash, TotalFinaElf, France
2:20 p.m. Suzanne Lacasse, Managing Director, Norwegian Geotechnical Institute
2:40 p.m. Tamaki Ura, Director, Underwater Technology Research Center, Institute of Industrial Science, University of Tokyo, Japan
3:00 p.m. Tommy D. Dickey, Professor, University of California, Santa Barbara

3:20 p.m.	Break
3:40 p.m.	Paul Egerton, Executive Scientific Secretary, European Polar Board, European Science Foundation, France
4:00 p.m.	Larry Mayer, Director, Center for Coastal and Ocean Mapping, University of New Hampshire
4:20 p.m.	Kiyoshi Suyehiro, Director, Deep Sea Research Department, Japan Marine Science and Technology Center
4:40 p.m.	Panel discussion

5:30 p.m. Meeting adjourns for the day

Wednesday, May 15, 2002

9:00 a.m. Strategies for facilitating a coordinated international exploration program
Chair: John Norton Moore, Director, University of Virginia Center for Oceans Law and Policy
(Member, NRC Exploration of the Seas Committee)

- *Charge to speakers: Recommend strategies to facilitate a coordinated international ocean exploration program. What type of organizational structure would be needed to facilitate your nation/organization's participation? Is there a particular program you could suggest for a model to administer a large-scale, international, cooperative ocean exploration program?*

9:00 a.m.	Jean-Francois Minster, Chairman of the Board and Executive Director, French Research Institute for Exploitation of the Sea (IFREMER)
9:20 a.m.	Mario Caceres, Head, Technical Division, Oceanography Department, Hydrographic and Oceanographic Service of the Chilean Navy
9:40 a.m.	Fangli Qiao, First Institute of Oceanography, State Oceanic Administration, China

10:00 a.m. Robert Knox, Research Oceanographer and Associate Director, Ship Operations and Marine Technical Support, Scripps Institution of Oceanography, California

10:20 a.m. Break

10:40 a.m. Montserrat Gorina-Ysern, Adjunct and Assistant Professor, School of International Service, American University, Washington, D.C.
11:00 a.m. Sergey Shapovalov, Head, Center for Coordination of Oceanographic Science, Russian Academy of Sciences
11:20 a.m. Steven Bohlen, President, Joint Oceanographic Institutions, Washington, D.C.
11:40 a.m. Nii Odunton, Chief, Office of Resource and Environmental Monitoring, International Seabed Authority, Jamaica

12:00 p.m. Panel discussion

12:30 p.m. Closing plenary: Sylvia Earle, President and Chief Executive Officer, Deep Ocean Exploration and Research Inc., California

12:50 p.m. Meeting adjourns

PARTICIPANTS

Constance C. Arvis, *Department of State, United States*
Jodi Bachim, *The National Academies, United States*
Joseph Baker, Queensland Government, Australia
George F. Bass, *Texas A&M University, United States*
Patricio Bernal, *Intergovernmental Oceanographic Commission, France*
Steven Bohlen, *Joint Oceanographic Institutions, United States*
Bryandis Brandsdottir, *University of Iceland*
Harry Breidahl, *Nautilus Educational Pty Ltd., Australia*
Jane Breidahl, *Woodleigh School, Australia*
Mario Caceres, *Hydrographic and Oceanographic Service of the Chilean Navy*
Tommy Dickey, *University of California, Santa Barbara, United States*
Earl H. Doyle, *Shell Oil (ret.), United States*

Rene Drucker-Colin, *Universidad Nacional Autonoma de Mexico*
Sylvia Earle, *Deep Ocean Exploration and Research Inc., United States*
Paul Egerton, *European Science Foundation, France*
Marta Estrada, *Institut de Ciencies del Mar, Spain*
John Field, *University of Cape Town, South Africa*
Christopher Fox, *National Oceanic and Atmospheric Administration/ Pacific Marine Environmental Laboratory, United States*
Sally Goodman, *Nature, France*
Morgan Gopnik, *The National Academies, United States*
Montserrat Gorina-Ysern, *American University, United States*
Adolfo Gracia Gasca, *Universidad Nacional Autonoma de Mexico*
Fred Grassle, *Rutgers University, United States*
Jeremy Green, *Western Australian Maritime Museum*
James C. Greenwood, *U.S. House of Representatives*
Elizabeth Gross, *E&G Associates, LLC, United States*
Nergis Gunsenin, *Istanbul University, Turkey*
Stephen Hammond, *National Oceanic and Atmospheric Administration/ Pacific Marine Environmental Laboratory, United States*
Maria Hood, *Intergovernmental Oceanographic Commission, France*
Norberto Olmiro Horn Filho, *Santa Catarina Federal University, Brazil*
Susan Humphris, *Woods Hole Oceanographic Institution, United States*
Su Jilan, *State Oceanic Administration, China*
Kazuhiro Kitazawa, *Japan Marine Science and Technology Center*
Robert Knox, *Scripps Institution of Oceanography, United States*
Isao Koike, *University of Tokyo, Japan*
Hermann Kudrass, *Bundesanstalt fur Geowissenschaften und Rohstoffe, Germany*
Suzanne Lacasse, *Norwegian Geotechnical Institute*
Ulf Lie, *Centre for Studies of Environment and Resources, Norway*
Richard Lutz, *Rutgers University, United States*
David A. Malakoff, *Science Magazine, United States*
Catherine Marzin, *National Oceanic and Atmospheric Administration, United States*
Larry Mayer, *University of New Hampshire, United States*
Craig McLean, *National Oceanic and Atmospheric Administration, United States*
Marcia McNutt, *Monterey Bay Aquarium Research Institute, United States*
Michael Meredith, *British Antarctic Survey*
Jennifer Merrill, *The National Academies, United States*
Jean-Francios Minster, *French Research Institute for Exploitation of the Sea*

Alain Morash, *TotalFinaElf, Norway*
Robin Morris, *The National Academies, United States*
Robert Murdoch, *National Institute of Water and Atmospheric Research, New Zealand*
John Norton Moore, *University of Virginia School of Law, United States*
Nii Odunton, *International Seabed Authority, Jamaica*
Temel Oguz, *Middle East Technical University, Turkey*
Annelies Pierrot-Bults, *University of Amsterdam, Netherlands*
Ian Poiner, *Commonwealth Scientific and Industrial Research Organization, Australia*
Jeremy Potter, *National Oceanic and Atmospheric Administration, United States*
Fangli Qiao, *State Oceanic Administration, China*
Muthukamatchi Ravindran, *National Institute of Ocean Technology, India*
George Satander Sa Freire, *Ceara Federal University, Brazil*
Shubha Sathyendranath, *Bedford Institute of Oceanography, Canada*
Sergey Shapovalov, *Russian Academy of Science*
Sunil Murlidhar Shastri, *University of Hull, United Kingdom*
Victor Smetacek, *Alfred Wegener Institute, Germany*
Anders Stigebrandt, *University of Gothenburg, Sweden*
Kiyoshi Suyehiro, *Japan Marine Science and Technology Center*
Anne Tenney, *National Science Foundation, United States*
Jörn Thiede, *Alfred Wegener Institute, Germany*
Tamaki Ura, *University of Tokyo, Japan*
Edward Urban, Jr., *Scientific Committee on Oceanic Research, United States*
Victor Vicente-Vidal Lorandi, *Instituto Politecnico Nacional, Mexico*
James Yoder, *National Science Foundation, United States*
Marsh Youngbluth, *Harbor Branch Oceanographic Institution, United States*

D

Report on the International Global Ocean Exploration Workshop

To solicit ideas for program direction, feasibility, and international interest in an ocean exploration program an international workshop was held that included invited talks from oceanographers, explorers, educators, national ocean agencies, and nonprofit organizations. The International Global Ocean Exploration (IGOE) Workshop took place in Paris, at the headquarters of the Intergovernmental Oceanographic Commission (IOC), from May 13-15, 2002. Approximately 80 participants from 22 countries attended the meeting.

The IGOE Workshop was organized to address the major issues in the statement of task to the committee:

- the value of implementing an ocean exploration program at the international level;
- existing programs—and their strengths, weaknesses, and gaps;
- priority areas for exploration;
- technology and infrastructure needed; and
- strategies for cooperation to implement such a coordinated, international program.

What follows below is a summary of the remarks of the speakers, as well as a synopsis of the open floor discussions that concluded each session.

OPENING PLENARY SESSION: THE VALUE OF AN INTERNATIONAL OCEAN EXPLORATION PROGRAM

Speakers

The Plenary Session began with an address and welcome by the Executive Secretary of IOC, **Patricio Bernal**. Dr. Bernal expressed regret that the ocean science community has had relatively little success in capturing the public imagination, especially in comparison with the public's interest in space exploration. Exploration has always been motivated by discovery (e.g., the discovery of new civilizations) and economic benefits (e.g., access to new resources), and ocean exploration is no exception. Scientific breakthroughs often come from the most unexpected places, and a program of ocean exploration would open up new directions for scientific thought. Exploration now seeks things and places, but not processes. While exploration of the deepest ocean regions has resulted in dramatic discoveries, less dramatic—but no less important—are discoveries in other areas. For example "interfaces" between distinct objects such as the air-sea interface, and oceanic fronts have yielded new and exciting information. This theme of "interfaces" was repeated by several workshop participants throughout the event.

Dr. Bernal described many challenges a new ocean exploration program would face. Certain provisions of the Law of the Sea (LOS) must be considered, there is the potential for conflicts between exploration and conservation, and exploration in waters of national jurisdiction may be problematic. A coordinated, international program should focus resources on high priority areas and should take advantage of the opportunity to craft new partnerships. It should foster not only an international, but an intercultural dialog among scientists, industry, and the general public. Before establishing any program the concepts of ocean exploration must be agreed upon, and research, exploration, and prospecting must be clearly distinguished.

