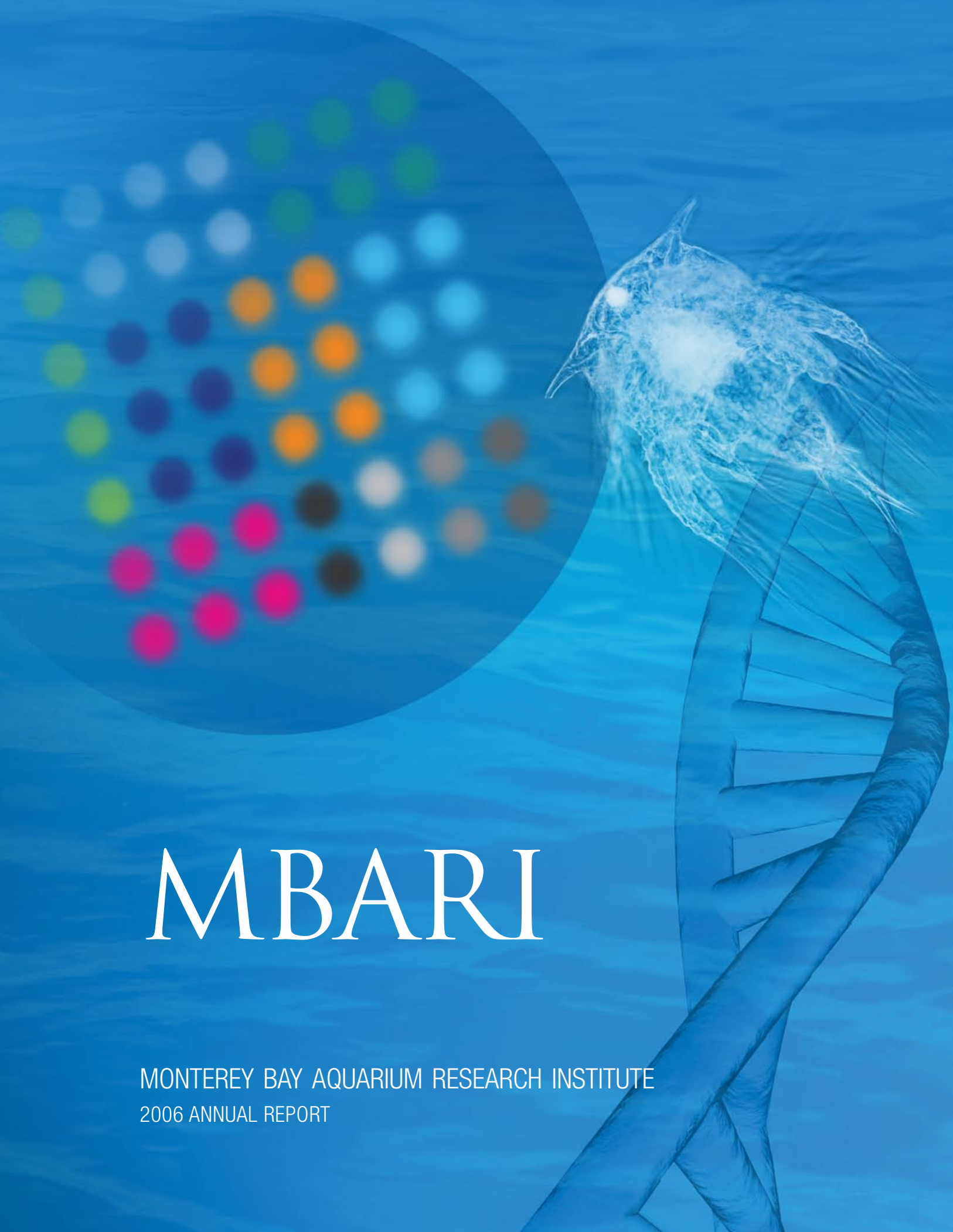

MBARI

MONTEREY BAY AQUARIUM RESEARCH INSTITUTE

2006 ANNUAL REPORT

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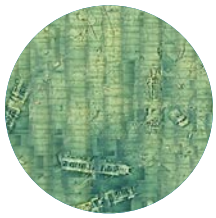
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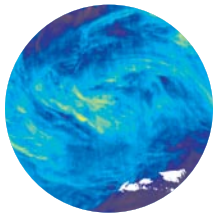
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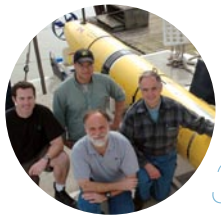
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View From the Masthead

The year 2006 began with MBARI creating and adopting its first new strategic plan in nearly a decade. A new roadmap for our research effort was long overdue, and a number of internal and external factors had changed since the prior plan was penned in 1998. First, funding from the David and Lucile Packard Foundation for MBARI's programs and facilities had leveled off after the first decade of institutional building and rapid growth. We needed a new plan to help make transparent decisions on retiring programs and assets in order to maintain the flexibility to pursue new opportunities. Second, many of the inaugural trustees of the Packard Foundation who had participated in the founding of MBARI had now retired. MBARI would need to make strong connections to a new generation of Packard trustees and program officers and to communicate to them how our research impacts issues that matter to them. Third, MBARI was just finishing the Monterey Ocean Observing System (MOOS, highlighted later in this report), a large project that had been undertaken and supported broadly across the institute. The MOOS project had strategically positioned MBARI to take a leadership position in the new age of ocean observing. A strategic plan was needed to help the institute anticipate where next to position its effort for maximum impact. Finally, growing awareness of the importance of the ocean to the health of the planet and the well-being of the nation made it timely to explore additional methods for communicating the societal implications and excitement of our discoveries to policy makers and the public.

The greatest challenge in creating the new plan was the old plan itself. It was so vague that it provided practically no guidance at all. By allowing, and perhaps even encouraging, MBARI researchers to dilute their focus by pursuing any oceanographic research topic, it did not capitalize on one of MBARI's greatest strengths, namely our centralized, rather than distributed, funding structure. In contrast, the new plan has adopted just three research themes:

- Human perturbations to the ocean, such as ocean acidification, toxic algal blooms, and eutrophication (an increase in nutrients caused, in part, by fertilizer runoff which can result in suffocation of fish);
- Natural rhythms of complex ocean systems, such as seasonal, El Niño, and decadal oscillations in the ocean food web;
- Phenomena at the ocean's edge, such as processes in ocean upwelling systems, stability of seafloor methane hydrates, and the formation of submarine canyons.

Each theme was chosen based on its societal relevance, fit to MBARI's unique marine assets, and the need for an interdisciplinary or unconventional approach unlikely to self-assemble from individual principal investigator grants.

The new MBARI Strategic Plan focuses on three research themes and emphasizes technology transfer.

MBARI's approach to executing the research themes in the new plan makes quite explicit a trend towards more affordable, more easily transferable technology for ocean research. While the remotely operated vehicle *Tiburon* is indeed one of the most remarkable achievements of MBARI's engineers, its impact on ocean research has been compromised by the fact that it is too expensive and complex an asset for most other research institutions to operate. The new MBARI plan has an express goal of reducing the total lifecycle costs of acquiring high-quality scientific data from the ocean, such that ideally the technology we develop can be transferred to countries like Mexico or Peru, two nations with growing interest in preserving their marine resources. MBARI's autonomous underwater vehicle program, highlighted later in this annual report, and the Land/Ocean Biogeochemical Observatory, highlighted in the 2004 annual report and now commercially available from Satlantic, Inc., are two examples of affordable technologies that are lowering the cost of ocean access and making their impact beyond the institution. In addition to looking at the cost of new technologies for ocean research, MBARI wants to build on and enhance its reputation as an environmentally responsible research institution. To that end, we are exploring platforms and instrumentation with minimal environmental impact (such as avoiding "disposable" components, discharges, and significant impacts to the seafloor) and remaining alert for opportunities to pass on our data, models, and understanding to organizations overseeing the health of the oceans.

