OCEAN SCIENCE SERIES

OCEAN EXPLORATION

Highlights of National Academies Reports

THE NATIONAL ACADEMIES
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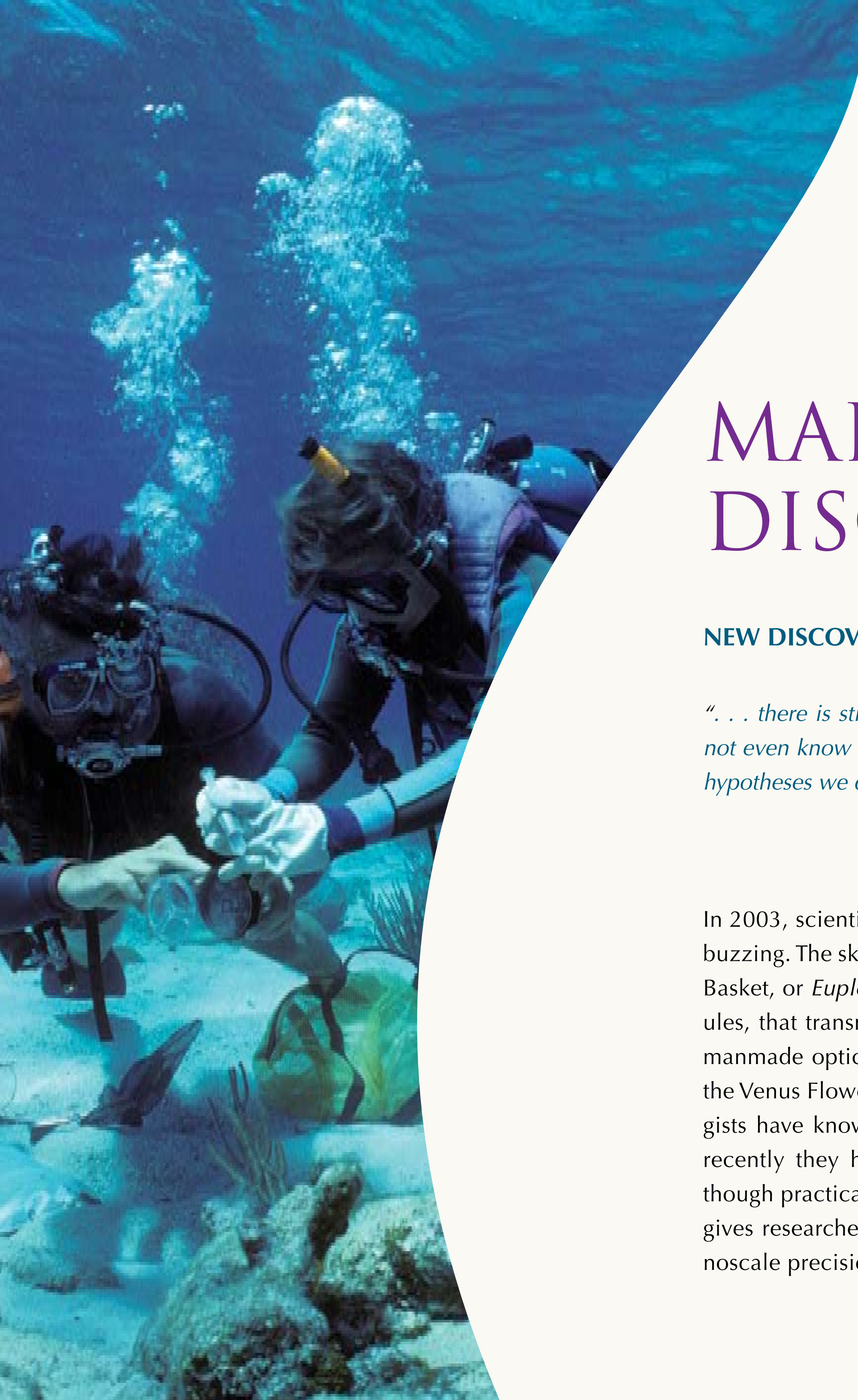
AMONG ALL THE PLANETS OF THE SOLAR SYSTEM, EARTH STANDS OUT AS A WATERY OASIS.

The ocean is the largest biosphere on Earth, covering nearly three-quarters of our planet's surface and occupying a volume of 1.3 billion cubic kilometers. Despite the major role of the ocean in making the Earth habitable—through climate regulation, rainwater supply, petroleum and natural gas resources, and a breathtaking diversity of species valued for their beauty, seafood, and pharmaceutical potential—humankind has entered the 21st century having explored only a small fraction of the ocean.

Some estimates suggest that as much as 95 percent of the world ocean and 99 percent of the ocean floor are still unexplored. The vast mid-water—the region between the ocean's surface and the seafloor—may be the least explored, even though it contains more living things than all of Earth's rainforests combined. Similarly, the ocean floor and sediments encompass an extensive microbial biosphere that may rival that on the continents, which is not yet understood and remains largely unexplored.

The impacts of human activities on the ocean drive a growing urgency for its exploration before permanent and potentially harmful changes become widespread. Even events that occur far inland, such as nutrient runoff from agriculture and pollutants and debris carried by stormwater, have impacts. The ocean bears a double burden from the burning of fossil fuels and associated climate change; not only is it warmer, but the additional carbon dioxide dissolves in the ocean, making it more acidic.

Although mariners have traversed the ocean for centuries, exploring its inky depths is no easy task. Recent technological advances now make possible scientific investigations only dreamed of 20 years ago. The development of state-of-the-art deep-sea vehicles and a host of other technologies have opened doors for finding novel life forms, new sources of energy, pharmaceuticals, and other products, and have promoted a better understanding of the origins of life, the workings of this planet, and of humanity's past.



MAKING DISCOVERIES

NEW DISCOVERIES ARE BEING MADE ALL THE TIME.

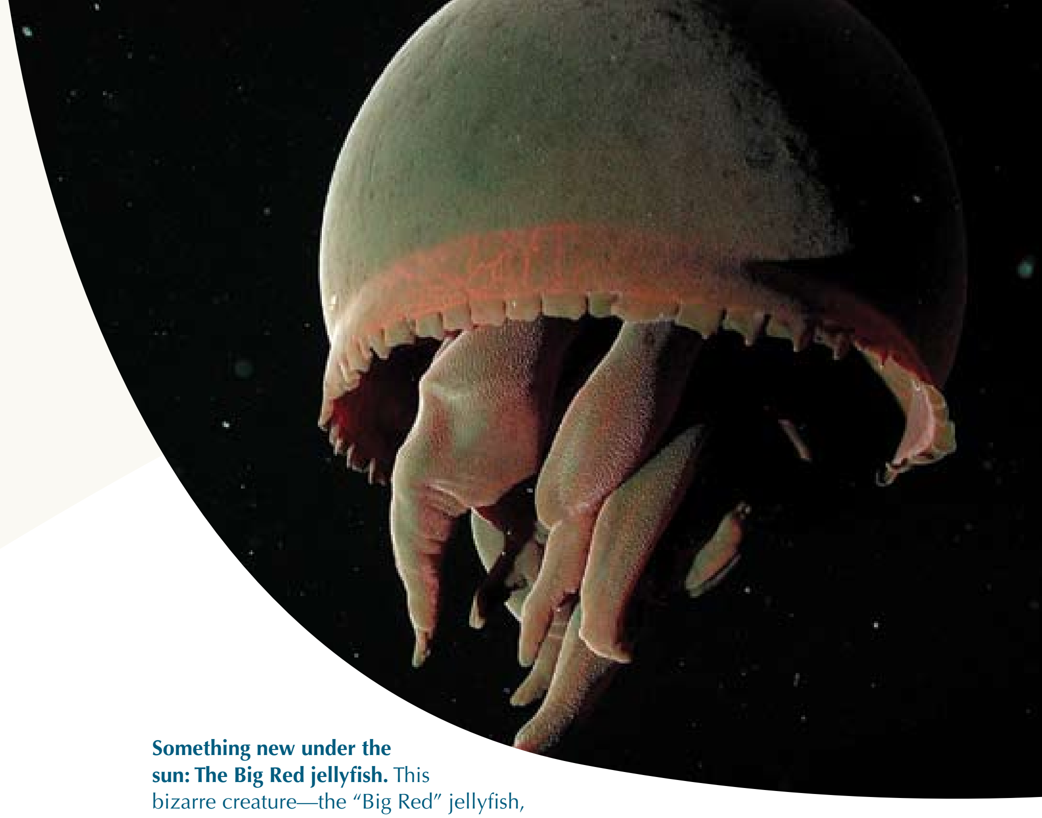
". . . there is still so much we do not know about the oceans that often we do not even know the proper questions to ask or an unambiguous way to test what hypotheses we do have. For that reason, I am a fan of ocean exploration."

—Marcia McNutt, president and CEO,
Monterey Bay Aquarium Research Institute

In 2003, scientists made a discovery that set the telecommunications industry buzzing. The skeleton of a type of deep-sea sponge known as the Venus Flower Basket, or *Euplectella*, was shown to consist of thin silicon fibers, called spicules, that transmit light at least as well as commercial optical fibers.[1] Unlike manmade optical fibers that will break if bent too far, the silicon spicules of the Venus Flower Basket can be tied in a knot without breaking. Marine biologists have known for decades that sponge skeletons transmit light, but until recently they hadn't studied the light carrying properties of spicules. Even though practical applications could be decades away, this deep-sea discovery gives researchers new perspectives on how nature creates materials with nanoscale precision.

There are many such discoveries. An enzyme, taken from bacteria that break down fats in cold water, has been used to improve laundry detergent. A glowing green protein from jellyfish has been widely used in medicine, helping researchers illuminate cancerous tumors and trace brain cells leading to Alzheimer's disease—an accomplishment that garnered the 2008 Nobel Prize in Chemistry for the researchers Osamu Shimomura, Martin Chalfie, and Roger Y. Tsien, who discovered and developed this technology. Each new discovery is a reminder of how little is known about the ocean environment, which is so critically important to health and life on Earth.

To enable the full exploration of the oceans and seafloor and the sustainable development of their resources, the National Research Council report *Exploration of the Seas: Voyage into the Unknown* (2003) recommended that the United States vigorously pursue the establishment of a global ocean exploration program. Such an effort could be modeled after the federally funded space exploration program, involving multiple federal agencies as well as international participation.



Something new under the sun: The Big Red jellyfish. This bizarre creature—the "Big Red" jellyfish, named for its impressive size and blood-red color—was discovered in 1998 by a team of marine biologists at the Monterey Bay Aquarium Research Institute. The team first glimpsed Big Red in video recordings from exploratory missions off the coast of San Francisco. When, after a 3-year search, the team was finally able to capture a specimen, they determined that Big Red represented not just a new species, but also a new genus and sub-family, which is a relatively rare biological find.[2] Photo courtesy Monterey Bay Aquarium Research Institute.

Sea creature sheds new light on fiber optics. In 2003, Dr. Joanna Aizenberg, a research scientist at Bell Labs, and her colleagues discovered that the thin and supple fibers of the Venus Flower Basket (*Euplectella*), a sponge that lives deep in the tropical ocean, transmit light in a manner strikingly similar to commercial fiber optics. Venus Flower Baskets are among the brightest creatures on the seafloor, transmitting the light of tiny bioluminescent (light-producing) shrimp that live inside them. Photo courtesy Harbor Branch Oceanographic Institute, Florida Atlantic University.

The “Rasta” sponge, discovered a few miles off the Florida Keys in early 2000, contains an antitumor agent used to treat cancer. Photo courtesy Harbor Branch Oceanographic Institute, Florida Atlantic University.