Marcia McNutt clarified many of the distinctions between scientific exploration and scientific research (Table D.1). The first wave of ocean exploration was the voyage of the *Challenger* in the 1870s, during which mid-ocean ridges were discovered, a new understanding of ocean sediments was gained, and nearly 4,500 new species were identified. Ocean exploration should be revived to take advantage of the many new platforms, tools, and techniques available to ocean science and marine archeology. These include:

TABLE D.1 Differences between Research and Exploration

Question	Research	Exploration
What is it?	Testing of hypotheses	Search for discoveries
Who does it?	Specialists	Generalists
Where is it done?	Where it is needed to test a hypothesis	Unknown area
What do we use?	Specialized tools	Broad suite of tools
How is it done?	One-of-a-kind approach	Systematic, broad-based approach
Data policy?	Initially property of principal investigator	Immediate wide distribution
What is role of public?	Little involvement	Public can be present

- autonomous underwater vehicles (AUVs) which could be deployed in particularly harsh environments, such as the Arctic;
- advanced mooring systems to enable exploration in time;
- methods for macrobiological sampling that permit the capture of organisms that have not been well-studied;
- techniques for microbiological sampling that permit the in situ analysis of samples and genetic discrimination of organisms;
- chemical sampling tools such as an in situ ultraviolet spectrometer and laser instruments for the in situ analysis of sediments; and
- software tools that enable new ways to visualize, analyze, and integrate data, resulting in products that are often data, rather than samples.

Such a program should include voyages of discovery, targeted technological development, data management, education and public outreach activities, and full international involvement. The science community needs to emphasize the excitement of discovery of new life forms and habitats to capture the interest of the general public. International cooperation is required because the oceans are so large that no single country can explore them alone. Expertise and assets from other countries are needed. The financial investment will result in new knowledge leading to new hypothesis that can feed a robust oceanographic research program.

Joe Baker, Chief Scientist for the Queensland Department of Primary Industries and Commissioner for the Environment, discussed the value of ocean exploration—exemplified by Australia's dependence on marine resources for its economic well-being. The *scientific* value of exploration is not the highest priority. It is the use of the data—and the assimilation and transmission of information to decision-makers—that is essential. Australia is one of the 12 mega-biodiverse countries, and the only developed country among the 12 mega-biodiverse countries. With the exception of Australia, the other eleven have an inverse proportion of gross national product to mega-biodiversity. Australia has a well-educated population, is politically stable, and has many special features such as the Great Barrier Reef. There is significant expertise in tropical marine systems, and as a result, Australia has responsibility for leadership in management and conservation for protection of mega-biodiversity.

Dr. Baker's definition of ocean exploration is broad and includes a comprehensive awareness of the nature, role, and function of the oceans. It should be multidisciplinary and multinational. A coordinated international exploration program adds value by sharing costs and assets, sharing output, and eliminating overlap. Such a program should include studies of impacts of change on human populations, interactions at boundaries (e.g., ice, coastal margins, sea beds), the interdependency of living and nonliving components of ecosystems, bio-prospecting for pharmaceuticals, and bio-mining for exploitation of natural resources. The challenge is to determine priorities and develop criteria for study selection.

He emphasized that ocean exploration should not focus exclusively on offshore oceanic environments. Coastal ocean exploration is equally important as offshore because these are the areas where the impacts of change will be the most severe. Finally, he offered the opinion that good exploration shares costs and benefits with developing countries in order to help all parties achieve sustainable development of ocean resources.

Victor Smetacek offered unique insights into exploration. Early in childhood exploration begins as the senses develop and sensory perception can only be used after the target of discovery has been determined. The simplest approach to problems—the box model—does not reveal understanding or perception of dimensions. The best instrument for exploration is the human brain; perhaps one way to integrate the human brain into an exploration program is to identify new ways to perceive and communicate our discoveries.

As an example, consider the relationship between form and function. Beautiful and ornate *radiolarians* and *foraminifera* were described during the *Challenger* expedition, but the relationships between their form and function still is not understood. The distribution and behavior of planktonic species should be a priority for ocean exploration, but funding such exploration will be difficult without evidence for an economic benefit at the conclusion.

Dr. Smetacek reviewed problems related to the oceans and carbon cycling, and introduced a new interdisciplinary program being conducted by the Alfred Wegener Institute on exploration of the Antarctic Circumpolar Current. This expedition is exploratory because so little is known about the Antarctic Circumpolar Current, which is important to global cycles. The questions being posed are not yet hypotheses.

Summary of Plenary Discussion

During discussion of the plenary lectures, some important issues were introduced:

- How can results of exploration be reported in peer-reviewed journals? What will be the reward system for explorers in our universities? What can be done to encourage and develop the next generation of explorers?
- Ocean versus space exploration: Why is there an apparent lack of public and political support for exploration of the oceans compared with space exploration? Space agencies mobilize billions of dollars for satellites that sometimes fail, but centralized space exploration maintains an effective public relations program. Perhaps the public perceives that the ocean is more accessible than space and does not require large-scale initiatives. This fallacy (e.g., ocean access must overcome difficulties of pressure and energy that do not exist in space) has not been adequately addressed. To initiate and develop an ocean exploration program the imagination of our children—the oceanographers of the future—must be captured.
- How can priorities be identified that will provide the most impact for human populations? This is especially important to encourage the participation of developing countries.
- Perceptions of competition for funding between ocean exploration and ocean research must be avoided. The resource base must be expanded and new sources of funding clearly delineated to support an ocean exploration program.
- The old treaties of the 1970s and 1980s (LOS, Sea Bed Authority) will be very difficult to renegotiate in this new and different political environment.

FIRST SESSION: EXISTING PROGRAMS

United States

Craig McLean, director of the National Oceanic and Atmospheric Administration's (NOAA) Office of Ocean Exploration, described the current NOAA effort that is founded on a long tradition of ocean exploration in the United States. In 1998, the National Ocean Conference recommended the development of U.S.-based priorities on the ocean. In 2000, a panel of experts was convened by an Executive Order from President Clinton. This President's Panel made recommendations for priorities of an ocean exploration program, and NOAA's Office of Ocean Exploration was initiated at a level of $4 million. The program has grown to $14 million annually. Ocean exploration initiatives involve three types of partners: 1) government agencies; 2) academic institutions and researchers; and 3) commercial, or industrial, partners. Currently, the Office views industry advocacy and inter-agency collaboration as critical to the success of the program, and nontraditional funding alternatives are being sought. As demonstrated by the National Aeronautics and Space Administration (NASA), public awareness of program initiatives is also very important. Ten percent of the budget of the Office of Ocean Exploration will be spent on education and outreach, and there will be a strong focus on incorporating ocean themes into the curricula at the K-12 level.

Accomplishments of the NOAA program will be measured by miles mapped and new species found. The initial focus will be on developing an inventory of our national maritime history, providing real time data telemetry, and producing education and outreach tools. As the program develops other challenges will be addressed. In particular, opportunities for specific projects and their products to be used in an international program will be identified.

South Africa

John Field, University of Cape Town, and Past-President of the Scientific Committee on Oceanic Research (SCOR) and the SCOR-supported Joint Global Ocean Flux Study (JGOFS), provided both an international and southern hemisphere perspective on ocean exploration. Most of the current international ocean research programs are interdisciplinary and share characteristics of exploration, especially with respect to large time and space scales.

Many of the oceanographic scientific research projects SCOR supports include exploratory investigations, and have produced surprising discoveries of how the biological, chemical, and physical properties of the oceans interact. The JGOFS program produced unanticipated results on the role of dissolved oxygen, variability in deep mixing, and the importance of nitrogen-fixing organisms following the Southern Ocean Iron Enrichment Experiment (SOIREE). SOIREE enriched the waters with iron to determine if primary production could be increased. To the surprise of the researchers the response was delayed and lasted much longer than expected. JGOFS, as a time series study, detected the longer-term effects of the iron fertilization. Similarly, Global Ocean Ecosystem Dynamics has found unexpectedly tight links between fish stock abundances and climate indices. Other SCOR activities include the emerging ocean biogeochemistry and ecosystems program and the Global Ecology and Oceanography of Harmful Algal Blooms project.

Citing personal research experience, Dr. Field described the South African Benguela Environment Fisheries Interaction Training program Benguela Ecology Program, which depends upon an effective partnership between government and academic institutions and uses an ecosystem approach in studies of fisheries. Features of ocean exploration in this program include the use of new conceptual models linking physics and ecosystem structure and functioning to yield understanding of regime shifts. Unexpected aspects of the ocean circulation in this region have been revealed in ocean color images. Regionally, the Benguela Environment Fisheries Interaction Training program Benguela Ecology Program involves scientists from South Africa, Namibia and Angola in studies of the Benguela upwelling region, and has a significant training and capacity building component.

Dr. Field also summarized the differences between international intergovernmental organizations such as IOC and the World Meteorological Organization, and nongovernmental organizations like SCOR. In the former, members are governments and their decisions are binding on government policy. The latter are made up of individual scientists and, since they are much less formal, can be flexible and responsive to scientific needs. These two types of organizations can be complementary; a future program of ocean exploration should take advantage of the strengths of each.

Australia

Jeremy Green, a marine archeologist at the Western Australia Museum in Freemantle, described the experience of Western Australia, which has taken the lead in the protection of Australian underwater cultural heritage sites. Their first archeological project was the exploration of a c. 1620 wreck of the Dutch East India Company vessel *Batavia*. Unexpectedly, the wreck contained building block for a Dutch fortress in Indonesia.