MBARI is the world leader in creating the capacity to achieve advanced understanding for informed stewardship of the ocean in a world of expanding human impact.

—Vision Statement, MBARI Strategic Plan, 2006

Another aspect of the new plan is an emphasis on technology transfer by engaging in national initiatives. Until recently, MBARI resisted "jumping on the bandwagon" of some of the large, community-wide initiatives in the ocean sciences. We did not want to marginalize the impact of funding from the Packard Foundation by using it to merely supplement initiatives that were already being strongly supported by the federal government. Now that MBARI is more established and has had the time to develop an arsenal of platforms, instruments, and software tools that we want to share with the larger research and education community, the time is right for us to actively engage in national initiatives that are aligned closely with MBARI's pre-existing internal efforts. Excellent examples are the National Science Foundation's Ocean Observatories Initiative and the Ocean Exploration Program within the National Ocean and Atmospheric Administration (NOAA). Partnerships with national laboratories also offer an attractive route to move research systems into operations.

Randy Prickett, left, and Peter Walz prepare a time-lapse camera system for deployment from the R/V *Western Flyer* during an expedition to study methane hydrates on the seafloor.

Steve Fitzwater, left, and Hans Jannasch recover a mooring from the Elkhorn Slough, as part of the Land/Ocean Biogeochemistry Observatory project, which provides insight into the impact of human activity onshore on nutrient fluctuation in the tidal waters.

In our early years, MBARI developed a reputation for being somewhat insular. Because the institute was trying to create a completely new model for an oceanographic research center, one quite unlike our larger and more famous peers, such distance was necessary to allow us to find our own way without being overrun or dominated by a more established partner. MBARI is now confident in our unique formula and contributions; the time is right to bring that different point of view to multi-institutional collaborations. The new plan has MBARI enhancing partnerships with like-minded research institutions to mitigate our small size. We are very excited about MBARI's involvement in the budding Center for Ocean Solutions, a collaborative, multi-disciplinary research and educational program being jointly pursued by Stanford University/Hopkins Marine Station, the Monterey Bay Aquarium/Center for the Future of the Ocean, and MBARI. These institutions together combine strengths in science, engineering, law, policy, and communications for finding strategies to solve some of the most pressing challenges in the ocean and explaining those solutions to policy makers and the public in ways that they will understand.

As complements to the new strategic plan, MBARI has also completed a new Education Strategic Plan to guide our investments in students and outreach, and has begun an Ocean Access Plan to look ahead to MBARI's fleet and research vehicles of the future. MBARI is kicking off a new Master Planning process to look long term at space and property use in Moss Landing. It seems like so much change is in the air! But in reality, the new strategic plan makes official changes in direction and emphasis at MBARI that had been under way for some time, but were poorly communicated to anyone outside of the institute, especially our longtime sponsor, the Packard Foundation. Very often, strategic plans are viewed as being only for internal consumption and are kept hidden away as deep secrets. But in this case, we are proud of our plan, and have posted it for everyone to see at http://www.mbari.org/about/sp/StrategicPlan06.pdf. We welcome your comments on where we are going, your encouragement along the way, and your help in letting us know when you think we have arrived!

Marcia McNutt
President and Chief Executive Officer

Undersea Genetics Lab Detects Marine Microbes and Toxins

Detecting toxic organisms that are invisible to the naked eye has long presented a daunting challenge to public officials charged with ensuring the health of our oceans and waterways. By the time a water sample is collected, transported to a laboratory, and observed under controlled conditions to determine whether it poses a public health risk, it may be too late. In the time that it takes to obtain a result, for example with the standard culturing technique used by the Environmental Protection Agency (EPA), hospital emergency rooms and emergency medical workers are already aware that there's a problem in the ocean or waterway, or the problem itself may be long gone.

For this reason, the 2004 report of the U.S. Commission on Ocean Policy highlighted the importance of developing a device to rapidly and remotely detect microorganisms such as bacteria or harmful algae based on unique attributes, such as their genetic codes. Now, just a few years after the U.S. Commission report was published, the technical barriers to what must seem like a futuristic capability are being overcome. MBARI's Environmental Sample Processor (ESP), a "portable laboratory," has proven its ability to detect harmful algae and other microorganisms in real time. Originally envisioned as a research tool for in situ exploration of the microbial ocean, the ESP has successfully completed a number of high-profile field trials. The ESP team of scientists and engineers is working with coastal managers to create versions of this instrument that can be used not only for research, but for public health and resource management missions as well.

In ocean research, application of genetic analytical techniques is pervasive, yet to date the vast majority of work typically occurs in shore-based laboratories on samples collected from the ocean. Therefore, although the analyses are state-of-the-art, there is still a large gap in time between when the water is sampled and when the results are obtained. Furthermore, this mode of collection and analysis does not adapt itself to the new paradigm of ocean observatories in which scientists seek to have data, not samples, returned to shore by fielding instruments that perform their analyses in situ. Conducting the requisite genetic analyses outside of a laboratory, let alone under the water, poses many technological challenges.

The original ESP underwent field trials from 2001 through 2005 during which mechanical functions and genetic tests for several different species were successfully implemented for deployments lasting up to 20 days. These field trials

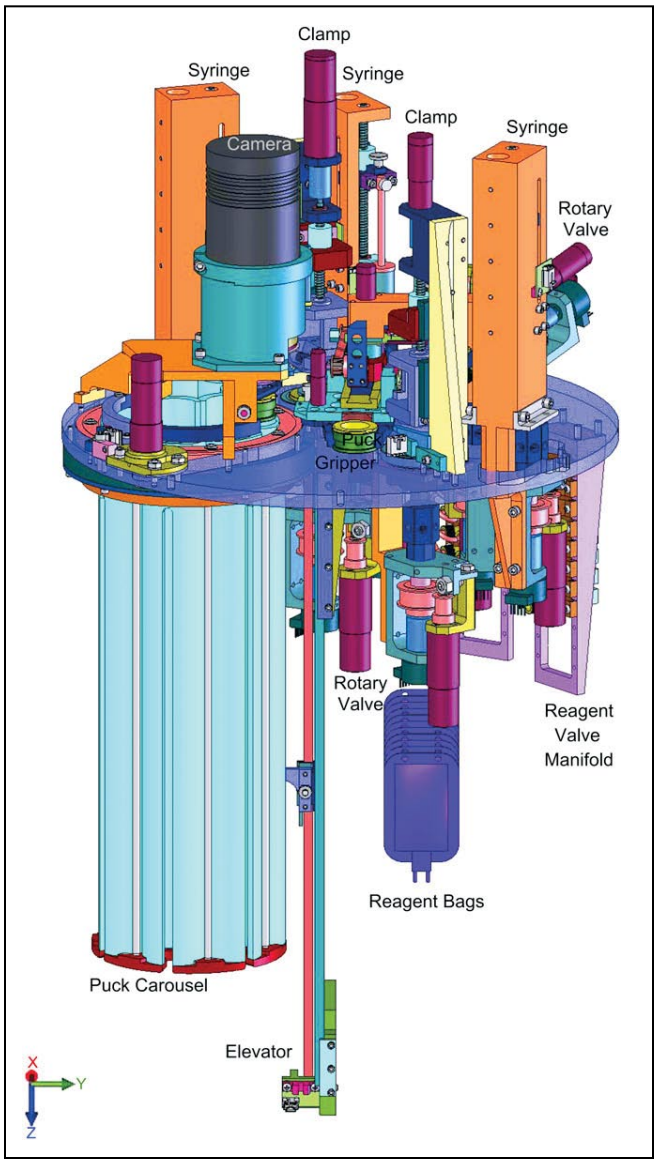


Figure 1: Annotated solid model of the second-generation ESP mechanism, with the electrical and most fluidic components omitted for clarity. Overall dimensions are approximately 41 centimeters in diameter by 76 centimeters high.

emphasized engineering design iterations and refining assay chemistry and methods for validating results obtained using the instrument. Based on that work, a "second generation" (2G) ESP was developed with a grant from the National Ocean Partnership Program/National Science Foundation, and is now being refined with support from several federal agencies and private foundations, including the David and Lucile Packard Foundation and the Gordon and Betty Moore Foundation.