OCEAN EXPLORATION AND HUMAN HEALTH

At least 20,000 new biochemical substances from marine plants and animals have been identified during the past 30 years, many with unique properties useful in fighting disease. “Biodiscovery” researchers have had success in all types of ocean environments. A 1991 expedition by the Scripps Institution of Oceanography’s Paul Jensen and William Fenical resulted in the discovery of a new marine bacterium, *Salinispora tropica*, found in the shallow waters off the Bahamas. This bacterium produces compounds that are being developed as anticancer agents and antibiotics. It is related to the land-based *Streptomyces* genus, the source of more than half of our current suite of antibiotics.[3]

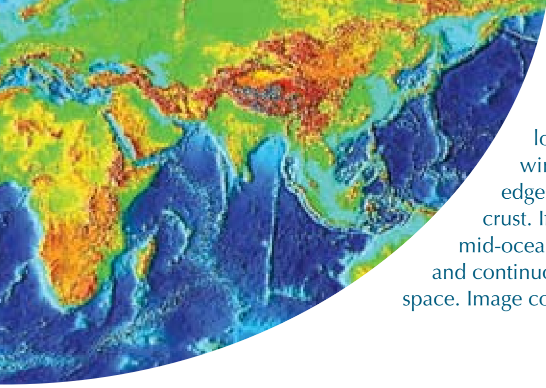
Deep-water marine habitats constitute a relatively untapped resource for the discovery of drugs. In early 2000, Shirley Pomponi and Amy Wright from Harbor Branch Oceanographic Institution explored deep waters a few miles off the shore of the Florida Keys. Using the robotic claws and high-powered vacuums of the *Johnson Sea-Link* submersibles, the team gathered a host of deep-water organisms. They met success with the discovery of a new genus of sponge, nicknamed the “Rasta” sponge, containing anticancer compounds.[4]

The promise and problems of developing novel marine chemicals into bioproducts, from pharmaceuticals to compounds used in agriculture, is examined in the National Research Council report *Marine Biotechnology in the Twenty-First Century.* The report recommends revitalizing the search for new products by making it a priority to explore unexamined habitats for new marine organisms.

OCEAN DISCOVERIES HAVE ANSWERED CRITICAL QUESTIONS ABOUT EARTH’S PROCESSES AND HISTORY.

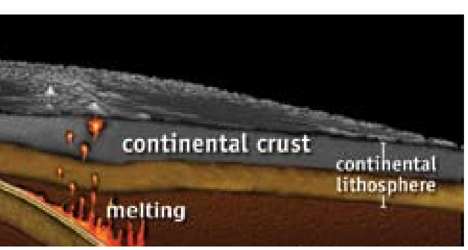
Since its inception in the late 1960s, the theory of plate tectonics—that heat from Earth’s interior drives the movement of plates on the surface—has revolutionized our understanding of the forces that shape Earth. This groundbreaking idea, which contributes fresh insights into disciplines ranging from earthquake science to mineral and gas exploration, could not have been developed without ocean exploration.

As early as the 16th century, it was thought that the continents could once have been joined, suggested by the apparent fit of the facing shores of South America and Africa. In the early 20th century, German researcher Alfred Wegener published the hypothesis of “continental drift,” which posited that the continents had drifted apart from a single large land mass he called Pangaea. At the time, Wegener’s theory wasn’t generally accepted because there was no explanation for the forces required to drive the continents apart.



A chain of underwater mountains 65,000 kilometers (40,000 miles) long known as the *mid-ocean ridge* winds its way around the globe at the edges of the plates that make up Earth's crust. If the oceans were drained, the mid-ocean ridge would be the most massive and continuous feature on Earth as viewed from space. Image courtesy NOAA.

The key to the puzzle lay on the seafloor at one of the ocean's most distinctive features: a 65,000-kilometer-long (40,000 miles) underwater, volcanic mountain range that winds its way around the globe, known as the mid-ocean ridge. New seafloor mapping technologies available by the 1940s and 1950s brought many explorers to the ridge. In 1961, scientists from Scripps Institution of Oceanography studying the mid-ocean ridge off the U.S. northwest coast documented a distinctive pattern of magnetized rocks that resembled the stripes on a zebra.[5] In a landmark 1963 publication, scientists hypothesized that the striping resulted from shifts in Earth's magnetic field during a period when hot magma erupted at the mid-ocean ridges and solidified to form new ocean floor.[6] Other supporting evidence for this phenomenon, known as seafloor spreading, eventually developed into the theory of plate tectonics.



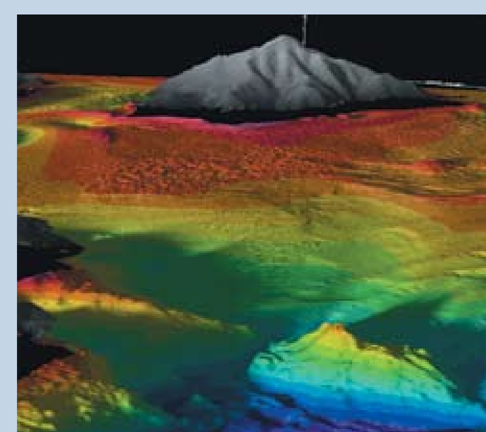
Earth's crust is made up of a series of tectonic plates, analogous to a hardboiled egg with a cracked shell. It forms at mid-ocean ridges, where two tectonic plates move away from each other, and is destroyed at subduction zones, where the plates collide. Many of the world's great volcanoes and earthquake-prone regions are located near subduction zones, driven by these tectonic forces. Image courtesy NEPTUNE and the Center for Environmental Visualization, University of Washington.

MAPPING THE SEAFLOOR

As early as the 16th century, navigators began measuring ocean depth with heavy ropes, called sounding lines, that were dropped over the side of the ship. By the 19th century, deep-sea line soundings (*bathymetric surveys*) were routinely conducted in the Atlantic and Caribbean. In 1913, the use of sound waves (echo soundings) to measure ocean depth was patented by German physicist Alexander Behm, who was originally searching for a method to detect icebergs following the *Titanic* disaster. With echo sounding, the time it takes for an outgoing pulse to go to the seafloor and back is measured and used to calculate distance based on the average speed of sound in water.

The next breakthrough came with the introduction of sonar—"sound navigation and ranging"—first used in World War I. Multibeam sonar, developed by the U.S. Navy in the 1960s, uses an array of beams at varying angles, enabling much larger swaths of ocean floor to be mapped with much greater precision. A project in Tampa Bay generated continuous maps of that area from land out through the shoreline and beneath the water. The National Research Council report *A Geospatial Framework for the Coastal Zone* examines the requirements for generating such maps, which help show how natural and manmade forces interact and affect processes in complex coastal areas. All of the new mapping techniques have revolutionized our understanding of the topography of the ocean floor and helped to develop ideas about the fundamental processes responsible for creating seafloor terrains and modifying the oceanic crust.

This image of San Francisco Bay (right) is created by combining multibeam sonar data with topographic data. Such images allow complex ocean environments to be explored in ways that are both intuitive and quantitative. Image courtesy the Center for Coastal and Ocean Mapping, University of New Hampshire.



Ocean exploration continues to illuminate details about Earth processes. The Ridge Inter-Disciplinary Global Experiments (RIDGE) program, established in 1987 and supported largely by the National Science Foundation and other federal agencies, funded expeditions that served to broaden understanding of the global ridge system and the life it hosts. Since 2001, the new NSF-sponsored Ridge 2000 program (http://www.ridge2000.org) has conducted detailed integrated studies at three mid-ocean ridge sites in the eastern and western Pacific.

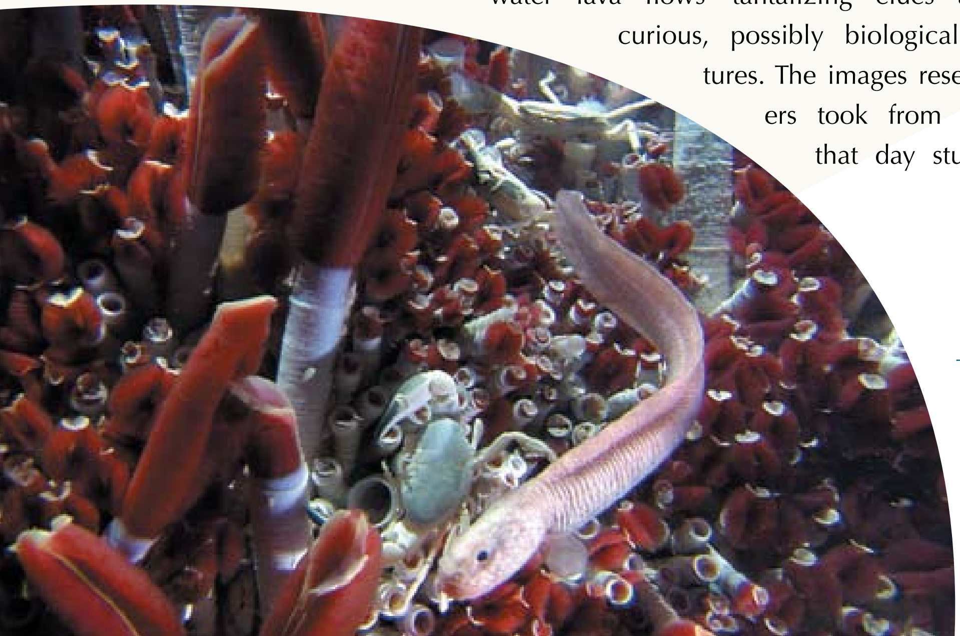
OCEAN DISCOVERIES HAVE ANSWERED CRITICAL QUESTIONS ABOUT LIFE ON EARTH.

In 1977, the deep-sea submersible, *Alvin*, was sent to explore a part of the mid-ocean ridge north of the Galápagos Islands known as the Galápagos Rift. *Alvin* was following in the tracks of an unmanned vehicle, towed by the research vessel *Knorr*, that had detected unusually high bottom-water temperatures and had taken photographs of odd white objects among the underwater lava flows—tantalizing clues about curious, possibly biological features. The images researchers took from *Alvin* that day stunned and amazed people everywhere. They revealed a rich oasis of life, teeming with never-before-seen varieties of shrimp, large clams, huge red tubeworms in white casings, and other creatures.

These images attracted a flurry of attention from scientists. One of the most puzzling questions was how this assortment of creatures managed to thrive in the dark in the absence of photosynthetic algae—the base

VENT ORGANISMS AND DNA DETECTION

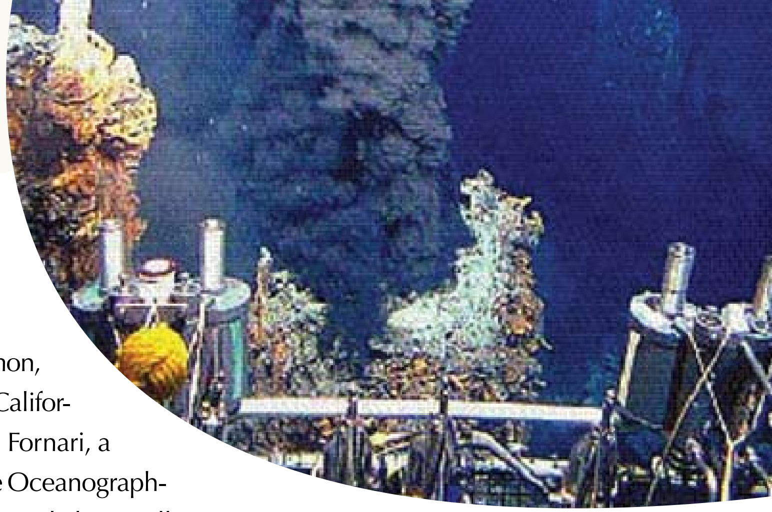
Microbes associated with hydrothermal vents have evolved enzymes that can withstand some of the harshest conditions on Earth. One such enzyme, Vent DNA polymerase, has been employed by researchers to improve the polymerase chain reaction (PCR), a technique used to detect and identify trace amounts of genetic material. PCR involves many cycles of heating and cooling to separate and replicate the two strands of the DNA molecule. The heat-stable DNA polymerase from the vent microbes is a perfect fit for this revolutionary technology. This technique is widely used in biological research and in practical applications, such as DNA forensic analysis in criminal investigations, medical diagnostic procedures, biowarfare agent detection, and genetic studies of extinct species, for example, woolly mammoths.