A diploma program teaching graduate students the practice of maritime archeology has generated a cadre of trained experts for state and national governments in Australia. An unexpected spin-off has been training programs in Thailand and China, tailored for local needs, specifically their underwater sites under threat from pollution, coastal development and treasure hunters. The objective is to aid local authorities in these countries to manage and preserve their underwater heritage.

Dr. Green gave examples of the use of new technologies that are advancing the possibilities for underwater archeology. For instance, a new side-scan mosaic makes it possible to locate wrecks even in very low visibility waters. Aerial magnetometers are used to survey "underwater graveyards" of shipwrecks, taking only a few hours to map tens of square kilometers in deep water beyond the reach of divers. After sites are mapped new software allows three-dimensional visualization of the sites. Finally, Dr. Green highlighted the importance of international collaboration on large archeology projects, such as one off the Turkish coast in which his museum cooperates with the Institute for Nautical Archaeology from the United States.

Canada

Shubha Sathyendranath, Executive Director of the relatively new international organization Partnership for Observation of the Global Ocean (POGO), reviewed the needs for international partnerships to conduct large-scale experiments of global dimensions. POGO's perspective is global, and its objective is to enhance participation by developing countries. She provided examples of POGO programs with international partnerships:

- POGO supports and promotes the Array for Real-Time Geostrophic Oceanography float program by assisting in developing inter-institutional partnerships to work in under sampled regions of the ocean.
- POGO's 2000 "São Paulo Declaration" called for enhanced ocean observations in the southern hemisphere, and assisted in establishment of the Chilean National Centre for Excellency in Oceanography

and planning of the Japan Marine Science and Technology Center Southern Ocean circumpolar expedition in 2003-2004.

Dr. Sathyendranath reviewed POGO's capacity building efforts. Training courses have been held in developing countries. The Austral Summer Institute was organized in South America. Finally, POGO, IOC, and SCOR cosponsor a fellowship program that provides intense training experiences in oceanographic labs of developed countries.

China

Jilan Su, the current Chairman of IOC and senior scientist at the Second Institute of Oceanography in China, described some of the major ocean exploration efforts in China in the last decade, focusing primarily on physical oceanographic efforts, such as:

- participation in international programs (e.g., JGOFS, the World Ocean Circulation Experiment [WOCE], the Land-Ocean Interactions in the Coastal Zone Project, the Global Ocean Ecosystem Dynamics, and the Array for Real-Time Geostrophic Oceanography);
- expeditions in the Nansha (Spratly) Islands and in the Philippine seas;
- studies of the circulation of the South China Sea, conducted jointly with scientists from Taiwan, and including synoptic mapping and monsoon studies;
- joint projects with Japan on features of the Kuroshio near the Ryuku Islands, and the subtropical circulation system;
- Indo Pacific's warm pool study being planned to look at relative impacts of El Niño and monsoons on the climate of China (international collaborations are still being developed);
- long-term monitoring of the Southern Ocean program utilizing the transects of supply ships between two Chinese Antarctic stations; and
- an Arctic Expedition.

Dr. Su felt that all of these activities had features to contribute to an international program of ocean exploration. He emphasized, however, that for China to participate in an international ocean exploration program initiatives would need to be framed in economic terms and/or national priorities. Such priorities might include the exploration of Antarctica, or an improved understanding of the ocean's role in climate change and variability.

United Kingdom

Sunil Murlidhar Shastri, University of Hull, described the International Ocean Institute and its activities. Founded in 1970, when the first "Pacem in Maribus" (Peace in the Oceans) workshop was held, the International Ocean Institute is based in Malta and now operates from twenty offices around the world. The organization focuses on developing countries to promote training, education, and research to facilitate the management, regulation, and protection of coastal resources. Dr. Shastri emphasized the importance of involving individuals, the community, and the country in efforts to safeguard the oceans. He reminded meeting participants that it is critical to capture the imagination of the young people to sustain any program. Dr. Shastri ended his presentation with a comment that underscores his concern about a U.S.-led IGOE program: "Although Britannia no longer rules the waves, this does not mean we need to be the hands of Americans."

Mexico

Rene Drucker-Colin, Vice Chancellor of the Mexican Academy of Sciences, introduced the Mexican oceanography program. From its modest beginnings in 1957 to its present breadth it now utilizes a substantial infrastructure, the result, at least in part, of cooperation with the United Nations Development Programme. Through the efforts of the National Council for Science and Technology (Mexico), the Universidad Nacional Autonoma de Mexico, and the Petroleos Mexicanos, two vessels have been acquired which provide the infrastructure for a successful oceanography program. A diversified research program has been developed, concentrating mainly on the waters off eastern and western Mexico. Subsequent to the development of a national oceanography program, substantial international collaboration evolved. In many instances the collaboration is with institutions from the United States and other major players in ocean research, and the Mexican institutions are eager to pursue their ocean research programs in close collaboration with institutions from abroad.

Dr. Drucker-Colin concluded by noting that developed and developing countries may have very different priorities in scientific research. Economic, cultural, and historical differences between such countries will influence their attitudes to management and conservation of resources and their priorities for participation in an international ocean exploration program. He expressed the opinion that large countries that can contribute a larger proportion of the funding for international research programs must take care not to control the planning and implementation of the programs. In other words, international participation must be meaningful to all participating countries.

New Zealand

Rob Murdoch, Director of the National Institute for Water and Atmospheric Research, described the oceanic conditions around New Zealand and noted that many areas of seabed in this complex and geologically active region are still unmapped. A recent expedition explored and mapped 24,000 km^2, discovering many new undersea features. Many habitats are threatened, especially by destructive or unsustainable fishing methods.

Exploring marine biodiversity is a priority for New Zealand. Although little of New Zealand's exclusive economic zone (EEZ) has been explored, it is estimated to contain up to 10 percent of global species. A program of biodiversity and natural products research seeks to discover new bioproducts. The New Zealand Antarctic program is conducting seabed mapping of the Ross Sea region and conducting biodiversity studies with Italian scientists.

International collaboration is important to New Zealand. New Zealand collaborates with Japan and Australia in the Southern Ocean, and the country also participates in the Ocean Drilling Program (ODP). Dr. Murdoch described international marine ecosystem studies that seek to explain the decline of top predator species in the Southern Ocean. New Zealand also participates in SOIREE to decipher the factors controlling deep sea productivity and the potential impacts of deep sea sequestration of carbon. Dr. Murdoch noted several potential problems in international collaboration, referring to issues of intellectual property, permits for research in EEZ, and the failure of some research vessels to provide data or meet other requirements of the permitting process.

Summary

During the presentations and ensuing discussion the following ideas were repeated. Programs that can incorporate government/academia/

industry partnerships, education and public outreach/awareness, and an interdisciplinary approach to ocean science appear to be more sustainable and effective.

During the development phase of an ocean exploration program the following issues should be considered and resolved:

- priorities of individual countries should be established;
- from these, priorities for international collaboration should be developed;
- work at the multi-institutional, rather than multi-national, level that involve governments to create a new awareness in politicians;
- technology transfer is very important for developing countries; and
- effective and open communication and interaction between parties is essential.

The major point of discussion during this session was the concern that an international program of ocean exploration may not address the priorities of the participants, and will focus on the objectives of the countries or organizations funding the program(s). An international exploration program must rely on interactions between scientists and institutions rather than at the governmental level. Bilateral agreements seem to be the most effective mechanism to allow this collaboration; the ODP model was cited as an example of a successful arrangement. A program of global ocean exploration that will ensure equal participation and benefit sharing must use an international framework—individual participating and contributing parties can develop ownership. An international organization, such as IOC, could help address issues of national participation by countries with different economic capacities. Similarly, it is important to understand the needs of developing countries before deciding what should be done in the areas of training and capacity building, and to realize that it often takes time to see the results of these efforts.

Workshop participants generally agreed the barriers to data exchange must be reduced or eliminated. Security concerns of developed countries increase the difficulty encountered in sharing data. Developing countries are hesitant to share data fearing unfair commercial exploitation of discoveries in their region by more advanced, wealthy countries.

SECOND SESSION: PRIORITY AREAS FOR OCEAN EXPLORATION

Biodiversity

Fred Grassle, Chair of the international Scientific Steering Committee for the Census of Marine Life (CoML), discussed the importance of integrating a marine life census with fixed taxonomic standards into an international ocean exploration program. Dr. Grassle presented his priorities for a global ocean exploration: hydrothermal vents, Indo-Pacific deep coral reefs, an inventory of all species, ocean canyons and trenches, high-velocity current systems, mid-ocean vertical transects, and migratory routes of large pelagic species. Sampling standardization is essential, and an ocean biogeographic information system should be a critical component of ocean exploration database handling.

CoML is a true exploration program with only the broadest questions posed as its objectives. Criteria for selection of CoML projects are the following: potential to change present perspectives; exploratory, original, and interdisciplinary in approach; regional in scope; application of novel technology; opportunity for discovery of new taxa; focus on species distribution; interdisciplinary; potential for education and capacity building; and international availability of data. A reliable census of existing and newly discovered marine species will improve our understanding of marine ecosystems, their biodiversity, and their evolution. Representative examples are the bathypelagic and benthic regions in the Mid-Atlantic Ridge—the focus of the Patterns and Processes of the Ecosystems of the Northern Mid-Atlantic program. Other examples are the hydrothermal environments in the deep-sea and their evolution (e.g., Biogeographic Patterns of Chemosynthetic Ecosystems in the Arctic and North Atlantic), a tagging program of migratory species, and the study of deep coral reefs.