The 2G ESP is basically a molecular biology lab packed inside a canister 41 centimeters across and 91 centimeters tall (Figure 1). It can acquire water samples, concentrate small organisms by filtration, and apply molecular probe technology remotely. The instrument is used for handling small to moderate sized samples (milliliters to several liters) at depths to 50 meters. The core instrument offers a means of detecting numerous microorganisms, and the substances they produce, using DNA probe and protein array technology (Figure 2). The ESP can also be used to collect and store samples for later use on shore after the instrument is recovered. Field trials of the 2G ESP began in March of 2006 (Figure 3). In a single deployment, it successfully automated application of DNA probe arrays that targeted invertebrate larvae, harmful algae, and bacteria (Figures 4 and 5).

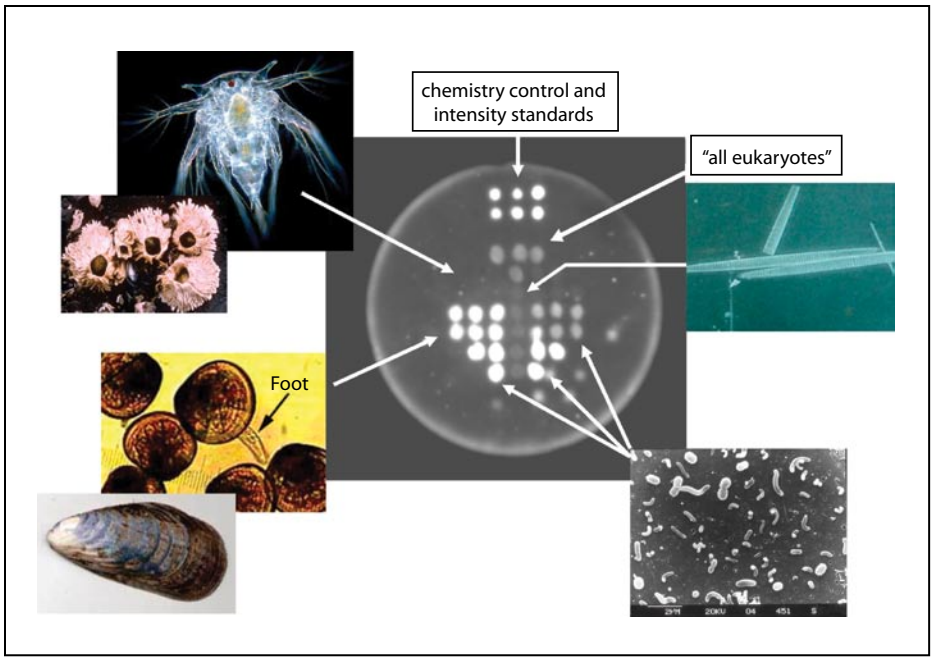


Figure 2. Example of a DNA probe array developed using a natural seawater sample and the first-generation ESP. Printed for demonstration purposes are chemistry controls (top center), and (clockwise, from top right) probes for "all eukaryotes," "pennate diatoms," specific groups of marine bacteria, mussels, and barnacles. Spots on the arrays glow when targeted organisms are present in a sample. This array illustrates the detection of mussel larvae, two different groups of marine bacteria, and pennate diatoms. Barnacle larvae were not present. Actual size of the array is approximately 20 millimeters in diameter, about the size of a U.S. quarter.

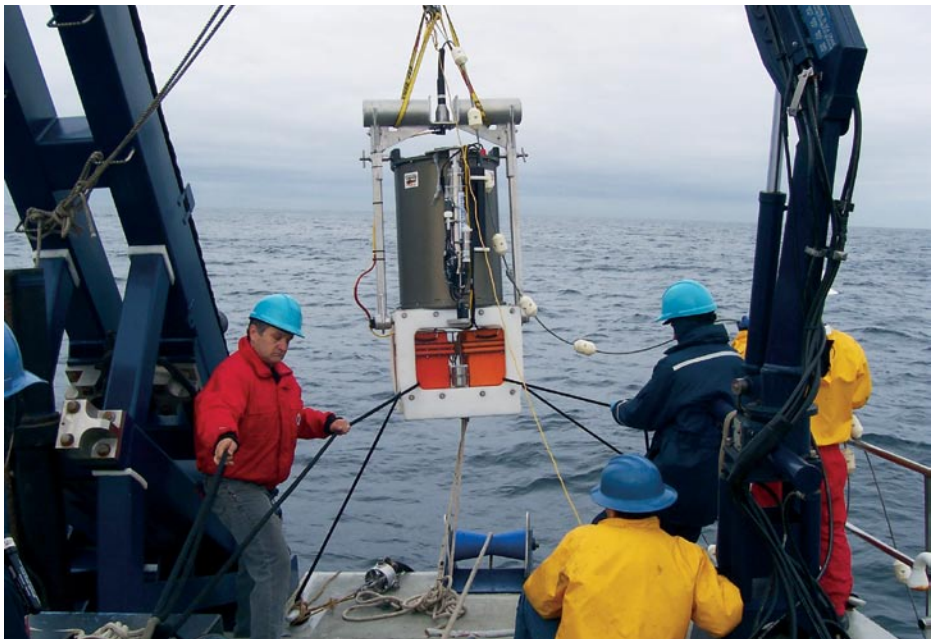


Figure 3. Members of the ESP team deploy the second-generation ESP off the R/V *Zephyr* in Monterey Bay in March 2006.

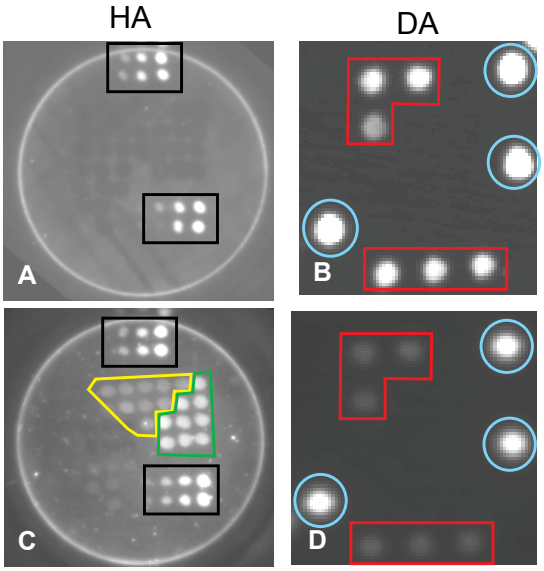
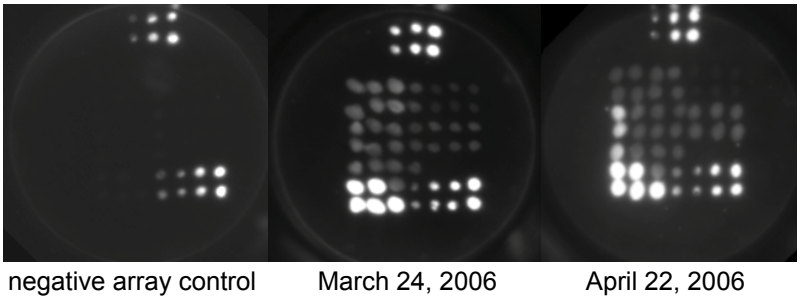