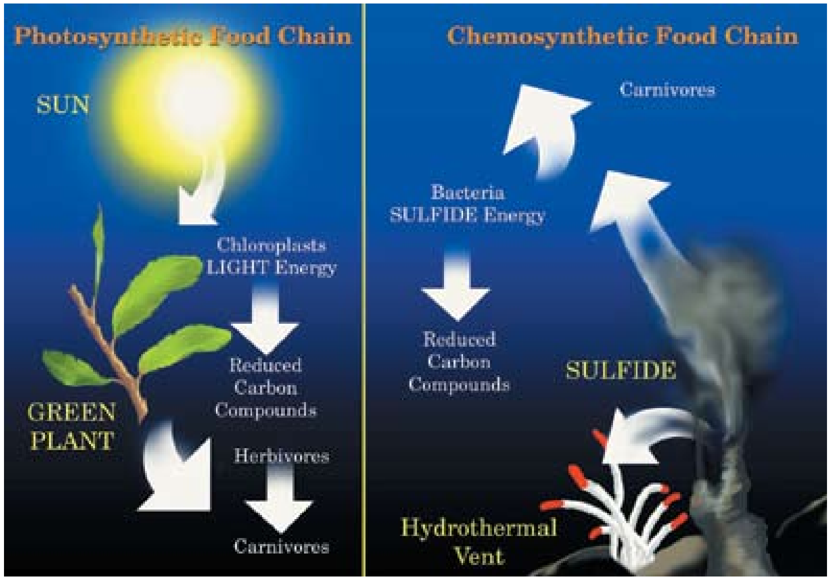
The discovery in 1977 of a world of colorful tube worms, crabs, and fish living off the chemosynthetic bacteria at the hydrothermal vents surprised scientists everywhere. Photo used with permission from Richard Lutz, Rutgers University, Stephen Low Productions, and the Woods Hole Oceanographic Institution.

of the food web for all known ecosystems in the ocean and on land. It turned out that the ecosystem *Alvin* had visited, and other hydrothermal vent ecosystems like it, are supported by *chemosynthetic* bacteria that derive energy from compounds such as hydrogen sulfide and methane that are found in the waters emanating from the vents. At vents on the Pacific ridge system, chimneylike structures known as *black smokers* spew large amounts of hydrogen sulfide into the environment. Large clams and tubeworms soak up hydrogen sulfide to feed the chemosynthetic bacteria they harbor in their tissues, a symbiotic relationship so central to their biology that these animals don't even have a mouth or a gut. More than 500 new species have been found at seafloor vents since their discovery—a rate of about one new species every 2 weeks for an entire human generation (~30 years). With much of the ocean ridge still unexplored, scientists expect that many new species await discovery.

In 1991, Rachel Haymon, from the University of California, Santa Barbara; Dan Fornari, a scientist at Woods Hole Oceanographic Institution (WHOI); and their colleagues working near the mid-ocean ridge in the eastern Pacific witnessed a new phenomenon— a "blizzard" of microbes and microbial debris spewing out of the seafloor[7]. The material rose more than 30 meters above the ocean bottom and formed a thick white layer on the seafloor. Since then, this phenomenon of rapid effusion of microbial material has been observed several times in the vicinity of undersea volcanic eruptions.



A black smoker, as seen from *Alvin*, is formed when superheated, sulfide-rich water from below Earth's crust comes through the ocean floor. At 2,500-3,000 m below sea level, pressures rise dramatically, preventing water from boiling. One of the highest temperatures recorded at a black smoker is 407ºC (765ºF), measured by the German remotely operated vehicle *Quest* in 2006 in the South Atlantic. Photo courtesy Woods Hole Oceanographic Institution.



Instead of photosynthesis, vent communities in the ocean are powered by chemosynthesis, a process that, in the absence of sunlight, harvests energy from the chemical compounds eminating from the vent. Image used with permission of E. Paul Oberlander, Woods Hole Oceanographic Institution.

DISCOVERY OF "LOST CITY" REVEALS VENTS OF A DIFFERENT KIND

In 2000, a team of scientists led by Donna Blackman from the Scripps Institution of Oceanography, Deborah Kelley from the University of Washington, and Jeff Karson of Duke University (now at Syracuse), were exploring the Atlantic on a National Science Foundation-supported expedition on the research vessel *Atlantis*. About 2,300 miles east of Florida, on the Mid-Atlantic Ridge, the team stumbled on an amazing sight: a hydrothermal vent field with mounds, spires and chimneys reaching18 stories high. Not only were these structures higher than the black-smoker vents discovered earlier, but they were very different in color, ranging from cream color to light gray. Kelley dubbed the find "The Lost City."

The Lost City vents were found to be made up of nearly 100 percent carbonate, the same material as limestone in caves. The fluids discharging at Lost City are very alkaline—the opposite of the acidic black smokers—and in some places as caustic as drain cleaner. The heat and chemicals at the vents come, in part, from the strong chemical reactions produced when seawater interacts with dark green rocks, called peridotites, which have been thrust up from deep beneath the seafloor. Lost City microbes live off methane and hydrogen instead of hydrogen sulfide and carbon dioxide that are the key energy sources for life at black-smoker vents. Kelley believes that many more Lost City-type systems may exist and study of these systems may be key to understanding the origin of life.[8]

This limestone vent, known as the Nature Tower, rises 30 meters (98 feet) above the seafloor and harbors unique microbes that thrive without oxygen in warm, methane- and hydrogen-rich alkaline fluids. Image courtesy D. Kelley, University of Washington.

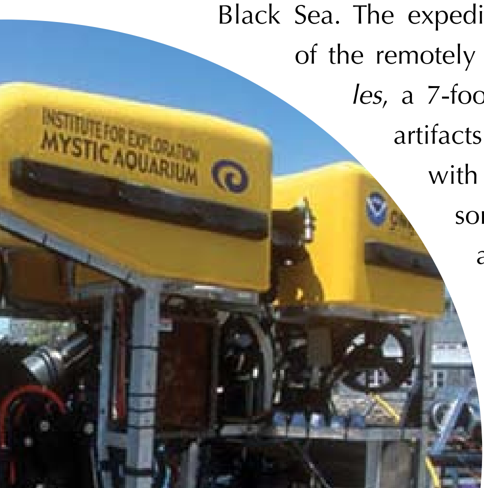
A blizzard of microbes witnessed at the East Pacific Rise advanced the hypothesis that a massive biosphere may exist beneath the ocean floor. Photo courtesy Woods Hole Oceanographic Institution.

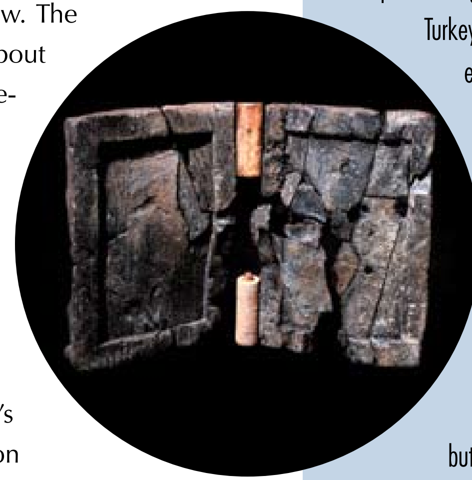
These discoveries led to the hypothesis that a massive, deep biosphere may exist beneath the ocean floor and overlying marine sediments that rivals the combined biomass in the entire ocean above the seafloor—or even on the planet. These microbes might have evolved when the Earth was much hotter, potentially providing new insights into the origins of life on Earth, as well as the possibility of life on other planets. Studies of how these life forms relate to energy from the Earth's mantle are being conducted within the NSF-sponsored RIDGE 2000 Program.

OCEAN EXPLORATION ANSWERS QUESTIONS ABOUT HUMANITY'S PAST.

In 1997, oceanographer Bob Ballard took an expedition to the Black Sea to search for the remains of ancient dwellings that might have been submerged there. Scholars agree that the Black Sea, once a freshwater lake, was flooded when rising sea levels, most likely from melting ice sheets, caused the Mediterranean to overflow. The flood was thought to have happened gradually about 9,000 years ago, but a 1997 report by marine geologists Walter Pitman and Bill Ryan at Lamont-Doherty Earth Observatory posited that the flood was sudden and took place about 7,150 years ago—a theory that could provide support for the biblical story of a great flood.[9]

Although the explorers found no evidence to indicate the loss of an ancient civilization, Ballard's team did find shells and other materials. Carbon dating of these materials supported the theory that a freshwater lake was inundated about 7,000 years ago. Ballard's team also made another serendipitous find: four ancient shipwrecks, one almost perfectly preserved because of low oxygen at the bottom of Black Sea. The expedition also saw the debut of the remotely operated vehicle *Hercules*, a 7-foot robot that can retrieve artifacts using high-tech pincers with pressure-regulated sensors that operate much like a human hand.[10]





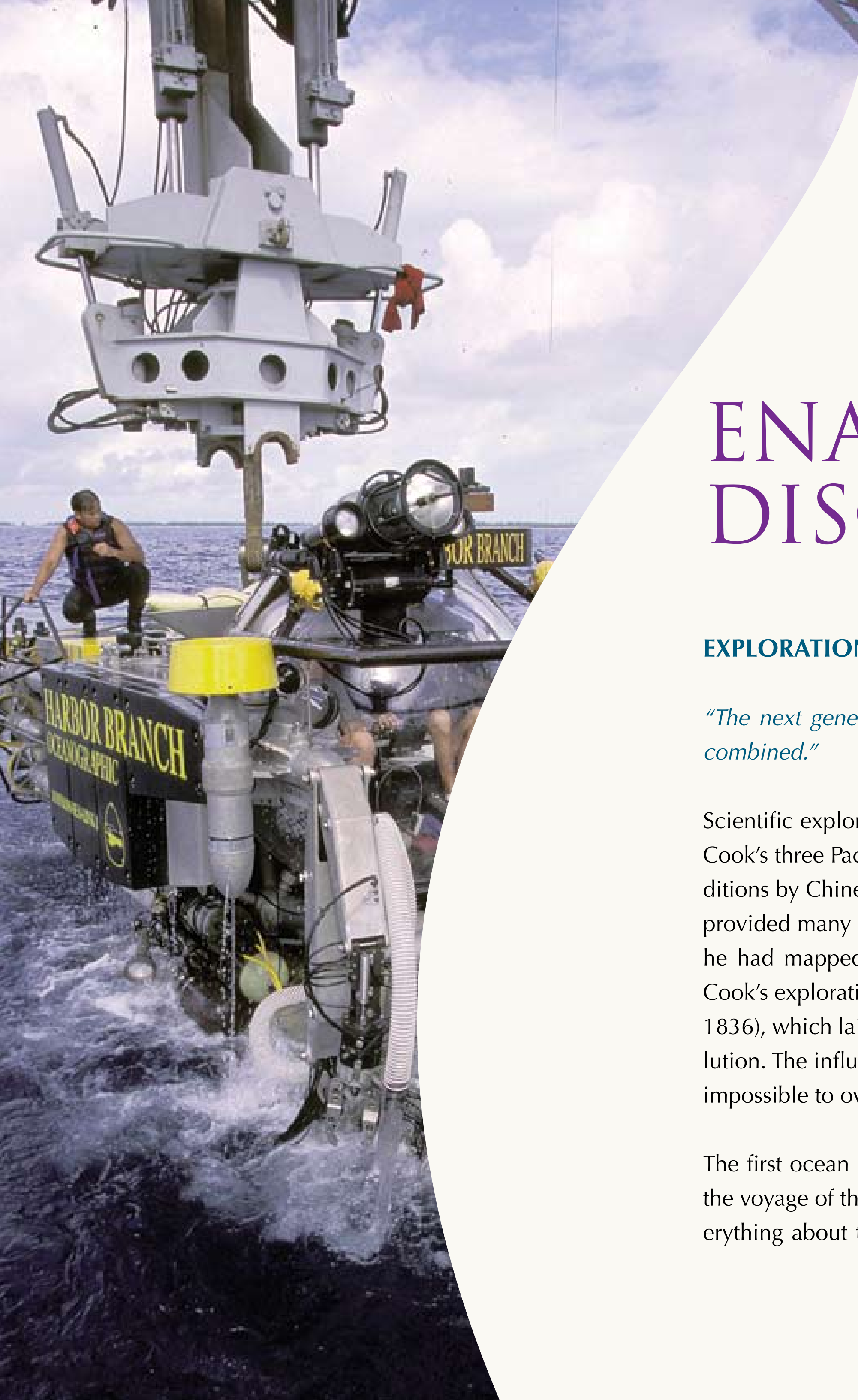
This early writing tablet, called a diptych, was recovered from an ancient shipwreck off the coast of Turkey. Photos (above and right) by the Institute of Nautical Archaeology.

HUMAN HISTORY REVEALED THROUGH NAUTICAL ARCHEOLOGY

Archeologist George F. Bass was the first person to excavate an ancient shipwreck in its entirety on the sea bed. Since 1960, Bass has excavated a number of shipwreck sites dating from the Bronze Age through the 11th century A.D. One of Bass's expeditions helped change the accepted history of the ancient Mediterranean.

Upon hearing news that a local diver had found metal artifacts off the coast of Turkey in 1982, Bass took a team of researchers to the site for a decade of expeditions. After more than 20,000 dives, the team uncovered what turned out to be the world's oldest known shipwreck and the largest collection of artifacts from a single site. More than 20 tons of metals, glass, ceramics, and fine wood were found, among which was found the oldest documented "diptych," an early writing tablet consisting of two wooden boards joined by an ivory hinge.