High Latitude Studies of the Southern Ocean

Michael Meredith, of the British Antarctic Survey, proposed the Southern Ocean as a priority for ocean exploration program. The Southern Ocean is the least explored region of the world's oceans. It is remote and inhospitable. There is a lack of observations from the austral winter, when Antarctica doubles in size due to sea ice formation. Even during the austral summer some regions remain inaccessible to ships—the seas beneath floating ice shelves are prime examples. Despite its remoteness, the Southern Ocean is of critical interest for ocean exploration. Dr. Meredith's priorities for ocean exploration were particularly aimed at the Southern Ocean: sea bed observation; bathymetry and mapping; international collaboration to obtain systematic coverage; ice sheets and biodiversity; history of ice sheet expansion and contraction; faunal distribution paths of vent species; austral winter investigations; over-wintering strategies of krill; deep water formation; exploration under ice shelves; and glaciological processes.

The densest water found in the world is formed in the Southern Ocean. This water mass is the precursor of the Antarctic Bottom Water that forms the abyssal layer of global thermohaline circulation. High mixing rates and water mass transformations occurring in the Southern Ocean are believed to be essential for closing this circulation, hence they may dictate and regulate global climate.

Although a diverse and complete infrastructure already exists to explore the Southern Ocean the emplacement of a Southern Ocean Observatory could revolutionize how this ecosystem is explored and studied. Vast areas of the Southern Ocean seafloor are unmapped, yet its bathymetric and age patterns contain records of the disintegration of the Gondwana supercontinent and the opening of the Drake Passage. Many believe the latter to be one of the key events leading to the present global climate. The Southern Ocean also maintains a high level of biological productivity, and contains large stocks of living resources that must be understood for effective protection and management. The products of Southern Ocean exploration include: 1) new observations from which new hypotheses can be formed; 2) leaps in understanding rather than steady progress; 3) enhanced knowledge for management and protection of resources; and 4) understanding of how the Southern Ocean influences the global system for climate.

High Latitude Studies of the North Atlantic

Bryndis Brandsdottir, of the University of Iceland, proposed that the unique geological, marine, climatological setting of the North Atlantic offers unique exploration opportunities within a global perspective. The region is astride the North Atlantic Ridge, on top of the Iceland Mantle Plume, and encircled by major ocean currents from the Caribbean and the Arctic.

There has been ample international collaboration between Iceland and other nations in ocean exploration and research. The Marine Institute of Iceland is a member of Sea-Search (a marine data and information center), the International Council for the Exploration of the Seas, the Northeast Atlantic Fisheries Commission, the Northeast Atlantic Fisheries Organization, and the Northeast Atlantic Marine Mammal Council. Iceland is a member of the European Science Foundation, the European Commission Framework Programs, and ODP. The Icelandic Research Council has also recently signed a Memorandum of Understanding with the National Science Foundation (NSF) to promote scientific collaboration between the two nations. Since it is a small nation, Icelandic participation in an international ocean exploration program would most likely be restricted to special fields related to Iceland's natural setting, economic framework, and exploration interests.

Marine resources constitute Iceland's largest national asset. Marine research, conservation, and exploration are of fundamental importance. The Benthic Invertebrates of Icelandic Waters program, initiated in 1992, is a baseline study to map the distribution of benthic fauna between 20 m and 3,000 m depth within Icelandic territorial waters. Icelandic priorities for ocean exploration include: seafloor mapping, refraction and gravity profiling, hot spot and ridge interactions, deep seafloor drilling, hydrothermal vents and biological diversity, and rapid response surveys of ridge events and seismic activity.

The Pelagic Ecosystem

Annalies Pierrot-Bults, from the Institute for Biodiversity of the University of Amsterdam, presented priorities that focused on pelagic species, which have the largest distribution areas on Earth. For example many macro-zooplankton species are distributed from approximately 40 °N to 40 °S and are found from 200 m to 600 m deep in all three oceans. For most macro-zooplankton and micro-nekton groups there are no great expectations of identifying new species. Since little is known about the genetic structure and variation within populations and between different regions, the description of species may need altering, and new species may not be identified in these groups. It is possible that a broadly distributed species is actually a complex of species containing several cryptic species. Recognition of the true spatial scales of population genetic structure is important for conservation issues and fishery policies.

Exploration of the deep-sea and the bentho-pelagic will need cooperative international efforts and the development of new sampling tools. The bentho-pelagic layer of the deep sea is still a relatively unknown habitat and may contain undiscovered species. Exploration in this area will present a new view about so-called species-poor pelagic systems. Both species-poor high latitude systems and species-rich low latitude systems should also be explored.

Dr. Pierrot-Bults suggested that an ocean exploration program include "voyages of discovery through existing collections." Programs such as the California Cooperative Oceanic Fisheries Investigation contain priceless ecological collections that can still yield valuable information.

Exploitation of Resources, Marine Archaeology, and Mitigation of Hazards

Muthukamatchi Ravindran, Director of the Indian National Institute of Ocean Technology, stated that India's priority for ocean exploration is to better understand the oceans in order to exploit both living and nonliving regional marine resources for the benefit of Indian society. Other priorities are: global environment monitoring; mapping of energy sources, such as gas hydrates and identification of sites for deep sea minerals; and evaluation of historical and present sea level rise and implications for the safety of islands, submergence of coasts, and the history of mankind.

India is supporting a number of ocean exploration and research programs. Exciting discoveries are being made in the form of buried structures of archaeological importance, which can illuminate the history of mankind. India is participating in various programs on ocean observation as a part of the Global Ocean Observing System, as well as other regional ocean observing system programs. India is a pioneer in the mining of deep-sea nodules and is conducting the required environmental impact studies of these mining technologies. As a participant in Antarctica expeditions, India is seeking to improve the understanding of the influence of Antarctica on monsoons. An understanding of the impact of Antarctica on the monsoon pattern in the Indian Ocean region, and the capability to forecast the sea state and cyclones will contribute to hazard mitigation.

Exploration Through Time and Deep Ocean Exploration

James Yoder, Director of the Ocean Sciences Division of NSF, challenged participants to consider the rules for ocean exploration (i.e., analogous to the scientific method). He suggested exploration advances the breadth of knowledge and basic research advances the depth of knowledge. Exploration and basic research share: 1) the goal of discovery and expanding our base of knowledge; 2) technology and infrastructure needs; and 3) the opportunity for integrating science and education. Several basic principles would guide the role of NSF in ocean exploration.

- Exploration should be conducted in areas or on topics where little is known.
- Academic institutions would play a prominent role and projects would be competitively selected.
- Program priorities must incorporate community input and careful review.
- Interagency and international cooperation are desirable for cost-effective implementation.
- There would be a strong link to outreach and education since exploration captures the imagination of schoolchildren, as well as the public, and helps generate interest in science.

NSF's ocean exploration priorities pursue the following objectives: explore over time using ocean observatories; develop and make use of more capable submersibles; explore under-sampled and poorly known ocean regions, such as the Arctic and the Southern Oceans; and understand the biology and biogeochemistry of deeply buried biosphere and its link to life in the water column. Ocean exploration should be a long-term venture—an exploration in time. This would help resolve episodic events such as eddies, seismic events, and unusual algal blooms. It would lead to the discovery of unexpected long-term trends, and would help to refine the meaning of global change.

A critical aspect of ocean exploration is the widespread use of submersibles. NSF plans to reinforce its submersible fleet with *Jason II* and a replacement for the deep submergence vehicle Alvin that will have the capability to go deeper than 6,000 m, have increased bottom time, improved manipulators, improved interior ergonomics, and increased science payload. The need for human occupied submersibles is an issue that must be defined in the near future.

The deeply buried biosphere is a critical region for exploration. Microbes have been encountered living hundreds of meters below the seafloor in sediment and possibly the ocean crust. ODP Leg 201 (January-March 2002) was the first dedicated expedition to study the deep biosphere. Researchers found evidence of active life in all of the sediments sampled. The deeply buried biosphere will be a scientific focus of the future ocean drilling program.

Dr. Yoder echoed other IGOE participants in identifying the Arctic and Southern Oceans as a priority area. Exploration in these regions engenders a great potential to contribute to understanding climate change via the long-term monitoring of sea ice thickness. Technology needs include long-range AUVs, ice-resistant moorings, retrievable seafloor instrumentation, and shallow drilling capabilities.

Education and Outreach

Harry Breidahl, an Australian educational consultant, is the author of a series of books for primary schools entitled “Life in Strange Places.” Translating the oceans and science for young people is his career. For an educator, the distinctive features of ocean exploration that make it a priority for Australia include: the nature of the ocean environment, which is so different from the terrestrial environment; the presence of the bizarre; commercial fish stocks and deep seamounts; oil and gas deposits and hydrocarbon seeps; deep ocean vents; and biochemical resources and extremophiles. Education and outreach are critical to promote ocean exploration and help make it a self-sustaining reality, promoting the wise use of marine resources. This message is repeated in the mission statements of the Marine Educators Society of Australia, the Australian Marine Education Alliance, and the National Oceans Office. The public should be excited by this exploration of the unknown and by the technology that will make it possible.

Stephen Hammond, Chief Scientist of NOAA’s Office of Ocean Exploration, provided further support of the importance of education and outreach in an IGOE program. NOAA allocates 10 percent of its budget for education and outreach. Priorities for NOAA’s Office of Ocean Exploration are diverse and include exploring the ocean’s biological, physical, and chemical environments, as well as maritime cultural heritage. A series of U.S. workshops are contributing to establishment of the U.S. priorities for an international ocean exploration agenda. While there is an initial emphasis on the U.S. EEZ, the program recognizes that there are many remote, relatively unknown regions of the global ocean where exploration will be greatly facilitated by international partnerships. Examples of such regions include the high-latitude oceans in the Arctic and Antarctic, and the Southern Ocean. The benefits of collaboration in international ocean exploration include: diversity of knowledge, economies of scale, a range of technical applications, better global stewardship of oceans and resources, and improved management of resources.