Figure 4. Examples of DNA probe arrays (on the left) for a variety of harmful algae (HA) and protein arrays (on the right) used to detect the algal toxin domoic acid (DA). The arrays illustrate remote detection of different groups of HA, and the DA that is produced by one of those groups. The ESP first performs the test for HA and then follows that immediately with the test for DA. For DNA arrays presence of the target organism results in light emission. For protein arrays presence of the toxin causes a reduction in light emission. The first set of samples (A, B) show no HA and no DA. Only the chemistry controls (black boxes) are visible on the HA arrays, and both the chemistry controls (blue circles) and toxin (red boxes) are present on the DA arrays. The second set of samples (C, D) shows the appearance of two groups of harmful algae (yellow and green outlines), both of which are associated with production of DA, and corresponding appearance of that toxin (dimmed spots in red boxes).

The basic instrument supports a generic, yet limited, set of sample collection and processing operations. The second generation version is designed to allow for the addition of specialized analytical modules: stand-alone devices that can be added to the existing core ESP to impart new and varied functions. This offers new possibilities for remote assessment of the genomic content and activities of microbial communities.

The MBARI ESP group and its collaborators are currently pursuing analytical modules for nucleic acid amplification and probe arrays. The nucleic acid amplification is based on a real-time polymerase chain reaction (PCR) device developed for detecting human pathogens by researchers at the Lawrence Livermore National Laboratory (LLNL). This module will allow the ESP to search for rare genetic markers that are not detectable using the ESP's current chemistries. The analytical module for probe arrays involves application of an optical microbead array in collaboration with Tufts University (Figure 6). The microbead array is reusable, compact, and requires smaller volumes of reagents compared to the current ESP arrays. The advantage of this new technology will be a five-fold increase in the number of assays achieved per sample collected.

Both the PCR module and microbead array place a requirement on the ESP to prepare reactions and pump reagents on a microfluidic scale. To meet that need, the engineers have designed a separate fluid handling station that can be added to the core ESP (Figure 7). This work was carried out



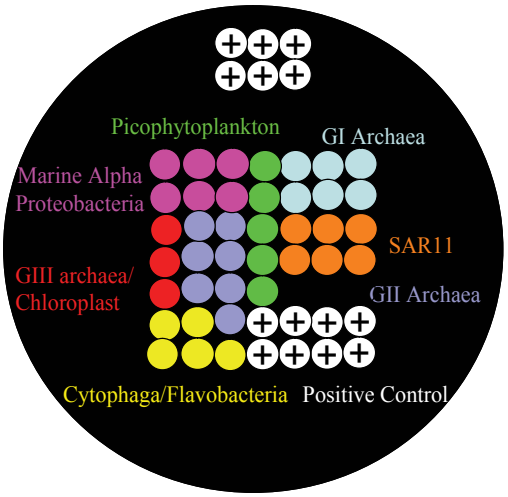


Figure 5. Examples of DNA probe arrays printed with probes for a variety of marine bacteria and archaea. The series shows shifts in species abundance over time in response to changing environmental conditions. Shown left to right are the negative control with filtered seawater and two field samples. At far right is a diagram showing locations of the different probes and chemistry controls.

in collaboration with the researchers at LLNL. This same sample handling and distribution block will also support the microbead array, as well as other analytical devices that will undoubtedly emerge in the near future.

But can the 2G ESP make the transition to the resource management arena? Researchers at the Marine Biotoxins Laboratory in Charleston, South Carolina, part of the National Ocean Service at NOAA, came to MBARI to work with the lab group on application of the ESP to detect algal toxins (Figure 8). They succeeded in developing a test for domoic acid, a neurotoxin produced by certain phytoplankton found in Monterey Bay and elsewhere. Domoic acid is linked to illness and mortality of humans and wildlife, with substantial economic impacts. In 2006 the ESP project reached a major milestone—the first record of sensing in situ both a harmful algal bloom species and the toxin it produces (Figure 4).

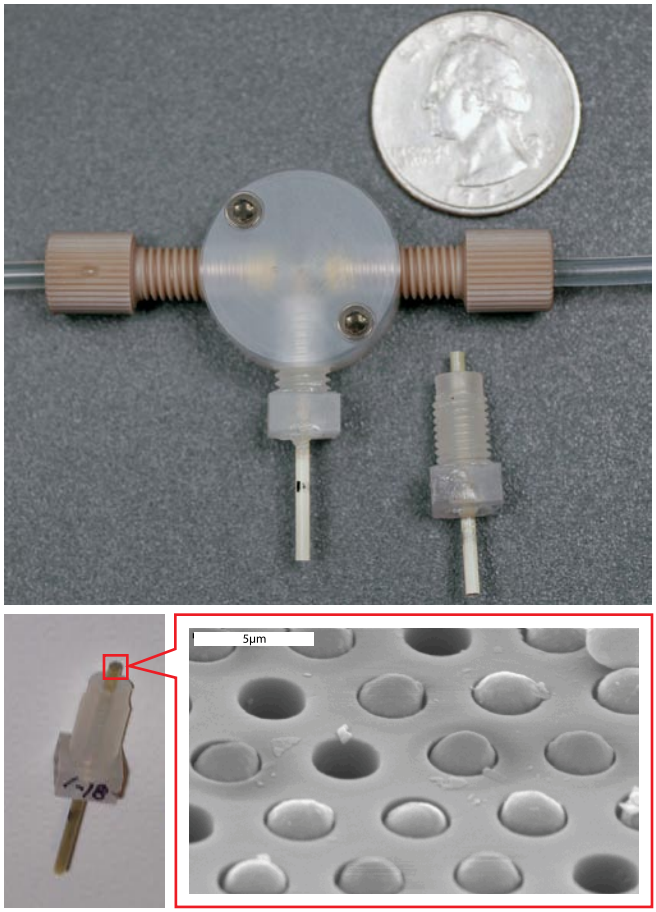


Figure 6. Walt microbead array. Top: Assembled flow cell and fiber bundle. Fluid flows horizontally across the mounted fiber bundle (bottom left), and the array is imaged using epiflourescence from below. The microbead array surface (bottom right) is inside the flow cell (top). Each fiber bundle can hold approximately 1,000 unique probes with appropriate replication. Scale bar = 5µm.

Nevertheless, solving the technical problems associated with performing in situ molecular analyses under water is not quite sufficient in terms of gaining acceptance of this new methodology in regulatory circles. The genetic approach to detecting toxics and harmful microbes may indeed be faster and more precise, but translating those measurements to new EPA standards is not a simple matter. Extensive comparisons are required to determine if the new methods provide results equivalent to or better than the EPA standard, which has its ultimate base in probabilistic models for people getting sick. And because there are large economic consequences with either complying, or not complying, with the EPA standards, until such comparisons can be completed, there will be issues surrounding how the 2G ESP can be used in water-quality monitoring. Fortunately, making those comparisons is a high priority for researchers and resource managers because it will ultimately improve their ability to protect public health.