The crew dated the ship to the 14th century B.C. Previously, historians had attributed all sea exploration at the time to the Greeks, but clues from the wreckage indicated that the people aboard the ship may have been of Middle East origin. Based on these and other important discoveries, George Bass was awarded the National Medal of Science in 2001 for his pioneering work as "the father of nautical archeology." He founded the Institute of Nautical Archaeology in 1973.[11]



ENABLING DISCOVERY

EXPLORATION IS THE FIRST STEP IN SCIENTIFIC DISCOVERY.

"The next generation will explore more of Earth than all previous generations combined." **—Robert Ballard, University of Rhode Island**

Scientific exploration of the oceans can be traced back at least to Captain James Cook's three Pacific Ocean expeditions between 1768 and 1779, although expeditions by Chinese explorers starting with the Ming Dynasty in 1405 had already provided many navigational clues for later expeditions.[12] By the time Cook died, he had mapped much of the Pacific's shoreline from Antarctica to the Arctic. Cook's explorations set the stage for Darwin and his voyage on the *Beagle* (1831-1836), which laid the groundwork for Darwin's development of the theory of evolution. The influence of the discoveries associated with these early expeditions is impossible to overestimate in terms of both science and culture.

The first ocean expedition undertaken purely for the sake of ocean science was the voyage of the HMS *Challenger* (1872-1876), which set out to investigate "everything about the sea." With support from the British Admiralty and the Royal

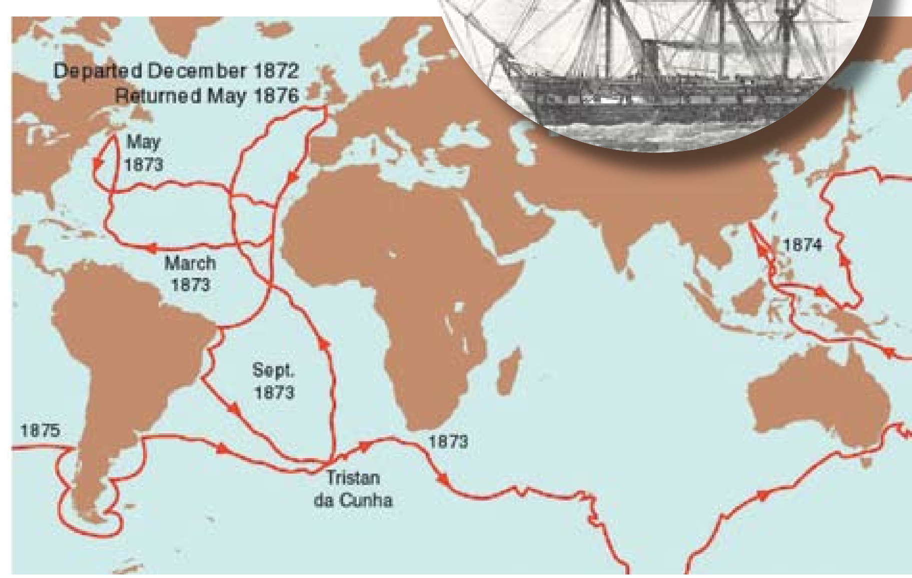
WHAT IS OCEAN EXPLORATION?

As defined by the President's Panel on Ocean Exploration (National Oceanic and Atmospheric Administration, 2000), ocean exploration is discovery through disciplined, diverse observations and recordings of findings. It includes rigorous, systematic observations and documentation of biological, chemical, physical, geological, and archeological aspects of the ocean in the three dimensions of space and in time.

Society, crew members made systematic measurements every 200 miles around the globe, traversing each ocean except the Arctic. Ocean depth was measured by lowering a sounding rope over the side; specimens were collected with nets and dredges. The results were staggering, filling 50 volumes and resulting in the identification of 4,417 new species. The *Challenger* also discovered that the ocean was not—as had been assumed at the time—deepest in the middle, giving the first hint of the existence of a global mid-ocean ridge system. The *Challenger* expedition also confirmed that life existed in the deepest parts of the ocean.

Exploration continues to evolve as a systematic endeavor. A recent example is the Census of Marine Life (CoML at http://www.coml.org)—a concerted 10-year effort involving thousands of scientists from more than 80 nations who are cataloging the diversity, distribution, and abundance of marine life in the world's oceans. Findings are collected in the Census database and will be issued in a final report in 2010. The Census has uncovered hundreds of previously unknown species—including 150 species of fish—and many new phenomena, such as a school of 20 million fish, roughly the size

Charles Darwin, voyaging on the *Beagle* in the 1830s, might have seen a Sally Lightfoot crab like this one on his visit to the Galápagos Islands. Photo courtesy Susan Roberts.



From 1872-1876, the HMS *Challenger* followed this expedition route to investigate "everything about the sea." Reprinted with permission of Brooks/Cole, a division of Thomson Learning. www.thomsonrights.com.

of Manhattan, swarming just off the coast of New Jersey. The Census is intended to help identify rare species and important breeding areas to aid in the pursuit of sustainable management of marine resources, among other goals.

Currently, a substantial portion of the limited resources for ocean research is spent revisiting established study sites to verify hypotheses and confirm earlier findings. For example, researchers return to hydrothermal vent sites due to their unique environmental conditions, biological diversity, and intriguing research questions. However, it is harder to secure funding to visit places yet unexplored—missions considered high-risk in terms of return on investment. Given the continued support for and successes of oceanographic research in the United States, a new program to fund exploration, as recommended in *Exploration of the Seas: Voyage into the Unknown*, could provide the resources needed to systematically survey the vast unknown regions of the ocean.

Research vessels: The basic platform for ocean research and exploration. Research vessels, or R/Vs, carry the scientists, equipment, and instrumentation from the shore to research sites in the coastal and deep ocean. Two of the newest R/Vs in the U.S. research fleet are the *Marcus G. Langseth* (top), owned by the National Science Foundation and operated by Lamont-Doherty Earth Observatory of Columbia University, and the *Kila Moana* (bottom), owned by the U.S. Navy and operated by the University of Hawaii. The *Marcus Langseth* is specialized to conduct geophysical research, such as imaging the ocean crust beneath the seafloor. The *Kila Moana* is a general purpose R/V with a unique "SWATH" hull (small waterplane area, twin hull) designed to provide a comfortable, stable platform in high sea conditions. Photos courtesy Columbia University and the University of Hawaii.

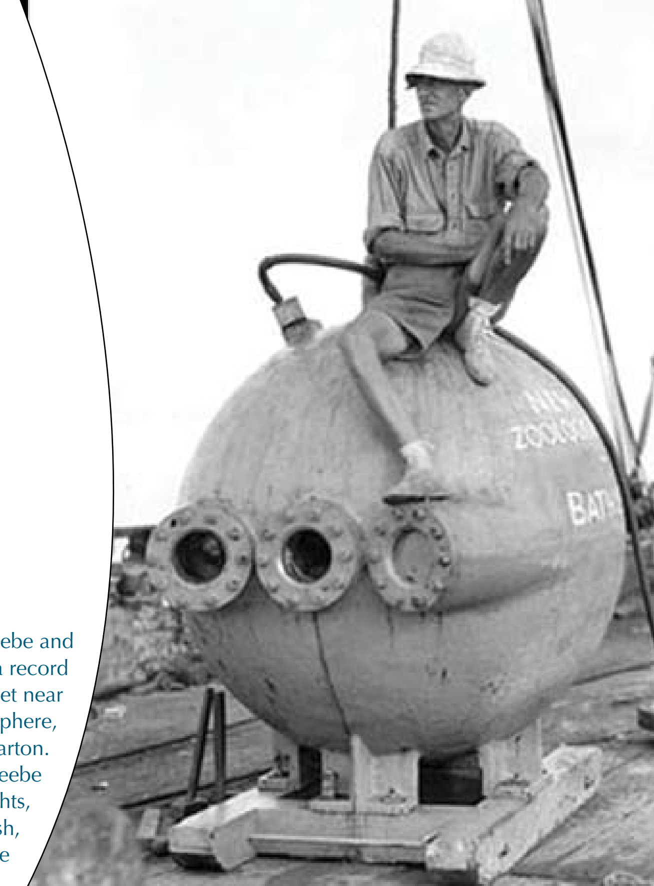
BEING THERE IS ESSENTIAL TO A TRUE UNDERSTANDING OF THE DEEP OCEAN.

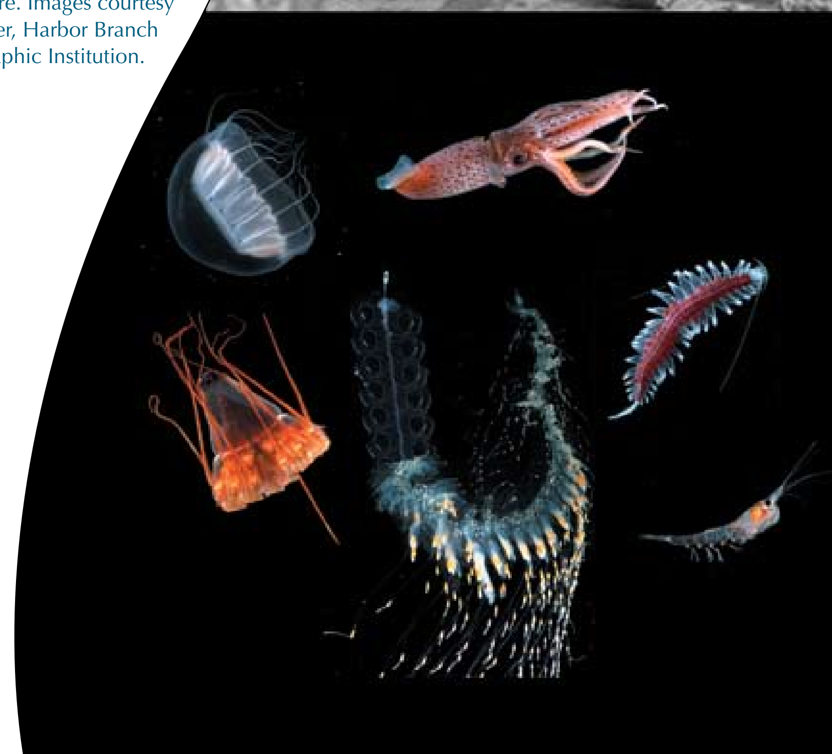
"This unattractive jello-like mass is the unfair land version of amazing and delicate creatures that can display their true beauty only in their natural watery environment."

—Lawrence Madin, Director of Research,
Woods Hole Oceanographic Institution

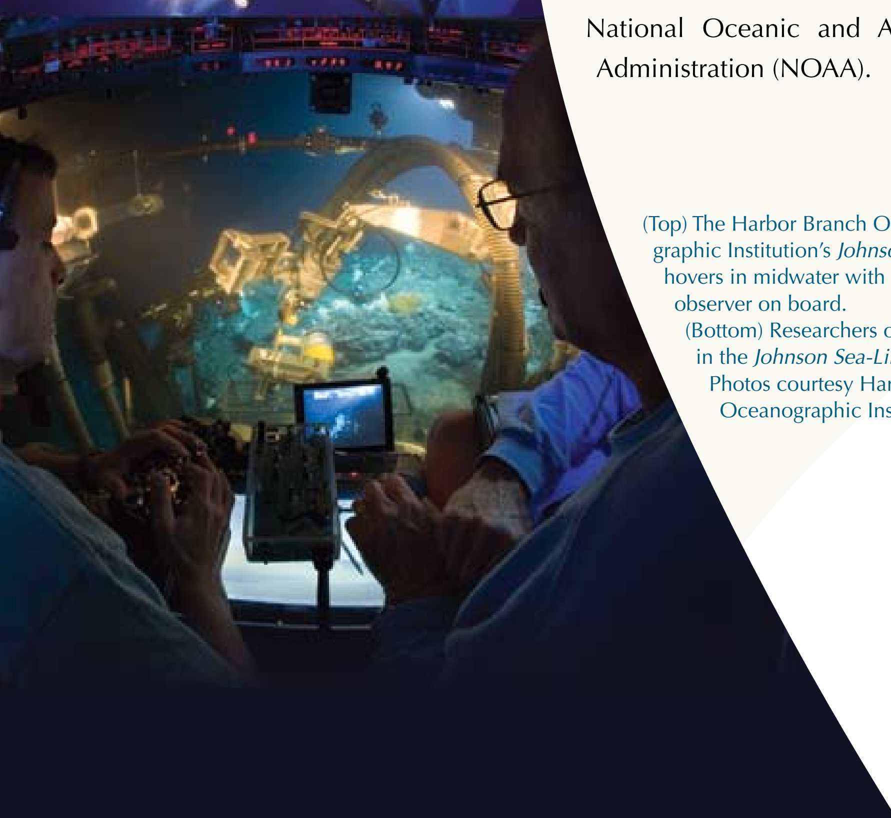
In 1934, William Beebe and Otis Barton crouched inside a 54-inch-diameter steel bathysphere and were lowered by cable to a record depth of 922 meters (3,025 feet) off the coast of Nonsuch Island, near Bermuda. With only two small windows and a 250-Watt light to illuminate the area directly outside the sphere, Beebe and Barton were able to view sea life that had never been seen before in the natural environment. The bathysphere had no propulsion capability and was raised and lowered by cable on the mother ship. It was reported that Beebe was so overcome with what he saw that he had difficulty describing it.[13]

Before researchers had the vehicles to transport them to the deep ocean, they relied on samples pulled to the surface by dredge or trawl—yielding sea creatures that were typically damaged, misshapen, and out of their element on dry land. Development of deep submergence vehicles by the U.S. Navy helped meet the scientific need to visit the deep ocean to systematically sample and obtain intact specimens, conduct experiments, and view animal behavior or habitat in real time.