Summary

The panel discussion focused on two questions: 1) How to set priorities? and 2) How to engage public interest and support? To facilitate multinational priorities the partner nations should: 1) find common priorities among regional priorities; and/or 2) try to establish a consensus among all parties. The former is the more common approach, while the latter was perceived as being more difficult.

Some suggestions were made for capturing public interest in ocean exploration. First, the message from the ocean community is fragmented between disciplines and between scales (i.e., local versus global). NASA's public relations programs should be used as a model for garnering public attention and support. Perhaps the relatively unsophisticated techniques used to explore the oceans exacerbate the perceptions of differences between space and ocean exploration. And yet human intervention (e.g., SOIREE), human presence in the sea, and marine archaeological discoveries are successful in capturing the attention of the press and public.

THIRD SESSION: TECHNOLOGY AND INFRASTRUCTURE

Speakers

Alain Morash, of TotalFinaElf, and a representative of the offshore oil industry, discussed the development of deep water drilling (>500 m). The main areas where oil is extracted from these depths are the Gulf of Mexico, Brazil, West Africa, the North Sea, Black Sea, and the Far East. In the past 30 years, deep water drilling capabilities have increased from 500 m to 2,900 m. Drilling in even deeper waters will require major advances in technology.

The industry is challenged by area selection and determination of the efficiency of deep sea areas selected for oil production. For the latter, there is a need to understand the geodynamic history of the margin and models of thermal history. Large and small scales are involved, from basin margin geometry to the nature of the rock and basin shape. To understand the geological history and structure of the seafloor global scales must be considered. At the small scale, work is needed to understand the relevant processes and to develop models of oil and gas reservoirs.

The oil and gas industry faces challenges in conducting pollution-free exploration, development, and production of offshore oil and gas. Local ecosystems and geohazards, such as currents, internal waves, slides, slope instabilities, growth faults, and mud volcanoes also present challenges. Deep water exploration is currently a high tech domain, and the oil and gas industry must be at the leading edge of new technology development. Collaborations to identify geohazards, and evaluate subsea equipment reliability should be utilized to meet these challenges.

Suzanne Lacasse, Managing Director of the Norwegian Geotechnical Institute, presented information on new developments in technology relevant for geological and geophysical exploration. Examples include electromagnetic wave technology and guided wave signal transmission applications that hold promise for offshore oil exploration. She emphasized the need to integrate geoscience studies to take advantage of technologies such as multibeam swath bathymetry, three-dimensional seismics, and models and soil investigations. She also discussed the monitoring of slope stability to help in the prediction of submarine landslides.

She stressed that funding for exploration is market-driven, so it is necessary to better communicate the importance of the contributions of science and engineering to society. Imaginative arguments for the cost-effectiveness, gains, and benefits of a program of ocean exploration are needed. She believes Norway would contribute to, and participate in, an international exploration program. The new "6th Framework" for the European Union has a new component encouraging the development of networks of excellence.

Tamaki Ura, Underwater Technology Center of the Institute for Industrial Science of the University of Tokyo, described recent advances in AUVs. Various opportunities for this technology are emerging. Since AUVs work without guidance from an operator they must be developed to: 1) recognize a situation; 2) decide what action is appropriate; and 3) execute the action. Innovative ideas for AUV development are often difficult to introduce because research and development requires significant funding. AUVs are 100 times more expensive than land robots, and the number of researchers developing AUVs is limited. Collaboration provides strong leadership and new insights into problems. Bureaucratic negotiations are often required to bring ideas to fruition.

Dr. Ura provided some examples of the successful use of AUVs in exploration. A lake survey by the 180 kg AUV *Tantan*, which carries an underwater microscope, counted plankton, took photographs of fish populations, and sampled for anoxic areas. This system could also be used to explore the thermocline, hypoxic zones, and investigate hydrothermal vent communities. The AUV *Aqua Explorer* tracked humpback whales using a compact hydrophone system for passive sonar. The AUV *R-One* explored the Teisi Knoll—a crater created in 100 m of water—by following a survey plan, diving into the crater, and taking sidescan images. Dr. Ura emphasized that an international program of ocean exploration should use AUVs to explore all mid-ocean ridges and the entire seafloor.

Tommy Dickey, a professor at the University of California, Santa Barbara, noted that the traditional expeditionary mode of ocean research has very limited ability to quantify change in the oceans. Observatories are common and valuable on continents, but rare in the ocean. The strengths of observatories are that they enable observation of abrupt changes (tsunamis, red tides, coccolithophore blooms), moderate to high frequency phenomena, and even transient phenomena (e.g., internal solitary waves causing sediment resuspension). Key long-term variables often have low signal-to-noise ratios and require long-term and high frequency observations. As an example, changes in atmospheric CO_2 were only revealed through long-term observations (the Mauna Loa time series). Although programs such as the Hawaii Ocean Time-Series have revealed some information on CO_2 increase in the ocean, atmosphere-ocean interactions are still relatively unknown and are a topic for more research.

Two observatories were reviewed. The Bermuda Atlantic Time-Series Study is the most heavily instrumented mooring with water samplers, sensors for CO_2, temperature, and nitrate, and an acoustic Doppler current profiler. The benefit of high-resolution sampling is seen in observations of rapid events (e.g., eddies passing through the area and not seen by satellites), as well as the impact of hurricanes on plankton blooms. Dynamics of Earth and Ocean Systems Program is an NSF-funded effort with three main elements: plate scale (e.g., NEPTUNE), coastal observatories (e.g., Long-term Environmental Observatory-15), and a global network of moorings. The cost and bandwidth is greatest for plate scale observatory, and least for moorings. Dr. Dickey recommended extending buoy spatial coverage by incorporating AUVs and he noted that power systems, for example diesel generators, will be required for buoys in high latitudes.

A key challenge to observatory science is the need for new sensors and systems, especially for biology. Nanotechnology holds promise in this area, but more platforms of various types are needed. Program coordination and data synthesis must be international, and stability of funding is critical.

Paul Egerton, Executive Scientific Secretary of the European Polar Board, described the European infrastructure and scientific assets for polar and sub-polar marine exploration and offered some perspectives for the future. European nations have a need for an optimized science platform to allow multi-disciplinary Arctic investigations of the sensitivity and responses of the Arctic system to global climate change. The European strategy is to tie together agencies, assets (such as ships), and science programs.

There is broad interest for a global exploration program from the European Polar Board, with three key missions identified: a Southern Ocean systems program (biogeochemistry, Earth systems and history); preparations for the International Polar Year; and a new research icebreaker for the Arctic, the *Aurora Borealis*. This is a new concept for an icebreaker that can operate at all seasons, will carry a removable drilling platform, and will also support traditional polar sciences. This will be the major European contribution to the Integrated Ocean Drilling Program (IODP).

Dr. Egerton recommended developing a truly international cooperation in Arctic science, with at least a 10-year plan, involving assets from European countries, the United States, and others. In addition, implementation of a flagship Southern Ocean exploration program could yield an understanding of global thermohaline circulation.

Larry Mayer, a professor from the University of New Hampshire, and an expert on ocean mapping technology, does not believe mapping can be separated from ocean exploration. Mapping is the first step in removing the veil of the unknown and the framework for future exploration. Technological advances have always preceded times of great exploration. The recent convergence of technologies (e.g., sonar, computers, navigation) as led to advances in ocean mapping.

Echo sounding was the first major advance in mapping of depth, and although it was not very accurate it could produce a standard hydrographic chart. Twenty years ago, the development of multi-beam sonar, which uses a broad beam of sound, made it possible to get a large number of measurements across a wide swath rather than a single measurement. Now three-dimensional images of the seafloor are readily attainable, but accurate only if combined with precise ship positioning technology. Current precision is approximately 5 cm in the x, y, and z dimensions. Vessel motion can also be accurately and precisely measured to identify where the mapping beam intersects the seafloor. Dr. Mayer maintains, however, that the future of deep-water mapping is shallow-water mapping; fleets of AUVs should be operated from platforms close to the bottom to get higher resolution.

One problem is the huge increase in data density, and the challenge is to manage the data, interact with the data, present it, and verify it. Current computer technology is up to this challenge. By combining different kinds of data sets and representing them in ways that are natural, we will be able to visualize data in new ways that are easy for the public to understand.

Ireland recently completed mapping 880,000 km^2 of its EEZ at a cost of $30 million (U.S. dollars). Canada, Norway, New Zealand, and France all have similar plans. International collaboration would benefit all parties involved. Promising applications of these advanced technologies lie in marine archaeology, fisheries habitat mapping, prediction of effects of sea level rise, and aids to navigation. The technology exists to complete incredibly detailed ocean mapping, but is there the will to do so?

Kiyoshi Suyehiro, Director of the Japan Marine Science and Technology Center's Deep Sea Research Department, focused on the realization of long-term seafloor observations. Seafloor cabled networks are being designed to use decommissioned telecommunications cables, for example the Ocean Hemisphere Network, and VENUS projects. Fiber-optic systems have been established around Japan since 1997 for earthquake monitoring. These systems are employed to understand earthquake dynamics, with increased accuracy in hypocentral resolution, and especially in depth and detection threshold. One example of international cooperation is the Borehole Geophysical Observatory Network, part of an international ocean network using ODP drill holes. This program is studying the aseismic motion of the Pacific plate beneath Japan.

Japan is now building a new drilling vessel *Chikyu*, with the shakedown cruise planned for 2005-2007. Plans are to initially drill in water less than 2,500 m, but to then go to deeper water and to drill into seismogenic zone. *Chikyu* will be the major drilling vessel for IODP.

Summary

Opportunities for ocean mapping were discussed. Since the cost of mapping increases exponentially as water gets shallower the speed a maneuverability of AUVs could save hundreds of millions of dollars from current costs. There was some discussion of new advances in AUV technology, including the possibility of launching them from planes.