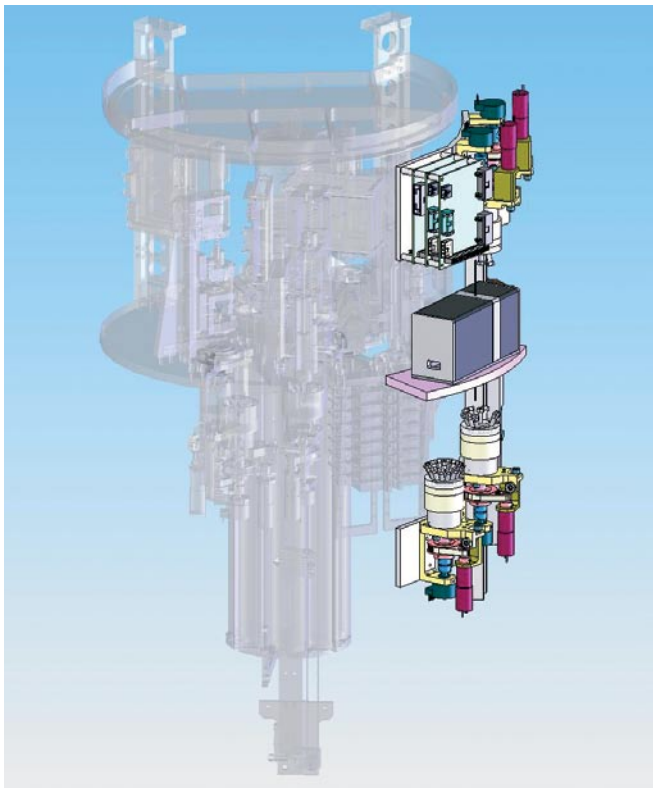


Figure 7. Solid model showing components of the microfluidic block and polymerase chain reaction (PCR) module (black box) attached to a core ESP.

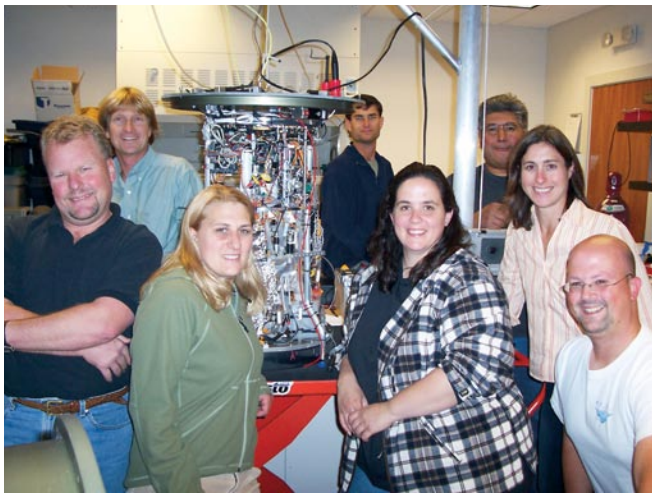


Figure 8: Members of the MBARI ESP team with collaborators from the National Oceanic and Atmospheric Administration's (NOAA) Marine Biotoxins Laboratory. Gathered around the instrument, from left to right are Greg Doucette (NOAA), Chris Scholin, Christina Preston, Scott Jensen, Tina Mikulski (NOAA), Roman Marin III, Dianne Greenfield, and Joe Jones.

The team is experiencing an increasing demand for the ESP. Three copies of the core 2G ESP are being built at MBARI in response to requests from outside groups for their own instrument. The initial units are aimed at toxic algae found along the coasts of Florida, New England, the Pacific Northwest, and Central California. Each area represents a unique ocean regime and poses different problems for studying and mitigating the impacts of harmful blooms. The MBARI ESP group will be working to validate the utility of these systems with researchers and managers in a coordinated, multi-region fashion, understanding that they will face a learning curve for operating the ESP in these different environments as well. The dream of the U.S. Commission on Ocean Policy—a device that resource managers can use to rapidly and remotely detect harmful organisms based on their unique genetic code—is indeed becoming a reality.

Applications of the Second Generation Environmental Sample Processor

Project leads: Scott Jensen, Chris Scholin
Project managers: Doug Pargett, Kevin Wheeler
Project team: Nilo Alvarado, Dianne Greenfield, Joe Jones, Roman Marin III, Gene Massion, Christina Preston, Brent Roman
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Ed DeLong and Robert Vrijenhoek, MBARI; Greg Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Allison Haywood and Karen Steindenger, Florida Fish and Wildlife Conservation Commission, St. Petersburg

Deep-Sea Environmental Sample Processor

Project leads: Scott Jensen, Chris Scholin
Project managers: Doug Pargett, Kevin Wheeler
Project team: Nilo Alvarado, Jon Erickson, Dianne Greenfield, Joe Jones, Roman Marin III, Gene Massion, Christina Preston, Brent Roman
Collaborators: John Dzenitis, Lawrence Livermore National Laboratories, Livermore, California; Jason Feldman and Sabrina Feldman, Jet Propulsion Laboratory, Pasadena, California; Joe Jones and Robert Vrijenhoek, MBARI; Victoria Orphan, California Institute of Technology, Pasadena

Microbial Environmental Genomics Applications

Project leads: Scott Jensen, Chris Scholin
Project managers: Doug Pargett, Kevin Wheeler
Project team: Christina Preston, Brent Roman
Collaborators: Ed DeLong, MBARI; David Walt, Tufts University, Boston, Massachusetts

Probe Chemistries for Use with the Environmental Sample Processor

Project lead: Chris Scholin
Project manager: Christina Preston
Project team: Nilo Alvarado, Dianne Greenfield, Joe Jones, Roman Marin III
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Francisco Chavez, Arlene Haffa, Scott Jensen, Zbigniew Kolber, George I. Matsumoto, Reiko Michisaki, Doug Pargett, Tim Pennington, Brent Roman, Robert Vrijenhoek, Kevin Wheeler, and Jon Zehr, MBARI; Greg Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Alison Haywood and Karen Steindenger, Florida Fish and Wildlife Conservation Commission, St. Petersburg

Probing the Tip of the Iceberg: Methane Hydrates on the Seafloor

Everyone is familiar with ice—cold, hard, slippery, and buoyant. Icebergs and ice floes are common and instantly recognizable forms of ice found on the surface of the ocean in polar regions. But there are other, higher-pressure forms of ice trapped at and beneath the seafloor that are strange and far less familiar. These ices are called gas hydrates, created by the reaction of gases—such as methane, ethane, and hydrogen sulfide—with water at low temperature and high pressure to form a crystalline solid. These compounds are a common occurrence buried in continental slope sediments around the world ocean. In the case of methane hydrate, the water and gas combine in a ratio of six molecules of water to one of gas (Figure 9). The gas draws in the water molecules to form a cage within which the methane molecule flutters in a strange molecular dance, feeling the attraction and pull of the hard ice walls of its prison, but without ever touching.

Methane is a fuel, and despite being trapped in an "ice," it will readily burn (Figure 10). Vast quantities are buried beneath the continental margins—more than all of the world's conventional oil and gas reserves combined. Unfortunately, this resource is so sparsely distributed that economic recovery poses a difficult challenge. Moreover there are dangers associated with disrupting the hydrate deposits. If the ocean warms enough to melt the hydrate ices, or hydrates are physically displaced to remove the overburden pressure that keeps them in the high-pressure form, then they can dissociate with vigor, releasing large amounts of gas and even sometimes destabilizing the sediments that contain them into submarine landslides. For these reasons, there is strong national and international interest in hydrates, and the U.S. has established a National Methane Hydrates Program to investigate these challenges.