In 1934, William Beebe and Otis Barton descended to a record depth of about 3,000 feet near Bermuda in this tethered bathysphere, which was devised in 1928 by Barton. Photo courtesy NOAA. Beebe described a world of "twinkling lights, silvery eels, throbbing jellyfish, and living strings," such as those shown here. Images courtesy E. Widder, Harbor Branch Oceanographic Institution.



Since World War II, more than 200 human-occupied vehicles, known as HOVs for short, have been built, although only a few of them are dedicated to scientific research. *Alvin* is the best-known HOV both in the United States and abroad. Built in 1964 with funding from the US Navy's Office of Naval Research, it is now operated as a research vessel by the Woods Hole Oceanographic Institution as part of the the National Deep Submergence Facility (NDSF) located in Woods Hole, Massachusetts. For about the past 20 years, the facility has been cooperatively funded by the National Science Foundation, the Office of Naval Research, and the National Oceanic and Atmospheric Administration (NOAA).

(Top) The Harbor Branch Oceanographic Institution's *Johnson Sea-Link* hovers in midwater with a pilot and observer on board. (Bottom) Researchers on a dive in the *Johnson Sea-Link*. Photos courtesy Harbor Branch Oceanographic Institution.

Just as the space shuttle is built to withstand the near total vacuum of outer space, *Alvin* is built to withstand the crushing pressure of the deep ocean. Its titanium hull can remain submerged for 10 hours under normal conditions, but its life support systems allow occupants to remain underwater for 72 hours if necessary. *Alvin* can dive to a depth of 4,500 meters (2.8 miles).

Two other U.S. academic and research organizations operate human-occupied submersibles: the University of Hawaii has two *Pisces* submersibles capable of diving to 2,000 meters (1.2 miles), and Harbor Branch Oceanographic Institution in Florida has two *Johnson Sea-Link* submersibles that can dive to approximately 1,000 meters (0.6 miles). France and Russia operate HOVs that can dive to a depth of 6,000 meters (3.7 miles), and Japan's *Shinkai* 6500 is able to dive down 6,500 meters (4.0 miles). China is building an HOV that will be able to dive to 7,000 meters (4.3 miles).

UNOCCUPIED VEHICLES GREATLY ENHANCE OCEAN EXPLORATION CAPABILITIES.

Descending beneath the surface to explore the ocean's depths provides unique opportunities for observation, but new technologies have made it possible to virtually see and study much more of the ocean than would be possible with just HOVs. Scientists and engineers continue to develop and improve unoccupied vehicles that can be remotely operated from ship or shore to increase access and enhance capabilities of ocean researchers. In the 1960s, towed instruments were first developed for underwater photography, acoustical mapping, and measurement of water temperature, magnetic field strength, and other properties. The first success was *Deep Tow*, developed in 1960 by Fred Spiess and his colleagues at Scripps for mapping the deep seafloor.

Towed vehicles were succeeded by unoccupied, remotely operated vehicles (ROVs), which were introduced in the 1980s and rapidly advanced in the 1990s. ROVs are controlled by a pilot on a surface ship and tethered by a fiber-optic cable. The cable transmits real-time data to the scientists and engineers on board the ship, and the pilot can use dexterous manipulator arms

The Woods Hole Oceanographic Institution's remotely operated vehicle *Jason II* is lowered into the water. Photo courtesy Woods Hole Oceanographic Institution.

The many faces of *Alvin*. The *Alvin*, which is operated by the Woods Hole Oceanographic Institution, Massachusetts, is the best known deep-diving vehicle in the world. *Alvin* has one pilot and routinely carries two scientific observers—the only deep-diving submersible that can do this—and dives as deep as 4,500 meters (2.8 miles). It is fitted with two manipulator arms and four externally mounted video cameras. Photo courtesy Woods Hole Oceanographic Institution.

(Left) The Woods Hole AUV known as *ABE* (*Autonomous Benthic Explorer*) can dive to depths of 5,000 meters (16,500 feet) for 16 to 34 hours and is equipped with innovative robotics and sensors to accomplish a variety of missions. (Right) The AUV *Xanthos*, which was designed by the Massachusetts Institute of Technology, can dive to 3,000 meters (1.86 miles). Photos courtesy Massachusetts Institute of Technology Sea Grant.

to collect samples. Because the cable provides power to the vehicle, ROVs can remain on the bottom longer than HOVs. The National Deep Submergence Facility operates the *Jason II-Medea* ROV system; many more ROVs are owned and operated by other institutions around the world (see Table 1).

ROVs are a good match for detailed experiments and observatory work at sites of interest on the seafloor. Special tool sleds equip ROVs with the specific sampling and observing gear needed for each mission. These tool sleds can be changed aboard ship within hours to reconfigure a vehicle for another type of mission.

Complementing the work of ROVs and HOVs is the autonomous underwater vehicle, or AUV. These unoccupied, untethered vehicles are sent on preprogrammed missions that can cover much more ground than ROVs in the same amount of time. The Woods Hole AUV *ABE* (*Autonomous Benthic Explorer*) has been used to survey the seafloor by night; when it surfaces at dawn, it delivers high-precision maps that scientists can use during daytime to guide their explorations in *Alvin*.

New types of autonomous robotic vehicles are being developed that can journey across hundreds of miles of ocean, gathering data along the way. One such vehicle, the glider, is a type of AUV with wings that can propel it-

With a body 1.8 meters (~6 feet) long, the University of Washington's pink Seaglider weighs 52 kilograms (~114 pounds) in air and has a low-drag shape enabling it to slip efficiently through the ocean. Seagliders have carried out missions lasting as long as seven months on a single set of batteries to profile temperature, salinity, dissolved oxygen, and bio-optical properties in the upper layer of the ocean. Photo courtesy Charlie Eriksen, University of Washington.

Deep-Sea ROVs Used for Scientific Purposes

ROV	Operator	Maximum Operating Depth (m)
UROV7K	JAMSTEC, Japan	7,000
Jason II-Medea	WHOI, United States	6,500
Victor 6000	IFREMER	7,000
ISIS	Southampton Oceanography Centre, U.K.	6,500
Kiel 6000	Leibniz Institute of Marine Sciences, Germany	6,000
LUSO	Portuguese Task Group for the Extension of the Continental shelf (EMEPC)	6,000
Ropos	Canadian Scientific Submersible Facility, Sidney, B.C., Canada	5,000
QUEST	Center for Marine Environmental Studies (MARUM), Germany	4,500
Tiburon	Monterey Bay Aquarium Research Institute (MBARI), United States	4,000
Hyper Dolphin HYSUB 75-3000	JAMSTEC, Japan	3,000

self through the water column, both horizontally and vertically. Gliders can be programmed to go to particular places both when they are launched and during their mission, via satellite, when they surface to transmit data. Equipped with diverse sensors, gliders can measure ocean currents, salinity, temperature, phytoplankton concentrations, and chemical changes. Gliders could very soon measure the properties of the ocean on a near constant basis, whereas 20 years ago, such measurements could be made only during infrequent research cruises.

GETTING UNDER THE ARCTIC ICE

The Arctic Ocean is the world's most isolated ocean—cut off from the deep waters of the rest of the world's oceans by geologic changes almost 65 million years ago. Interest in the Arctic Ocean's hydrothermal vent activity has stimulated many expeditions. In 2007, a 30-member research team based at WHOI, with funding and support from the National Science Foundation, began exploring the Gakkel Ridge, located between Greenland and Siberia. The team used three new vehicles specifically designed for the Arctic ice—two AUVs, the *Puma* and *Jaguar*, and a tethered, remote-controlled sampling system called the CAMPER. NASA partially funded the project, because the findings and methodologies may be applicable to future space missions, such as the exploration of Europa, a moon of Jupiter, where liquid water lies beneath the icy surface. This Arctic venture is one of many projects involved in the International Polar Year (IPY), a multinational effort begun in February 2007 to explore the polar region that is described in the National Research Council report, *A Vision for the International Polar Year* (2004).

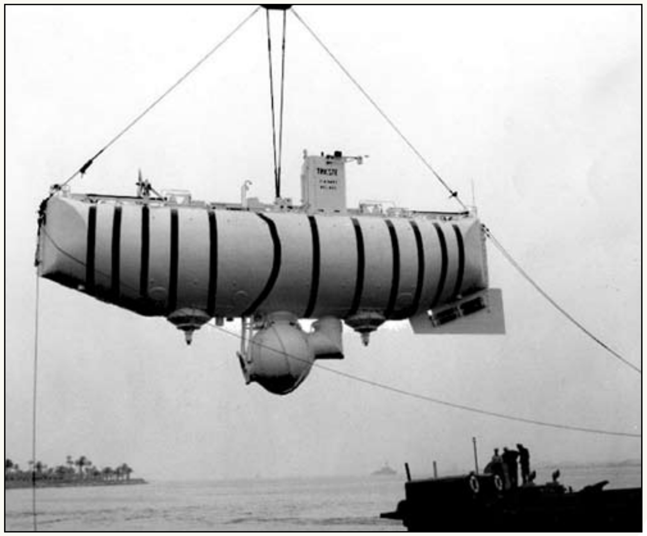
The AUV *Jaguar* being lowered into the ocean (below) and recovered (left). Photos courtesy Woods Hole Oceanographic Institution.

SUPPORT FOR RESEARCH IS INSUFFICIENT TO REALIZE THE SCIENTIFIC POTENTIAL OF DEEP-DIVING VEHICLES.

"The bottom of the ocean is Earth's least explored frontier, and currently available submersibles—whether manned, remotely operated, or autonomous—cannot reach the deepest parts of the sea."

—Shirley A. Pomponi, president and CEO of Harbor Branch Oceanographic Institution, Fort Pierce, Florida.

Although a dozen men have walked on the moon, just two have traveled to the farthest reaches of the ocean, but only for about 20 minutes—and it happened back in 1960. Lt. Don Walsh and Jacques Piccard descended in the *Trieste*, the deepest-diving HOV ever built. *Trieste* settled into the deepest part of the ocean, the bottom of Challenger Deep in the Mariana Trench off the coast of Guam at 10,915 meters (6.7 miles) below the surface. This remarkable HOV, purchased by the U.S. Navy in 1957, dove under her own power with forward control from a propeller and rudder. The *Trieste* was designed to descend only to a depth of 6,300 meters, but the Navy refitted her with a stronger sphere to withstand the water pressure at the bottom of the trench, which is more than 1,000 times the atmospheric pressure at sea level. Only one other vehicle to date has made it to the bottom of the Mariana Trench—Japan's ROV *Kaiko*, in 1995. Unfortunately, the *Kaiko* was lost in a typhoon in May 2003.