It was noted that many U.S. charts are outdated, even in the Gulf of Mexico. Bathymetry was identified in the U.S. regional workshops sponsored by NOAA as the top priority for data needed. The costs should be borne by mission-related agencies and not be deducted from research funding. Opportunities for collaborations should be sought; the missed opportunity for multi-beam mapping in the Arctic aboard the icebreaker *Healy* was lamented. Though navigating in the Arctic, and equipped with an advanced multi-beam sonar, no mapping will take place. Better planning and coordination could capitalize on these types of opportunities.

The speakers were asked to comment on how they would advise the World Bank as to which technologies would be most useful to a developing country in developing wise management of its resources. Dr. Mayer responded that a program of exploration and evaluation of resources must start with the best maps one can produce. It is relatively easy to estimate costs for mapping by water depth. If mapping is completed in combination with other methods, one could get even more results for other applications, for example fisheries monitoring.

Finally, participants were reminded that an important driver for mapping out to the edge of continental shelf is LOS. Jurisdiction of resources exists if the shelf extends beyond 200 miles. Each country with large shelves is required to make a recommendation on the base of the slope and the depth of sediments on the rise. Data will be submitted to a continental shelf commission.

FOURTH SESSION: STRATEGIES FOR AN INTERNATIONAL PROGRAM

Speakers

Jean-François Minster, Chair of the Institut Français pour l'Exploitation de la Mer, first identified the major research priorities for France: life sciences, environment issues, and science and technology for information and communication. These priorities are driven by socioeconomic demands. He then discussed available policy mechanisms for international cooperation in ocean exploration by providing specific examples of collaborative programs:

- shared investments that require formal long-term agreements at the national level (e.g., the *Jason II* satellite involved NASA, the Centre National d'Etudes Spatiales, NOAA, and the European Organization for the Exploitation of Meteorological Satellites);
- shared operational costs, which only requires informal, ad hoc agreements at the agency level (e.g., ODP and the International Marine Global Change Study);

- coordinated international programs without money exchange, just the informal, good-will cooperation of partners (e.g., the International Geosphere-Biosphere Programme and the World Climate Research Programme) (insecurity of funding is a disadvantage; the advantage is flexibility); and
- cooperative experiments that only need specific, short-term agreements between agencies (e.g., tectonics in the Gulf of Corinth or deep water formation in the North Atlantic).

Assuming that there is agreement on scientific objectives of a specific international program, formal agreements are preferred to share operation costs for infrastructure; to negotiate specific funding at the national level; and to pool funds for implementation of common objectives. But these agreements lack flexibility, and it is important to include assessment and evaluation procedures. Informal agreements are preferred for program management, sharing existing tools and infrastructure, and maintaining flexibility.

There are, however, barriers to effective ocean exploration: ocean sciences require a variety of large infrastructures; ocean exploration needs an investment strategy on the global scale; and coordination and efficient use of large asset needs to be improved. Ocean exploration can benefit from technology development; therefore, we need to accelerate technology transfer from other disciplines and include technology programs in ocean exploration.

European science management is moving towards a “European Research Area” to increase efficiency. New research management tools are being introduced in the European Union’s 6th Framework, which includes integrated projects and networks of excellence and will stimulate the construction of major assets in Europe. There will be a Marine Science Plan as part of this planning process. It will likely include:

- new networks (e.g., fisheries agencies, marine biogeochemistry);
- new integrated projects (e.g., Euromargins, operational oceanography); and
- new intergovernmental projects (e.g., IODP).

Mario Caceres, Head of the Technical Division of the Oceanography Department of the Chilean Navy, described an initiative on ocean exploration in the southeast Pacific Ocean that involves Colombia, Ecuador, Peru, and Chile. Its objective is to study the dynamics of an area of high biological productivity, intensive fisheries, and frequent harmful algal bloom episodes, especially in southern Chile. The area is significantly impacted by El Niño/ Southern Oscillation.

The goal of this effort is to establish a sub-tropical moored buoy and coastal network in the southeast Pacific to monitor ocean-atmosphere dynamics. Agreements have been concluded between numerous agencies from the four nations, and the World Bank is the source of funding for part of the program.

Dr. Caceres suggested that international organizations could coordinate a global ocean exploration effort in the Pacific. Regional Global Ocean Observing System alliances could be useful at the national level. The Permanent Commission of the South Pacific has facilitated scientific collaborations. He concluded that long-term studies are important. Existing programs should be strengthened and new ones added. Barriers include lack of funding, national awareness, and expertise.

Fangli Qiao, from the First Institute of Oceanography in China, emphasized that China's top priority is the coastal zone, which includes marginal and semi-enclosed seas such as the South China Sea and the Yellow Sea. This is driven by the need for marine resources. A second priority for Chinese ocean science is east Asian and global climate. This includes studies of the Asian monsoon systems, El Niño/Southern Oscillation cycles, and exploration of the warm pool. The third is polar exploration. Dr. Qiao reviewed a number of specific, current programs. Some have international and bilateral arrangements. International cooperation in China is mostly through the State Oceanic Administration and its three major institutes. The sensitive factors for international cooperation are that it must be important for the Chinese economy and not a threat to national security. They hope to share ships, instruments, technology, and data in an international ocean exploration program.

Robert Knox, Scripps Institution of Oceanography, addressed the problems involved in facilitating a coordinated international exploration program. First, there must be good funding resources with open and fair competition. The level of organization should be kept as simple as possible. As examples, he cited WOCE and ODP. Such programs may have a substantial organizational structure, as appropriate to their needs, but interested scientists are heavily responsible for program planning and administration.

He suggests the following as the principal barriers to effective ocean exploration:

- funding;
- early establishment of genuine collaboration—not as an afterthought;
- publication issues must be agreed early to avoid later misunderstanding; and
- language issues.

LOS rights of coastal states are not in dispute, but the machinery is bureaucratic. Exploration of "friendly privileges" between participating nations could improve results. Exploration needs more flexibility than traditional research cruises have to adapt cruise plans in real time. Such changes can imperil ships clearances and will need consideration ahead of time among the participating nations.

Montserrat Gorina-Ysern, American University, is an expert on the Law of the Sea Convention (LOSC). She provided a brief background on the regulation of fundamental oceanographic research and marine science research as distinct from exploration in the 1958 Geneva Convention on the Continental Shelf and the 1982 LOSC, Part XIII, respectively. She outlined the main principles, rights and duties concerning the conduct of marine science research in different jurisdictional maritime zones and proposed how these would apply to IGOE activities.

"Exploration" has different meanings for different purposes (i.e., marine science research versus discovery of natural resources). The definition problem is compounded because marine science research has not been defined in LOSC. IOC has defined marine science research as referring to the scientific investigation of the ocean, its biota and its physical boundaries with the solid Earth and the atmosphere. The results of marine science research, normally published in journals of international circulation, are said to benefit humankind at large; whereas, exploration (also referred to as applied research) is concerned with ocean resources, and the results of this type of research are considered to be the property of the persons, corporations, or governments initiating the research.

Four legal principles would apply to the IGOE project.

1. IGOE activities should be undertaken exclusively for peaceful purposes. This has a precedent in the provisions on exploration and scientific investigations under the Outer Space Treaty, and to scientific investigations, observations, expeditions and scientific research under the Antarctic Treaty.

2. IGOE activities must use appropriate scientific methods and means.
3. IGOE activities must not unjustifiably interfere with other legitimate uses of the sea compatible with LOSC.
4. IGOE activities should comply with all relevant regulations adopted in compliance with LOSC, including those for the protection and preservation of the marine environment.

The conduct of IGOE activities may straddle across several parts of LOSC and also across various international conventions, agreements or arrangements, all of which share a similar organizational structure. With slight differences, they are organized around a council, commission or equivalent, a representative advisory body, an executive secretary or secretariat, and a scientific committee or panel. The latter carries out the scientific research decided by commissioners, through joint planning, coordination and evaluation of results. The IGOE partners have a range of organizational and legal options at their disposal, such as establishing bilateral or multilateral agreements covering IGOE activities.

In light of the extensive array of international and regional agreements and arrangements dealing with all aspects of ocean science, the issue of compatibility between those regimes and LOSC was discussed, and some major programs and arrangements were identified. Effective coordination among those programs and arrangements would be desirable in order to avoid duplication of scientific efforts by IGOE, where the existing programs are considered effective and sufficient. IGOE activities can be effectively regulated under the marine science research cooperation regime of Part XIII, 1982 LOSC, in a manner compatible with existing bilateral and multilateral structures and programs for pure and applied marine science of global benefit.

Sergei Shapovalov, Head of the Center for the Coordination of Oceanographic Sciences of the Russian Academy of Sciences, reminded participants that many nations have developed ocean exploration programs. It is impossible to plan for discovery. One can only propose what areas one would search for new discoveries. After such a decision, it is worthwhile to combine resources and efforts to accomplish the agreed objectives.

A Russian initiative, World Ocean, has been under way since 1999. It consists of ten different programs, but only one is research and exploration; others are concerned with security and management. Research on the World Ocean includes Ocean and Climate, Ecosystem Dynamics and

Geochemical Cycles, Geology and Geophysics of the Ocean Floor, and Russian Surrounding Seas.

He argued that we need to know what resources would be available for an international program—we need a resource database as soon as possible. Russian resources include the vessels *Akademik Mstislav Keldysh* which supports two *Mir* deep sea submersibles, the *Akademik Ioffe* ice breaker, and the *Akademik Sergei Vavilov*. These two ships have acoustic capabilities and multi beam sonar. In Russia, the principal barriers to cooperative international ocean exploration are a shortage of young oceanographers, and conflicts with their own navy regarding permits to do ocean science in their EEZ.