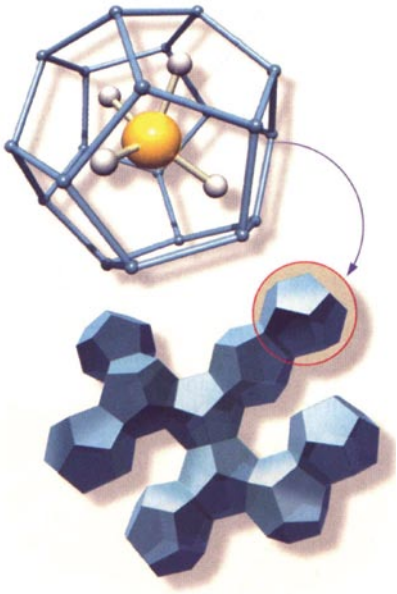


Figure 9: A model of methane hydrate's cage-like structure in which methane (the yellow/white molecule) is enclosed—without direct chemical bonding—inside a lattice of water (the blue molecules which are not drawn to scale). This "unit cell" joins together with other unit cells (bottom image) by sharing faces to build the hydrate solid.

Figure 10: Postdoctoral Fellow Rachel Dunk and AUV mapping leader David Caress with hydrates set ablaze on the barbeque grill on the back deck of the R/V *Western Flyer*.

Not all hydrates are buried. Buoyant solids can be exposed at the ocean floor where the "tip of the iceberg" protrudes through the sediments, thus providing a marvelous window into these structures. MBARI's unique ROV tools are ideally designed for locating and measuring these fascinating ices with some of the world's most sophisticated instruments.

In 2001 a trawler fishing in Barkley Canyon off the coast of Vancouver Island, Canada, pulled up a most unusual catch: tons of a strange white solid that fizzed and crackled on the deck. It was shoveled away, fortunately without harm, and the scientific world was thus introduced to a new, massive seafloor exposure of gas hydrate. Canadian scientists explored and verified this site in 2004, producing startling images of hydrate pinnacles jutting up through the seafloor at 850 meters depth. In August 2006 an MBARI science and engineering team visited the site with the R/V

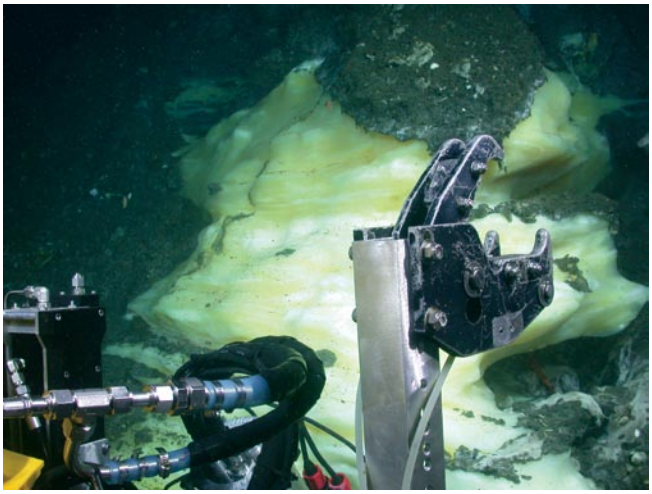


Figure 11: A large wall of hydrate topped with a thin layer of mud on the seafloor at a depth of 850 meters in Barkley Canyon off Vancouver Island, Canada. A trawler had scraped the surface, exposing the hydrate ice seen behind one of *Tiburon's* robotic arms.

Western Flyer and ROV *Tiburon*. They found strange mounds many meters wide covered with brown mud. Where the trawler had scraped across the seafloor, ice-like material was showing just beneath the mud surface (Figure 11).

The team planned to create high-precision maps of the area with MBARI's mapping autonomous underwater vehicle, use in situ laser techniques to determine the chemical composition and hydrate cage framework, and establish how long it would take the exposed hydrate to dissolve.

The map obtained by the AUV (Figure 12) showed the hydrate mounds to be perched on a ledge or shelf, jutting out from the side wall of the canyon. Astonishingly, they were scarcely detectable as a unique acoustic signature. Based on canyon morphology and the geologic province, the MBARI team predicted a much more extensive hydrate area must exist.

Chemical signals of the hydrates were obtained by the Deep Ocean Raman In Situ Spectrometer (Figure 13) simply by precisely pointing a laser and recording shifts in the frequency of light scattered back. The signal showed that these massive blocks of ice were a complex Structure II hydrate, with methane, ethane, propane, and traces of butane all present (Figure 14). The ice cages in which these molecules are trapped were more complex than the simple example shown in Figure 9. The hydrate fabric showed both a light oil-stained form, and under this, a layer of white, oil-free hydrate at which the laser is pointed in Figure 13. Both forms were sampled, with the yellow form being by far the harder material.

Plugs of the hydrate were taken, placed inside a mesh container, and suspended in front of a time-lapse camera just above the seafloor to measure how quickly the hydrate would dissolve when exposed to seawater. The results were clear—the yellow-stained, hard hydrate faces must be receding at close to 1.4 meters per year. The softer, white form dissolved almost twice as fast (about 2.1 meters per year), thus accounting for the pronounced overhang seen in Figure 13. The research team surmised that these mounds were nearly stable when protected by their sediment blanket,

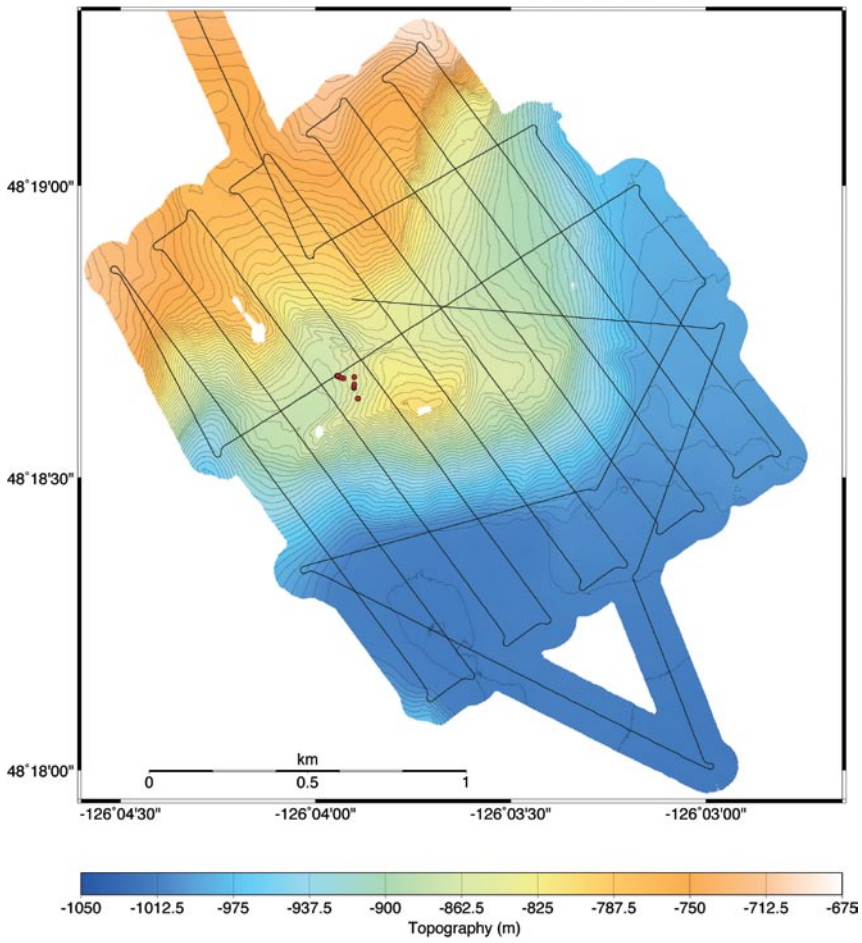


Figure 12: The bathymetric map obtained with the mapping AUV. The track lines show the pattern followed by the AUV in a single night. The red dots indicate locations of hydrate outcrops.