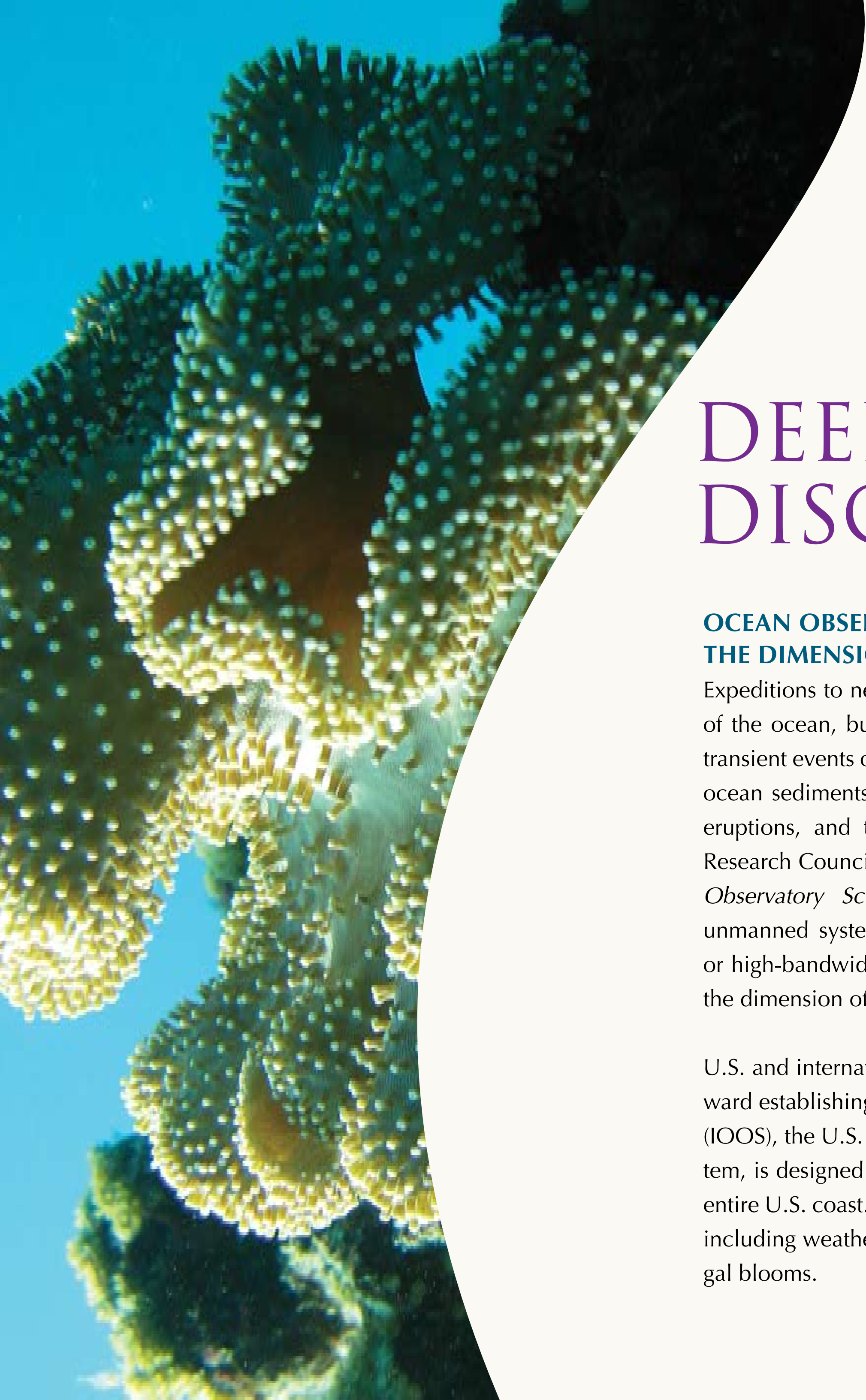
Trieste is one of two vehicles, and the only occupied vehicle, to make it to the deepest part of the ocean—the bottom of the Mariana Trench off the coast of Guam, 10,915 meters (6.7 miles) deep. The ship was originally built to dive to 6,300 meters, but after purchasing her in 1957, the Navy refitted her to withstand the 16,000 pounds (about 1,000 atmospheres) of pressure at the bottom of the trench. Photo courtesy U.S. Navy.

Scientists and engineers are now testing innovative hybrid vehicles to revisit these astounding depths. These vehicles can operate as both an AUV and ROV, thus bringing the advantages of both types of vehicles to the same expedition.[14] *Nereus*, being developed by engineers at Woods Hole, is one such vehicle; it can be converted during an expedition from an AUV that identifies the most promising sites for exploration into an ROV that can explore those sites in detail. *Nereus* will be able to dive down to depths of 11,000 meters (slightly deeper than the *Trieste*) and swim freely. It operates under intense pressures, icy temperatures, and complete darkness, and it is completely battery operated. The *Nereus* will be used for a variety of purposes, from taking samples of rock and fluids from the seafloor to surveying life forms that exist in the vast unknown expanses of the deep sea.

Although *Nereus* and other high-tech AUVs and ROVs are expanding scientists' reach into the deepest trenches of the world ocean, these tools do not yet emulate the way a scientist can perceive the seafloor from within a manned submersible. There is still high demand for HOV access. *Exploration of the Seas* called for a fleet of new manned submersibles capable of diving to at least 6,500 meters (21,325 feet). Since these reports were published, the National Science Foundation has funded a proposal to build a replacement for *Alvin*, with an expected completion date of 2011. If the new vehicle ultimately meets its goal of 6,500 meters, it will reach close to 99 percent of the of the global ocean seafloor. Ascent and descent speeds will also be improved to maximize the "bottom time" available per dive.

The National Research Council report *Future Needs in Deep Submergence Science* (2004) concludes that the scientific demand for deep-diving vehicles (both HOV and ROV/AUV) is not being met, primarily due to lack of operational funding support. Without operational support, the best-array vehicles, sensors, and other tools will remain grounded. The report recommends improvements in funding for and access to deep-diving vehicles.

Nereus, being developed by engineers at Woods Hole Oceanographic Institution, can serve as both an AUV and an ROV and will be able to dive to a depth of 11,000 meters. Photo courtesy Woods Hole Oceanographic Institution.



DEEPENING DISCOVERY

OCEAN OBSERVATORIES ENABLE EXPLORATION THROUGH THE DIMENSION OF TIME.

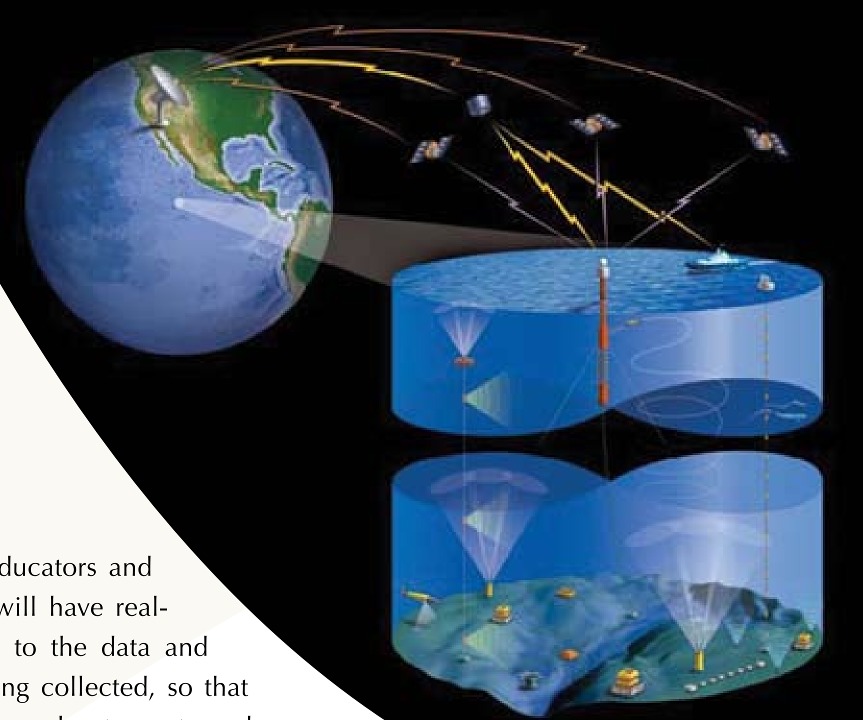
Expeditions to new areas for short periods can provide "snapshots" of the state of the ocean, but a revolution in technology is needed to observe change or transient events over time, such as the development of algal blooms, transport of ocean sediments, the generation of tsunamis, changes in fish stocks, volcanic eruptions, and the effects of climate change on ecosystems. The National Research Council report *Illuminating the Hidden Planet: The Future of Seafloor Observatory Science* (2000) concludes that ocean floor observatories—unmanned systems of instruments that collect and transmit data via satellite or high-bandwidth telecommunications networks—enable exploration through the dimension of time.

U.S. and international efforts have made significant progress in recent years toward establishing ocean observatories. The Integrated Ocean Observing System (IOOS), the U.S. contribution to the international Global Ocean Observing System, is designed as a large network that collects high-resolution data along the entire U.S. coast. This information supports a wide range of operational services, including weather forecasts, coastal warning systems, and the monitoring of algal blooms.

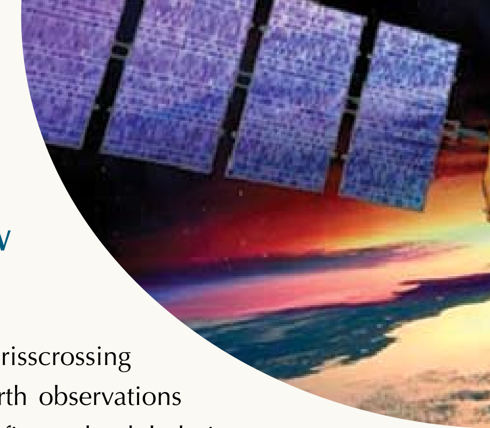
The Ocean Observatories Initiative (OOI), a National Science Foundation program, will enable land-based exploration and monitoring of processes throughout the seafloor, water column, and overlying atmosphere by real-time, remote interactions with arrays of sensors, instruments, and autonomous vehicles. For the first time, scientists, educators and the public will have real-time access to the data and imagery being collected, so that they can learn about events such as underwater volcanic eruptions and anoxia events as they happen, even if there are no ships in the area.

The world's first underwater cabled observatory to span an entire plate will be installed as part of a collaborative effort between the U.S. Ocean Observatories Initiative (OOI) and U.S. and Canadian institutions. Fiberoptic cables will extend high bandwidth and power to a network of hundreds of sensors across, above, and below the seafloor, allowing in situ, interactive monitoring of the ocean and seafloor for the next 20 to 30 years. Image courtesy University of Washington Center for Environmental Visualization.

The National Research Council report *Enabling Ocean Research in the 21st Century* (2003) concludes that research in the Ocean Observatories Initiative should be closely linked to the operational activities of the Integrated Ocean Observing System. The report recommends coordination in the areas of developing infrastructure, instrumentation, protocols for use of ships and undersea vehicles, and data integration and management. Today, this collaboration is supported by the Interagency Working Group for Ocean Observations.



Ocean observatories are unmanned systems of instruments, sensors, and command modules that are connected either to a surface buoy or to fiber optic cables that provide research scientists continuous interaction with the ocean environment. Image courtesy University of Washington.

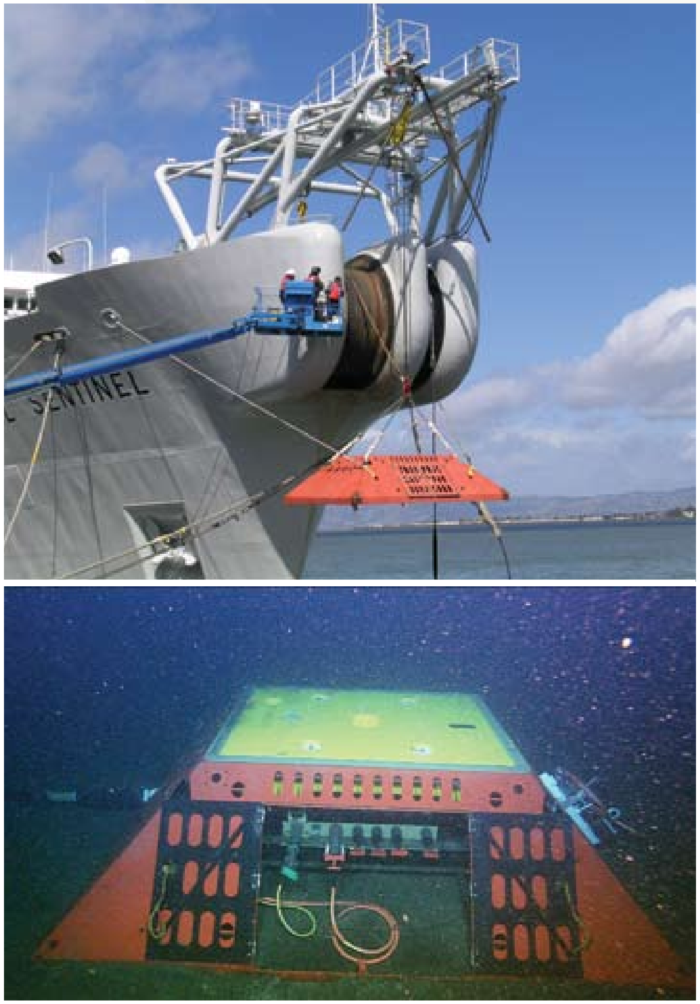


OBSERVATIONS FROM SATELLITES REVEAL NEW INSIGHTS INTO THE OCEAN.