Russia as a nation would like to see an IGOE program set up as an informal and decentralized program under an international organization such as SCOR or IOC. Institutions, however, would probably prefer bilateral or multilateral agreements between organizations. He used the example of WOCE as a good model.

Steven Bohlen, President of the Joint Oceanographic Institutions (JOI), noted that many participants suggested that ODP is an example of a successful international science program. He agrees, but pointed out that ODP is focused around a single facility and primary objective, whereas an international ocean exploration program may require many facilities. The parallels may not be direct.

The goals and advantages of international collaboration include: leveraging of funds; generation of new ideas; efficient use of resources; and facilitated consent requirements through direct involvement of scientists from the participating countries. He presented some examples of successful international collaborations:

- *International Physics*. For the large centers around the world that have international support, there are program advisory committees to help the facilities prepare for high priority scientific programs. Each one also has a research review board to review proposals. The research review boards work with collaboration boards that are charged to bring together the components of the project. There are also resource review boards to deal with funding.
- *International Planetary Exploration*. This model has proven to be fairly contentious. NASA has an "international" advisory council and a space science advisory committee, but they are actually heavily dominated by U.S. members. Subcommittees exist on vari-

ous areas of space exploration. The voice of the scientists themselves is fairly weak. Engineering issues dominate.

- *International Astronomy*. The focus is on the Gemini program with its two very large telescopes in Hawaii and Chile. It has mimicked the structure of ODP. There is a Gemini Program Office, independent of any national funding agency. A Science Committee plans use of facilities. The United States participates through a U.S. Science Support Program.
- *Ocean Drilling Program*. The 23 national members contribute \$46 million per year. There have now been 30 years of ocean drilling. ODP includes interdisciplinary research. NSF is the international banker, and funds go to JOI. JOI oversees the Joint Oceanographic Institutions for Deep Earth Sampling advisory structure, which is complex but independent of national funding control. The Science committee and its sub-groups determine the scientific program for each year. All this is in the context of international participation—membership in panels is roughly proportional to each nation's financial contribution.
- *Integrated Ocean Drilling Program*. IODP will be starting in 2003. The new science plan identifies three primary objectives. IODP will be a multi platform program with at least two vessels and equal partnership between the United States and Japan. Possibly, there will be a third equal partner (i.e., the Europeans may bring in a shallow water vessel).

The following factors contribute to a successful collaboration:

- facilities and science objectives need to be well matched and flexible;
- projects must be driven by science objectives;
- scientists must have a strong voice in decision-making;
- oversight must incorporate the needs of the international community; and
- management and governance must be viewed as ecumenical and balanced and should be distant from any strong national control.

Nii Odunton, Chief of Resource and Environmental Monitoring for the International Seabed Authority, described the work of the International Seabed Authority for management of deep sea mineral resources. The efforts of the International Seabed Authority have culminated in a set of recommendations for collaborative marine scientific research to assist the International

Seabed Authority in managing impacts from the proposed mining of deep seabed polymetallic nodules. As a result of a series of workshops, it was agreed that major knowledge gaps existed in at least three key areas that should be the focus of collaborative studies over the next five years:

1. levels of biodiversity, species ranges and rates of gene flow in abyssal nodule provinces (particularly the Clarion-Clipperton Fracture Zone);
2. disturbance and recolonization processes at the seafloor following mining-track creation and mining plume resedimentation; and
3. mining-plume impacts on water-column ecosystems (e.g., nutrient enrichment, sediment loading, iron enrichment and heavy-metal toxicity).

The value of cooperation and the development of consortia have been seen as an accepted way of sharing risk where the investments are too great for any one organization to commit.

Summary

An international ocean exploration program must be nonbureaucratic and flexible. Perhaps a decentralized structure, evolving through time, would be the most effective. Many countries already have ocean exploration programs. Others do not, often for financial reasons. As we consider "global" ocean exploration, we need to consider it not only in the geographic sense, but also in the sense of participation. The gap between developed and developing in science is widening. If we really want to carry out an international program, we must consider issues of wide participation. The cooperation must be rooted in shared interests. Standardization of data to facilitate data management, access, and transfer is important. The situation with regard to data accessibility is changing and some of these issues are being dealt with in international agreements. More data have commercial interest and this is a growing problem. More data are now being used in real time and this means they must be shared much more rapidly. Various international laws are forming the basis for changes in management of EEZs to protect the proprietary interests of nations. While fully respecting the rights of coastal states and LOS, we should seek to simplify the regulatory complexity where possible. The definition of "exploration" is not the same as it is defined in LOS (i.e., exploration as a precursor of production, but rather in the context of scientific discovery). An international ocean exploration program should ensure a strong education and public outreach component.

FINAL PLENARY SESSION

Sylvia Earle, Explorer-in-Residence at the National Geographic Society, recently met with other Explorers-in-Residence to discuss the past, present, and future of exploration. She felt that the greatest oceanography era is just about to begin. It has been more than 40 years since Piccard and Walsh made their historic deep dive in the *Trieste*, but we still have only explored less than one percent of the deep sea. A few men have walked on the moon, dozens have orbited Earth, and hundreds have climbed Everest. Why has not man been to the bottom of the ocean?

Dr. Earle acknowledged that some say manned exploration is not necessary. She believes that ocean exploration needs all available technology. Until we can design a tool, probe, or sensor that can perceive, understand, evaluate, and make decisions better than the human brain, there will be a role for human presence in the sea. No machine can evaluate the unexpected. Human presence in the ocean is a small, but important, component of exploration. As the new millennium begins, we have few vehicles capable of accessing the average depths of the ocean, and only one that can go to the greatest depths. She argued for underwater habitats and laboratories (only one now exists) and expeditions that incorporate deep diving components.

There is a growing sense of urgency for ocean exploration—the ocean is vital to humankind and it is under threat, as is the health of Earth. The ocean is the life support system of Earth. Dr. Earle concluded by urging participants to know everything we can about our life support system, and to do everything we can to maintain and protect that life support system. Our responsibility does not end at the seashore.

E

International Ship Listing

The research vessel information that follows was provided by the Ocean Information Center at the University of Delaware. Please note that this database uses voluntary information submittals, and may not be exhaustive. Furthermore, actual percentages of ship time devoted to the primary activity are not verified. Vessel seaworthiness is also not included in the database. This list is included to provide the reader with a sense of the existing assets that might be available for cooperative ocean exploration efforts, and the countries that support ocean-going research. Total vessels reported are given in parentheses.

Country	UNOLS Class[1]	Number of Vessels Reported in Class	Primary Activity[2]
Argentina (7)	G	1	oceanog
	I	2	fish, oceanog
	R	1	hydrog
	U	3	
Australia (8)	G	3	geo, hydrog
	I	4	fish, navigation training, oceanog
	U	1	
Belgium (1)	R	1	fish, geo, hydrog, oceanog
Bermuda (2)	G	1	fish, geo, hydrog, oceanog
	R	1	oceanog
Brazil (1)	R	1	oceanog
Bulgaria (1)	I	1	oceanog
Canada (11)	G	2	acoustic research, geo, oceanog
	I	5	fish, geo, hydrog, hydrology, oceanog, patrol
	L	2	biology, survey
	R	2	fish

continued

Country	UNOLS Class[1]	Number of Vessels Reported in Class	Primary Activity[2]
Chile (4)	I	2	oceanog
	R	2	fish, oceanog
China (18)	G	10	geo, hydrog, oceanog
	I	2	fish, geo
	R	1	fish
	U	5	
Colombia (2)	R	2	biology, fish, hydrog, meteo, oceanog
Denmark (2)	G	1	fish, oceanog
	I	1	geo, environmental, oceanog
Ecuador (1)	G	1	geo, hydrog, oceanog
Estonia (3)	G	2	oceanog
	U	1	
Finland (1)	I	1	geo, hydrog, oceanog
France (9)	G	3	biology, geo, logisitics, oceanog
	I	2	
	L	3	
	U	1	
Germany (14)	G	3	fish, geo, hydrog, oceanog
	I	6	biology, fish, geo, helcon-monitoring in the Baltic, wreck search, hydrog, oceanog, tests of Naval equipment
	R	1	
	U	4	
Greece (2)	I	1	fish, geo, hydrog, oceanog, pollution monitoring
	L	1	
Iceland (2)	R	1	fish, geo, hydrog, oceanog
	U	1	
India (7)	G	2	fish, oceanog
	I	1	oceanog
	R	2	fish
	U	2	hydrog, pollution monitoring
Indonesia (4)	U	4	
Iran (2)	I	1	fish
	R	1	fish
Ireland (1)	U	1	
Israel (1)	R	1	
Italy (4)	G	2	geo
	I	2	geo, hydrog, oceanog
Japan (68)	G	15	fish, hydrog, geo, oceanog, marine pollution, meteo
	I	27	fish, geo, hydrog, oceanog, meteo
	R	18	fish, hydrog, oceanog, meteo
	U	8	
Korea (12)	G	2	fish
	I	4	fish, geo, hydrog, oceanog
	R	5	fish, hydrog, oceanog
	U	1	