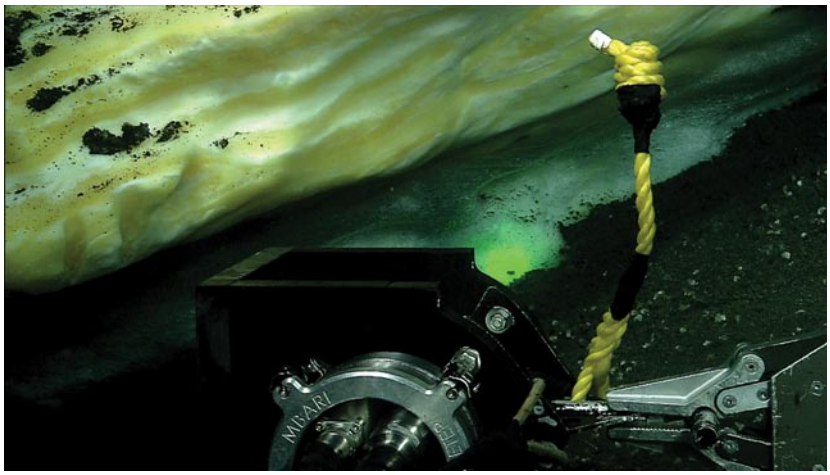


Figure 13: The green laser of the Raman spectrometer points at a wall of hydrate near *Tiburon's* robotic arm. By focusing the beam, and examining shifts in frequency of the light scattered back, scientists can provide not only a chemical analysis, but also determine the structure of the water cages that bind the gas into the massive seam seen here.

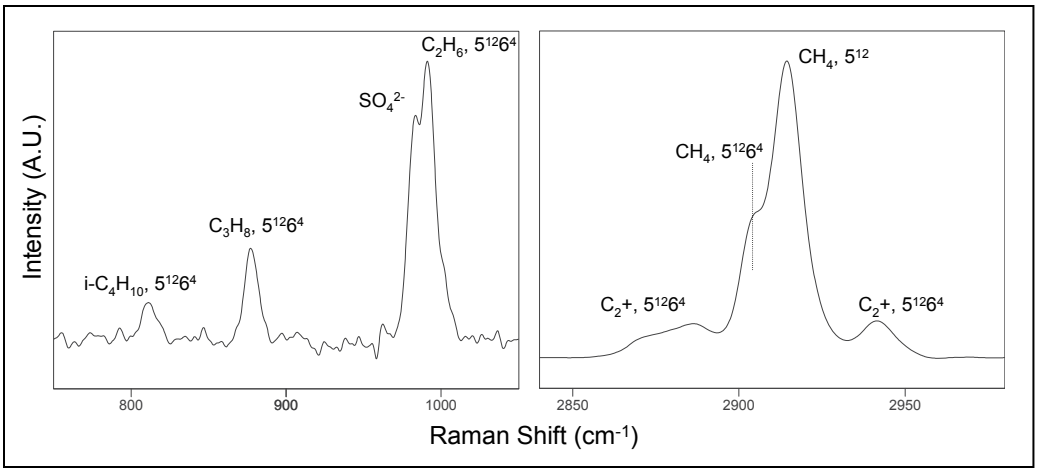


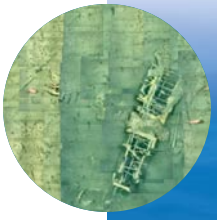
Figure 14: The Raman spectrum of the light scattered back in Figure 13. From the spectral peaks observed it is possible to detect not only the gases present, but the ice cage in which they are trapped.

but once this was scraped away by the trawler, events were set in motion and the exposed hydrates began receding with considerable speed. These amazing sights are disappearing before our eyes, dissolving hydrocarbons into the surrounding ocean.

These images of massive quantities of frozen gas in huge exposed seams on the seafloor are startling. It is astonishing that they were "discovered" by a trawler and not by conventional surveys, leading scientists to question how well they know these systems. The hydrates cleanly pushed apart the sediments as they formed, creating a pure mass of frozen gas—how did this occur? And these hydrates seem to form and disappear in ways and on time scales that were unimagined a few short years ago. Whether these are curiosities, huge energy resources, or geo-hazards remains to be seen but progress in finding out is rapid, and interest is strong.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter Brewer, Bill Kirkwood
Project manager: Edward Peltzer
Project team: Rachel Dunk, Cheri Everlove, John Ferreira, Dale Graves, Jim Scholfield, Farley Shane, Alana Sherman, Peter Walz
Collaborators: Eric Adams and Aaron Chow, Massachusetts Institute of Technology, Cambridge; Keith Hester and E. Dendy Sloan, Colorado School of Mines, Golden; W. Keith Johnson, Institute of Ocean Sciences, Canada; Scott McCallum, Phillip Szymcek, Patricia Taboada-Serrano, and Costas Tsouris, Oak Ridge National Laboratory, Tennessee; Jeff Summers, U.S. Department of Energy, Washington, D.C.



A Rare Visit to Sunken Treasure

Sixteen years ago, at the urging of David Packard himself, MBARI found, photographed, and recovered artifacts from the wreck of the USS *Macon* (Figure 15), a U.S. Navy dirigible that was lost during severe weather offshore of Point Sur on February 12, 1935. This flying aircraft carrier crashed while en route from the Channel Islands to its home base in Mountain View, California. Packard's interest was personal. He recalled that as a student at Stanford University, he and his friends would sit out on the roof of their fraternity house to watch as this behemoth was launched from its massive hangar at Moffett airfield. This was not the "Goodyear Blimp." The sky would darken overhead and the ground would rumble. It was as though the *Titanic* had taken to the skies. It was no surprise, therefore, that MBARI jumped at the chance to join with the National Oceanic and Atmospheric Administration's (NOAA) National Marine Sanctuary Program to embark on a return expedition to the submerged wreck site of the rigid airship USS *Macon* for the purpose of assessing its current state and what might be done to preserve this important piece of American heritage.

The National Marine Sanctuaries Act mandates the management and protection of submerged archaeological sites within our nation's marine sanctuaries. Heightening public awareness through the exploration of submerged historic resources off California's central coast is an important goal of the management plan of the Monterey Bay National Marine Sanctuary (MBNMS). The 2006 USS *Macon* expedition resulted in the first maritime heritage archeological survey within the Monterey Bay sanctuary's boundaries and represents a research effort to inventory and characterize these historic resources.

In September researchers working from the R/V *Western Flyer* off the Big Sur coast deployed the remotely operated vehicle (ROV) *Tiburon* to conduct a systematic deep-water visual survey of site features using high-definition video. The Stanford University robotics lab led the effort to create an "on-the-fly" photomosaic of the wreck site (Figure 16). This effort built on software from the robotics lab that allows ROVs to create navigation-grade video mosaics of the seafloor while underway, enabling them to return to previous locations using the stored mosaics. The photomosaic was enabled by new facets of MBARI technology that were not available during the first visit to the crash site: the high-definition television camera, high-efficiency arc lighting, dynamic positioning of the vessel, and advanced ultra-short baseline and geographic information system navigation systems. Given the scale of the dirigible, the size of the debris field (several football fields in dimension), the low visibility in the water, and the limited field of view of any high-resolution underwater imaging devices, these technologies are indispensable for putting the fine features in the larger context. The photomosaic illustrates the distribution of site features that can be used as a management tool, support a variety of outreach and educational initiatives, and perhaps even shed understanding on the crash itself.