Although ships have been crisscrossing the ocean for centuries, Earth observations from satellites provided the first truly global view of the ocean and its processes. Since the earliest satellites were launched more than 50 years ago, they have revolutionized ocean exploration. Satellites provided the first uniform view of seafloor topography, and, by the 1990s, global positioning system satellites had dramatically improved navigation for submersibles. Even through 4,000 meters of water, deep submergence vehicles can be precisely located within meters, enabling repeated visits to small, isolated sites.

Recent improvements in satellite communications on ships are fundamentally changing the nature of sea-going science. Many oceanographic ships now have Internet connections through a network known as HiSeasNet. With this network, shipboard scientists can work in real-time with their land-based colleagues. In preparation for the OOI, in 2005, the University of Washington used a Galaxy XR10 satellite connected to the research vessel *Thompson* and the ROV *Jason* to send, for the first time, real-time high-definition video of an active hydrothermal vent field off Vancouver to viewers throughout the United States, Europe, and Asia.

Satellite data are also vital to understanding ocean processes. For example, although ship-based expeditions



In 2007, this massive steel pyramid was placed on the seafloor at a depth of 900 meters off Monterey Canyon in California to house and protect the electronic heart of the Monterey Accelerated Research System (MARS) deep-sea ocean observatory. The MARS observatory is a testbed for future components of the Ocean Observatories Initiative. Photos courtesy Monterey Bay Aquarium Research Institute.

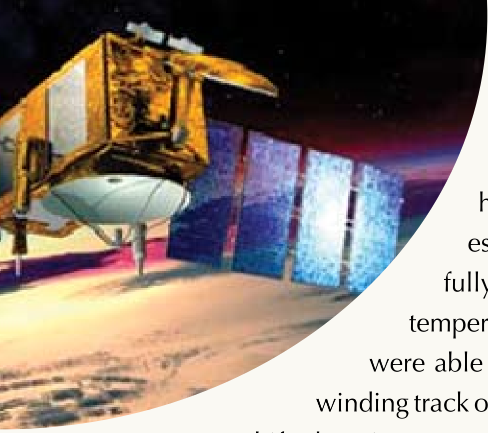


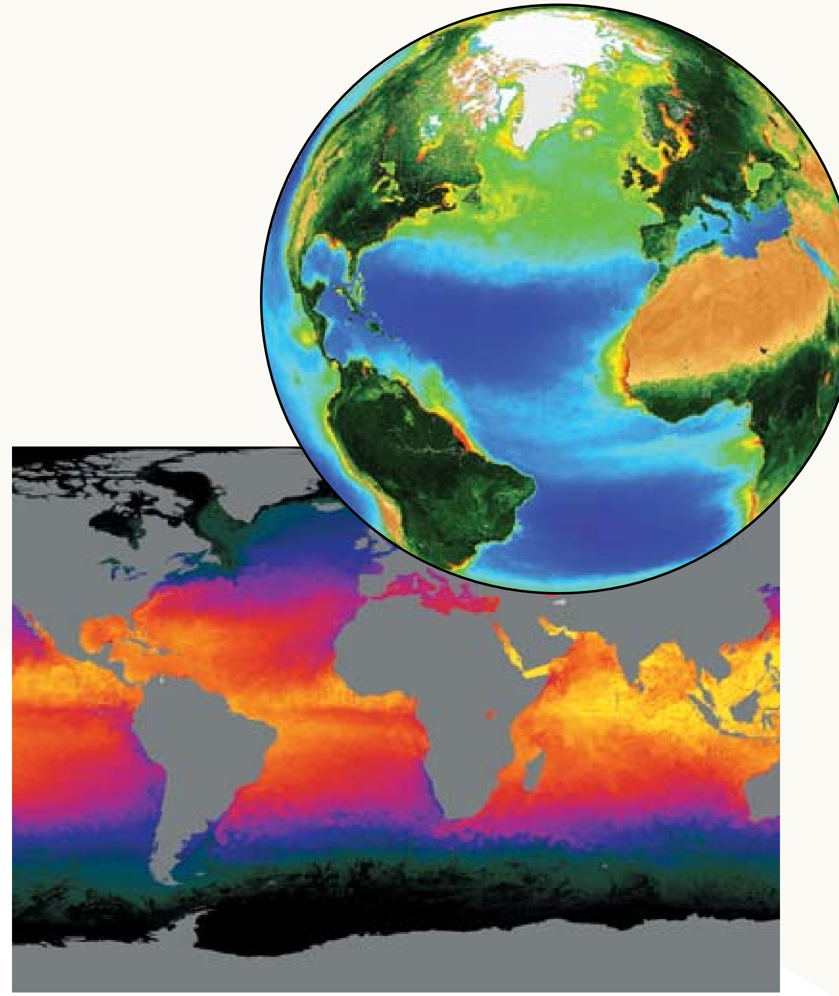
Image courtesy NASA.

had advanced some hypotheses, the Gulf Stream was not fully understood until sea surface temperature readings from satellites were able to clearly show the complex, winding track of the warm Gulf current, which shifts location over time. These measurements of sea surface temperature were made by Advanced Very High Resolution Radiometer that began in 1978 with the launch of the satellite TIROS-N. These temperature data have been used to address a broad range of oceanographic research questions, including studies of climate change and regional climate variability, and the dramatic sea surface warming associated with El Niño.

The ability to derive global maps of chlorophyll concentration in the upper ocean from satellite sensors such as SeaWiFS has been another groundbreaking achievement for the oceanographic community. Chrorophyll measurements are used to estimate the biomass of phytoplankton, which is an indicator of the biological productivity in various water masses around the globe. These images can be used to guide ship-based research related to harmful algal blooms, climate change, fisheries management, and other topics.

DATA MANAGEMENT IS VITAL TO SCIENTIFIC DISCOVERY.

New oceanographic sensor systems could potentially collect more data in one hour than the ocean exploration vessel *Challenger* collected in one year. But effective management of data—including making sure that



(Top) NASA's SeaStar spacecraft, launched in 1997, carries an instrument called the Sea-viewing Wide Field of View Sensor or "SeaWiFS." SeaWiFS takes ocean color measurements that can be used to calculate chlorophyll concentrations, which can help identify harmful algal blooms. (Bottom). NASA's Terra and Aqua satellites carry instruments known as MODIS (moderate resolution imaging spectroradiometer), which capture detailed measurements of sea surface temperature that are vital to climate- and weather-related research. Images courtesy NASA.

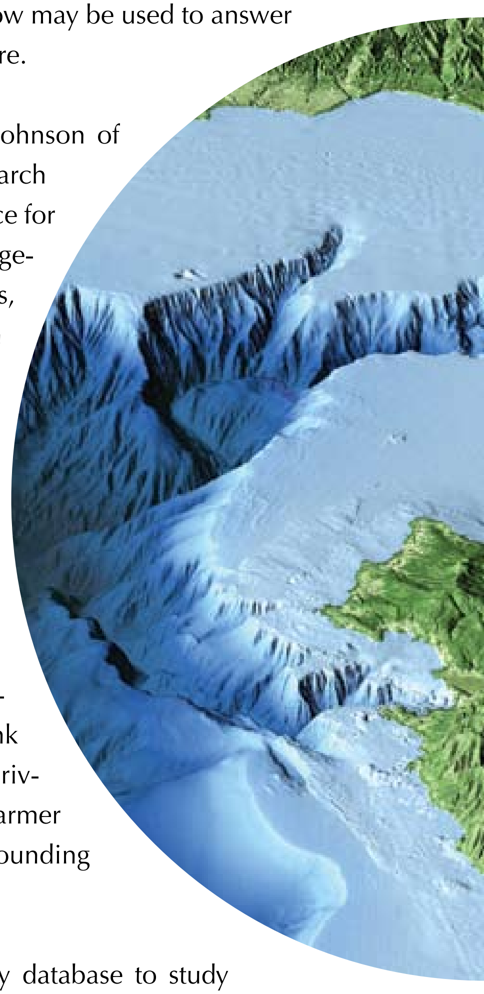
STUDYING THE SAME PLACES IN NEW WAYS USING "METAGENOMICS"

Researchers are now looking at the ocean through a new lens: the science of "metagenomics." In the ocean, as on land, thousands of species of tiny microbes play a key role in nutrient cycles, including the carbon cycle, and in maintaining Earth's atmosphere, among other important functions. Metagenomics enables researchers to quickly sequence the DNA of all microbes in a given sample, in this case seawater, revealing how microbes function and how they may work in different environments.

Working off the coast of Hawaii, Ed DeLong, of the Massachusetts Institute of Technology, and his team have been collecting marine microbes at various depths. After mapping 64 million base pairs (units of DNA), the team discovered thousands of new genes and also variations in the genetic composition of microbes at different depths. For example, microbes near the ocean surface had more genes devoted to taking in iron, an element necessary for growth in that zone. Genomes from organisms in the deep ocean had many "jumping genes," or pieces of DNA that can move from one part of the genome to another.

The National Research Council report *The New Science of Metagenomics* (2006) calls for more metagenomic research, not only in the ocean but in all environments on Earth.

data formats are compatible and that data are archived and retrievable—is a continuing challenge. Data management is important for many reasons, not the least of which is that data collected now may be used to answer questions that arise in the future.



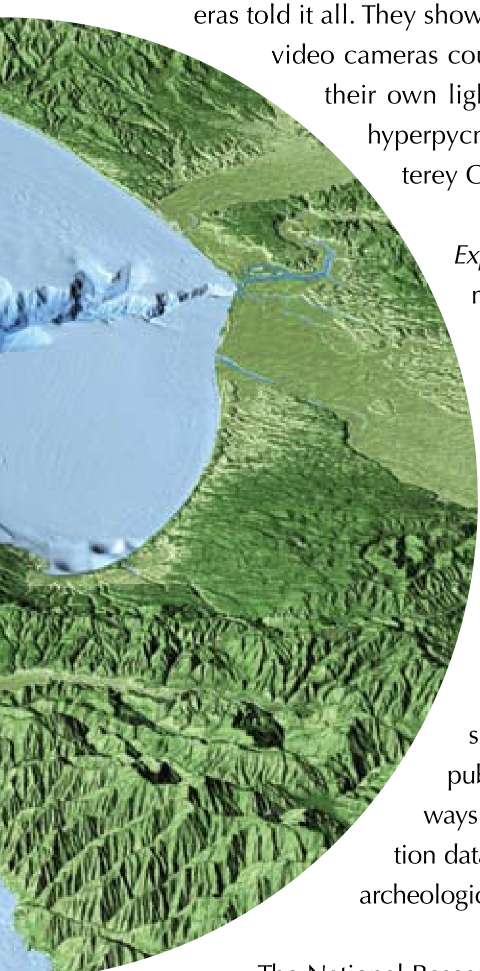
For example, scientist Ken Johnson of Monteray Bay Aquarium Research Institute set out to find evidence for one of the oldest questions in geology: how marine canyons, such as the one at the mouth of the Salinas River in Monterey Bay, are formed. In 1933, Francis Shephard of the Scripps Institution of Oceanography hypothesized that canyons are formed by infrequent but high-energy "hyperpycnal" river flows so thick with suspended sediment that they sink and scour the seafloor at the river's mouth despite being warmer and fresher than the surrounding ocean water.

Johnson used a Monterey Bay database to study 10 years of recorded ROV dives in Monterey Bay. The database stores information on the date, time and location of all dives, ocean conditions at the time of the dive, and video frames of any significant observations.

Johnson scanned the database for an example of a dive that occurred as the Salinas River reached flood stage, and he found one from March 1995. The video cameras told it all. They showed a mudflow so thick that the video cameras could not detect the energy from their own lights. Johnson had discovered a hyperpycnal flow actively eroding Monterey Canyon.[15]

Exploration of the Seas recommends that data access and management policies be established before a national ocean exploration program begins. In particular, the 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 program should seek ways to contribute to or link exploration data to existing oceanographic and archeological data archives.