Country	UNOLS Class[1]	Number of Vessels Reported in Class	Primary Activity[2]
Libya (1)	R	1	fish
Lithuania (1)	I	1	oceanog
Malaysia (2)	G	1	hydrog, geo
	R	1	fish, oceanog
Mexico (5)	I	3	geo, hydrog, oceanog
	R	2	oceanog
Namibia (1)	R	1	fish
National Atlantic Treaty Organization (2)	G	1	oceanog
	L	1	
Netherlands (4)	G	2	fish, geo, hydrog, military surveys, oceanog
	I	2	oceanog
New Zealand (3)	G	1	marine science
	L	1	
	R	1	fish
Norway (9)	G	1	fish, hydrog, oceanog
	I	3	biology, fish, geo, hydrog, logisitcs, oceanog
	R	2	fish, geo, hydrog, oceanog
	U	3	
Pakistan (2)	I	1	geo, hydrog, oceanog
	U	1	
Peru (1)	G	1	fish, geo, hydrog, oceanog
Philippines (4)	I	1	geo, hydrog, oceanog
	R	3	fish and demos, geo, hydrog, oceanog
Poland (2)	R	2	fish, geophysics, hydrog, oceanog, international monitoring
Portugal (2)	R	2	fish
Russian Federation (86)	G	41	fish, geo, hydrog, oceanog, meteo
	I	39	fish, hydrog, oceanog
	R	1	oceanog
	U	5	
South Africa (4)	G	2	Antarctic supply, fish, oceanog
	I	1	fish
	R	1	fish
Spain (3)	I	1	fish, geo, hydrog, oceanog
	R	1	oceanog
	U	1	
St. Vincent and Grenadines (1)	L	1	diving, expeditions
Sweden (1)	I	1	fish, hydrog
Thailand (8)	I	3	fish, geo, hydrog, oceanog, training
	R	4	fish
	U	1	

continued

Country	UNOLS Class[1]	Number of Vessels Reported in Class	Primary Activity[2]
Turkey (6)	I	1	geo
	R	2	fish, geo, hydrog, oceanog
	U	3	oceanog
Ukraine (13)	G	5	acoustic research, fish, geo, hydrog, oceanog, satellite observations
	I	5	fish, geo, hydrog, oceanog, satellite obeservation
	L	1	geo, hydrog, oceanog
	U	2	
United Kingdom (13)	G	5	Antarctic survey and support, fish, hydrog, monitoring, oceanog, pollution
	I	4	fish, hydrog, oceanog, monitoring, pollution
	L	1	fish, geo, hydrology, oceanog
	R	2	fish, oceanog
	U	1	
United States (129)	G	13	hydrog, oceanog
	I	24	acoustic research, fish, geo, hydrog, oceanog, salvage
	L	32	biology, fish, hydrog, hydrology, oceanog, pollution, test area surveillance, towing, training
	R	23	deep exploration, Education, fish, geo, hydrog, oceanog, sailing, survey, wildlife
	U	37	oceanog
Vietnam (3)	R	1	fish
	I	1	coastal survey
	L	1	biology, education

NOTE: Data was provided by Douglas White at the University of Delaware.

[a] The University-National Oceanography Laboratory System vessels are classed by their length (G Class I & II: 70-85m; I Class III: 51-62m; R Class IV: 32-41m; L Class V: <30m).

[b] oceanog=oceangraphy, fish=fisheries, hydrog=hydrography, meteo=meteorological, geo=geological

F
International Autonomous Underwater Vehicle Listing

Institution	Major Topics	Vehicles
University of Aberdeen Ocean Research Lab Scotland	Autonomous landers and acoustics	Aberdeen University Deep Ocean Submersible
Alfred Wegener Institute Deepsea Research Bremerhaven, Germany	Autonomous landers	Autonomous underwater vehicle (AUV) payload modules
Autonomous Undersea Systems Institute Marine Systems Engineering Laboratory Lee, New Hampshire	Environmental monitoring, generic behaviors, and control	AUVs
Australian National University Robotics Systems Laboratory Canberra	Underwater exploration and observation	*Kambara*
Bluefin Robotics Corp. Cambridge, Massachusetts	AUVs	*Odyssey I*, *Odyssey II B*, *Odyssey III*, and *Seasquirt*
C & C Technologies, Inc. Lafayette, Louisiana	AUVs and survey services	*Hugin 3000*
Instituto Automazione Navale Consiglio Nazionale delle Ricerche Robot Lab Genova, Italy	Control, navigation, and manipulation	*Romeo* and *Aramis*
Technical University of Denmark Department of Automation Lyngby, Denmark	Sonar for underwater inspection	*Martin*
Instituto Superior Tecnico Dynamical Systems and Ocean Robotics Laboratory Lisbon, Portugal	Installations, long range missions, exploration, and control	*Caravela*, Marine Utility Vehicle System, and *Sirene*

continued

Institution	Major Topics	Vehicles
University of Florida Machine Intelligence Laboratory Gainesville	AUVs for competitions	*SubjuGator*
Florida Atlantic University Advanced Marine Systems Laboratory Boca Raton		*Ocean Voyager II*, *Ocean Explorer*, and Bottom Classification and Albedo Package
Hafmynd Ltd. Reykjavik, Iceland	AUVs	*Gavia*
Harbor Branch Oceanographic Institution Ocean Engineering and Production Division Fort Pierce, Florida	AUVs	*Ocean Voyager*
University of Hawaii Autonomous Systems Laboratory Honolulu	Navigation, search, and recognition	*Omni-Directional Intelligent Navigator*
Heriot-Watt University Ocean Systems Laboratory Edinburgh, Scotland	Vision, sonar, manipulation, simulation, acoustics, electromagnetic and optical communication, positioning, navigation, and sampling	*Autonomous Light Intervention Vehicle*, *Aramis*, and *Rauver*
Hyland Underwater Vehicles Edinburgh, Scotland	Simple, small, proof-of-concept AUV	*MicroSeeker*
French Institute of Research and Exploration of the Seas Data Processing Systems Toulon	Control and navigation and control architectures	Open and Reconfigurable Vehicle for Experimental Techniques
International Submarine Engineering Ltd. Port Coquitlam, Vancouver, Canada	Cable laying, autonomy, and communications	*Autonomous Remotely Controlled Submersible*, Deep Ocean Logging Platform with Hydrographic Instrumentation and Navigation, *Theseus*, and *Aurora*
Japan Marine Science and Technology Center Marine Technology Department Yokosuka	Long distance inertial navigation	Long distance AUV
KDD Marine Engineering Laboratory Tokyo, Japan	Vision, cable tracking, and communications	*Aqua Explorer 2* and *Aqua Explorer 1000*

Institution	Major Topics	Vehicles
KISS Institute for Practical Robotics Norman, Oklahoma		*Dinky Robot in Pool*
University of Louisiana Apparel Computer Integrated Manufacturing Center Lafayette	Autonomous vehicle for underwater exploration	*Phantom S2*
Maridan Horsholm, Denmark	Design and manufacturing of AUVs	*Maridan*
Massachusetts Institute of Technology AUV Laboratory at the Massachusetts Institute of Technology Sea Grant Cambridge	Small, high performance vehicles; nonacoustic sensors; energy management; docking; adaptive sampling; multiple vehicle operations; coastal modeling; object mapping; and under-ice, autonomous ocean sampling	*Odyssey II B*, *Composite Endoskeleton Testbed Untethered Underwater Vehicle System*, and *Altex*
Monterey Bay Aquarium Research Institute Moss Landing, California		*Dorado*
John C. Stennis Space Center Naval Oceanographic Office AUV Program Mississippi	AUVs	*Seahorse*
Naval Postgraduate School Center for AUV Research Monterey, California	Shallow water applications	*Phoenix*
National Research Council of Canada Institute for Marine Dynamics Ottawa, Ontario	*Canadian Self-Contained Off-the-shelf Underwater Testbed* (C-SCOUT)	*C-SCOUT*
Memorial University of Newfoundland Ocean Engineering Research Centre St. John's, Canada	*C-SCOUT*	*C-SCOUT*
Norwegian Underwater Intervention Bergen, Norway	Route and area surveys, search, and logging	*Hugin*
University of Port Laboratory of Systems and Subaqueous Technology Portugal	Autonomous and remote vehicles and control	*Isurus* and remote operated vehicles

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Institution	Major Topics	Vehicles
Russian Academy of Sciences Institute of Marine Technology Problems Moscow	Solar powered AUVs	
Scripps Institution of Oceanography La Jolla, California	Passive synthetic aperture sonar; quiet propulsion, gravity, seafloor deformation (1 cm), multibeam, chirp sonar	*Bluefin Odyssey II B* and *Bluefin 21*
Sias Patterson Incorporated Gloucester Point, Virginia	AUVs	*Fetch2*
Simon Fraser University Underwater Research Laboratory Burnaby, British Columbia, Canada	Underwater acoustics, light-seeking AUVs, and autonomous sampling	*Purl* and *Purl II*
Southampton Oceanography Centre Ocean Engineering Division United Kingdom	Autonomous sampling and long-range missions	*Autosub*
University of Southampton Image, Speech, and Intelligent Systems Highfield, United Kingdom		*Neptune*
University of South Florida Center for Ocean Technology St. Petersburg	Sensors (optical, chemical, and acoustical) and seafloor classification	Bottom Classification and Albedo Package
Stanford University Aerospace Robotics Laboratory California	Dynamics, control, high-level command-interface, and autonomy	Ocean Technology Testbed for Engineering Research
University of Sydney Australian Centre for Field Robotics	Position and attitude estimation and control	*Oberon*
Texas A&M University AUV Laboratory College Station		
Tokai University Kato Underwater Robotics Lab Shizuoka, Japan	Control, docking, and cable inspection	*Aqua Explorer 2* and *Aqua Explorer 1000*
University of Tokyo Ura Lab Japan	Autonomy, learning, long-range operations, and gliding vehicles	*R1* (long-range autonomous operation), *Albac*, *Twin-Burger 2*, and *Manta-Ceresia*

Institution	Major Topics	Vehicles
Woods Hole Oceanographic Institution Deep Submergence Laboratory Massachusetts	Long-term seafloor monitoring, All kinds of marine operations	*Autonomous Benthic Explorer*, *Jason/Medea*, and *Remus*

SOURCE: modified from Institute of Electrical and Electronics Engineers, Inc., 2002