The National Research Council report *Earth Observations from Space* identifies resources needed to sustain



By combing through videos of exploratory dives, researchers discovered that underwater canyons, as shown in this image of Monterey Canyon, are cut when floodwaters from the Salinas River that are thick with sediments sink rapidly and erode the bottom of the ocean. Image courtesy Monterey Bay Aquarium Research Institute.

SEA WORMS IN METHANE HYDRATES

A few decades ago, a potential new source of fuel called methane hydrate was discovered in the ocean. Produced when water and methane mix under low temperatures and in deep water under high pressures, methane hydrates look like ice but will burn if ignited. By some estimates, the energy locked up in methane hydrate deposits could be more than twice the global reserves of all conventional gas, oil, and coal deposits combined. However, no one has yet figured out how to mine the gas inexpensively and safely.

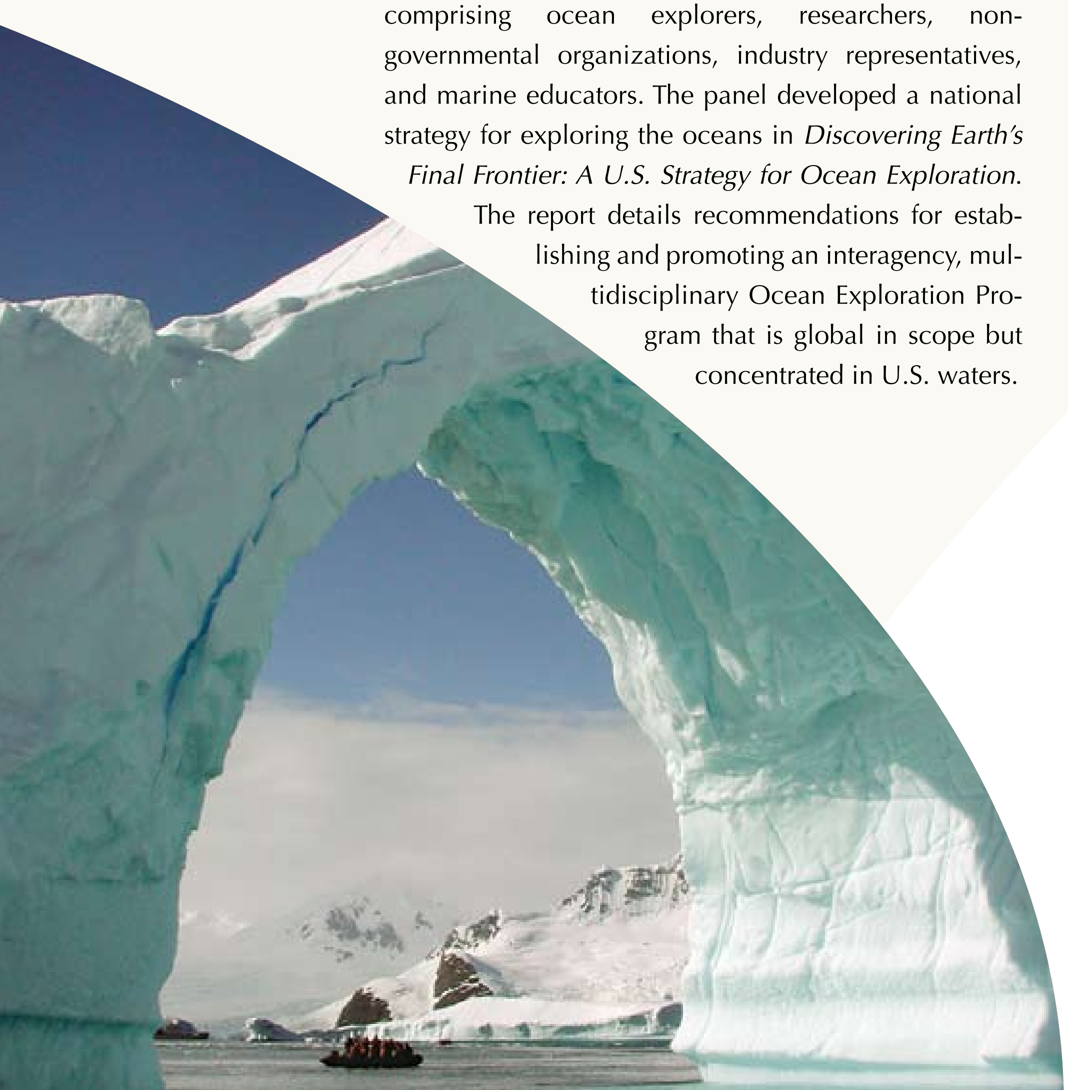
Scientists had hypothesized that bacteria might live in methane ice mounds, but in 1998 a surprising discovery was made. On a dive in the Harbor Branch Oceanographic Institute's *Johnson Sea-Link* in the Gulf of Mexico, pilot Phil Santos and Pennsylvania State University scientist Chuck Fisher came upon dense colonies of 1- to 2-inch-long, flat, pinkish worms that were living in the methane ice mounds. Researchers think that the worms may be living off bacteria that grow on the methane using energy from chemical reactions to produce organic compounds for food, rather than using sunlight (chemosynthesis). Study of the worms may shed light on the chemistry of methane hydrates that would be useful in the quest to extract, store, and use it as an energy source.

Photo courtesy Harbor Branch Oceanographic Institution.

the momentum in satellite observations. The report recommended funding for training the necessary workforce, developing more accurate instruments, and expanding the infrastructure to make the best use of satellite data.

TO BE OF MOST USE, EXPLORATION EFFORTS MUST BE COORDINATED AND SUSTAINED.

In June 2000, the President directed the Secretary of Commerce to convene an Ocean Exploration Panel, comprising ocean explorers, researchers, non-governmental organizations, industry representatives, and marine educators. The panel developed a national strategy for exploring the oceans in *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration.* The report details recommendations for establishing and promoting an interagency, multidisciplinary Ocean Exploration Program that is global in scope but concentrated in U.S. waters.



A sustained international exploration effort is not unprecedented. The International Decade of Ocean Exploration (1971-1980) is the most significant modern precursor, with 28 countries cosponsoring multidisciplinary research motivated in part by concern for the health of the world ocean and anticipated uses of marine resources, as well as scientific curiosity. The program is considered a great success; it enabled the discovery of the hydrothermal vent systems and provided data on the physics, geochemistry, biology, and geophysics of the ocean that fueled hypothesis-driven research for decades.

Following the publication of the Ocean Exploration Panel's report and the National Research Council's *Exploration of the Seas,* the National Oceanic and Atmospheric Administration (NOAA) took the lead in creating a new ocean exploration effort. To date, NOAA has conducted several multidisciplinary research missions sometimes with collaborative funding from the National Science Foundation. In 2008, NOAA launched the *Okeanos Explorer,* a ship dedicated to discovery expeditions. The ship is wired to send live images and data from the ocean via broadband satellite to scientists standing watch in any of five Exploration Command Centers, where those scientists can lend their expertise to the expedition from ashore.

Exploration of the Seas concludes that the sweeping goals of an exploration program can be met only if specific ocean regions or problems are tackled. The report

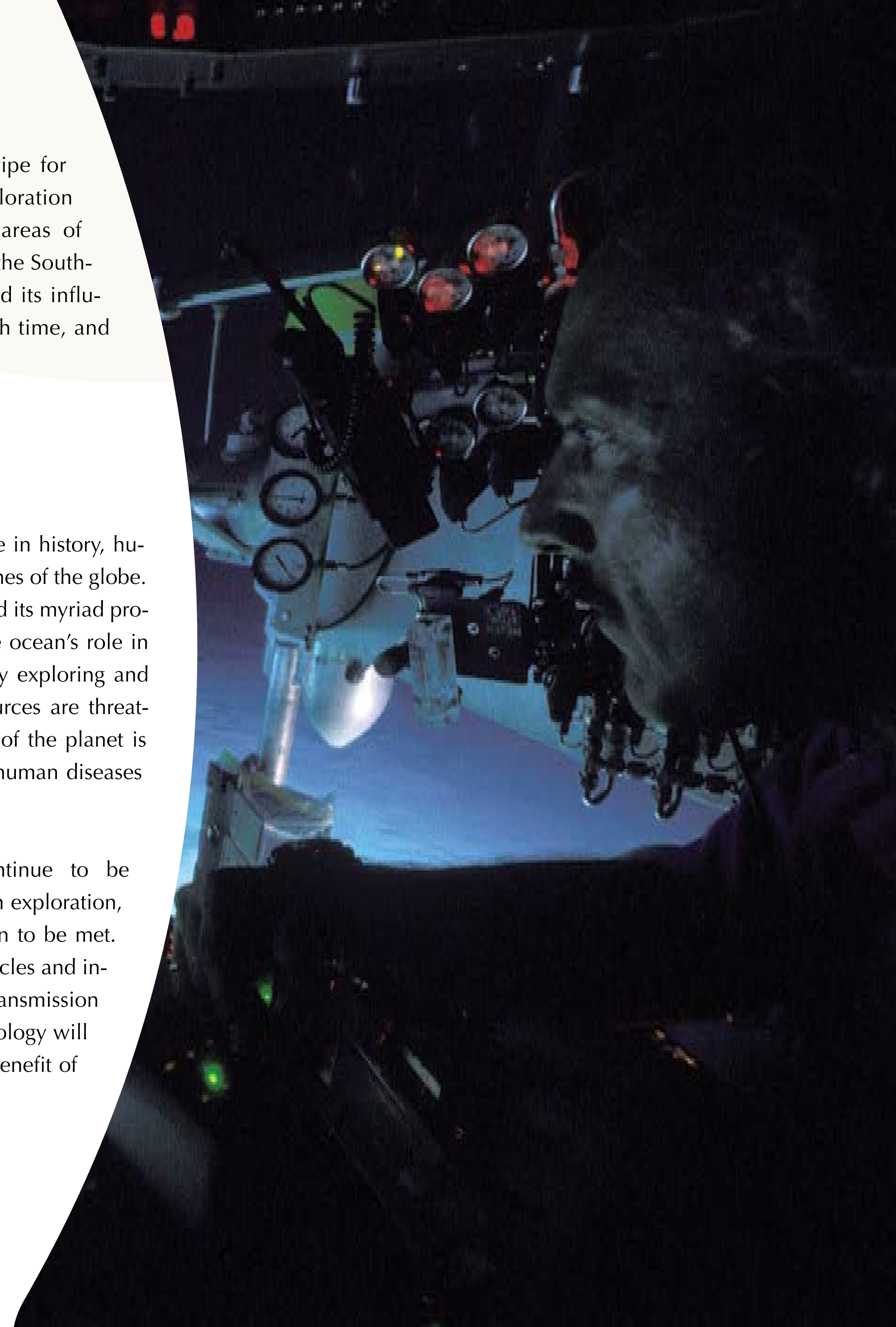
Image courtesy Woods Hole Oceanographic Institution.

recommends finding the "holes in the sea," areas ripe for discovery where there has been little systematic exploration to date. Suggested programmatic and geographic areas of study include 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 archeology.

CONCLUSION

Ocean exploration is at a crossroads. For the first time in history, human impacts on the environment are affecting all reaches of the globe. Despite our realization of how important the ocean and its myriad processes are to understanding coastal processes and the ocean's role in climate change, there remain great challenges to fully exploring and understanding the ocean. Meanwhile, its living resources are threatened by habitat loss and overharvesting, the climate of the planet is changing, and the need for new compounds to cure human diseases and new energy sources is growing.

Cutting-edge technologies and methodologies continue to be developed by the men and women dedicated to ocean exploration, but the potential of ocean exploration has only begun to be met. Those who invest now in state-of-the-art undersea vehicles and infrastructure, in data management and modeling, in transmission networks, and in the tools of modern marine biotechnology will likely produce discoveries and breakthroughs to the benefit of humankind and all life on this watery planet we share.



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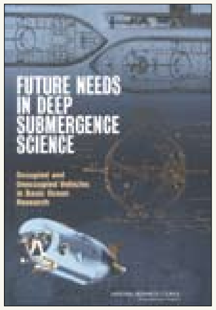

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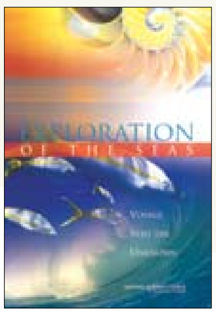

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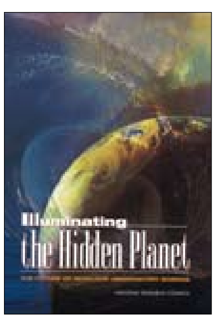

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