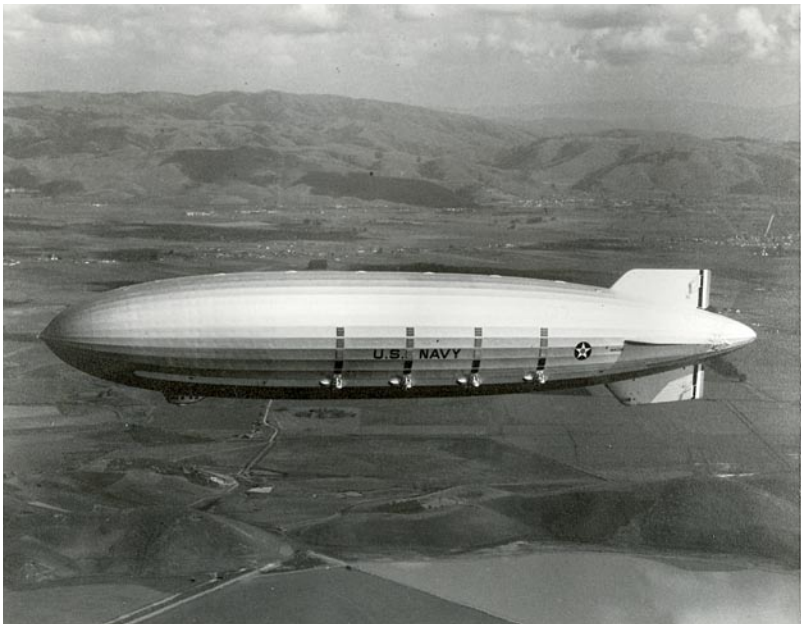


Figure 15: The USS *Macon* was a familiar sight across the United States. Thousands of people would turn out to observe the flying aircraft carrier conducting training maneuvers. The 240-meter-long (785 feet) USS *Macon* carried four biplanes on board.

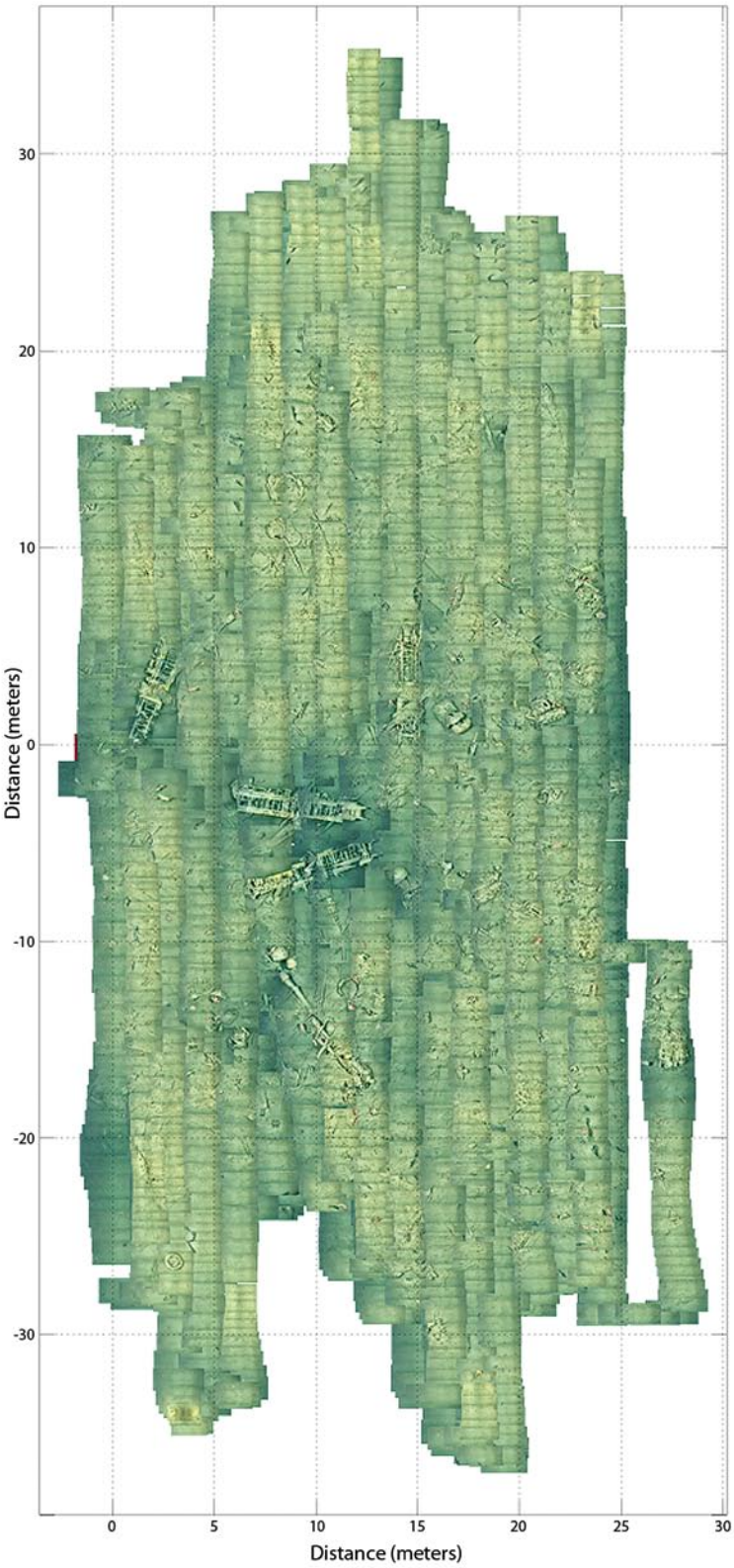


Figure 16: This navigation-grade photomosaic was compiled from several thousand overlapping frames from high-definition video collected during the expedition to the USS *Macon*. The most visible objects are the wings of four Sparrowhawk biplanes that were carried aboard the *Macon*. The construction of a high-resolution, science-grade mosaic is in progress.

A secondary objective of the mission was to identify and record in more detail specific relics, including newly discovered artifacts, and assess their condition. The survey was designed to build upon information gathered during MBARI expeditions in 1990 and 1991 so that estimates could be made on the rate of deterioration of the *Macon* artifacts. The research team concluded that sections of the aluminum girders that formed the structure of the airship exhibit advanced signs of degradation after 71 years in the marine environment. Photos show a measurable loss of crash site debris on the bottom since the earlier visits. There is less exposed girder, wood, and peripheral debris than was prevalent during the first missions, most likely due to corrosion of the duraluminum girder, deterioration of remaining wood and fabric, and increased sedimentation of the site. Much of the sheet metal structure which was intact 16 years ago is now riddled with large holes.

Figure 17 shows similar views of the Sparrowhawk aircraft, which the *Macon*-class dirigibles were designed to launch and recover in mid-air. Four of the biplanes were on board at the time of the crash. It is clear from the photos that there has been significant deterioration in the condition of these aircraft in the years between the two surveys, and that in a few decade's time there will likely be little of it left on the seafloor. This result is no surprise; the *Macon* was a "lighter-than-air-craft", and every part was designed to be as lightweight as possible. Thus little of the craft was made of iron, titanium, or steel. Canvas, aluminum, and wood do not survive long in the bottom of the ocean. In addition, large discrete objects are missing from around the Sparrowhawk aircraft. These photographs are of concern to the maritime historians, as there are no authentic examples of the Sparrowhawk aircraft anywhere but here, at the bottom of the ocean, off the Big Sur coastline. Furthermore, the condition of these aircraft, as currently noted, suggests that any attempt to recover them now might only hasten their demise. The photographic evidence from MBARI's ROVs may be the last record that closes out this interesting chapter in American aviation history (Figure 18).

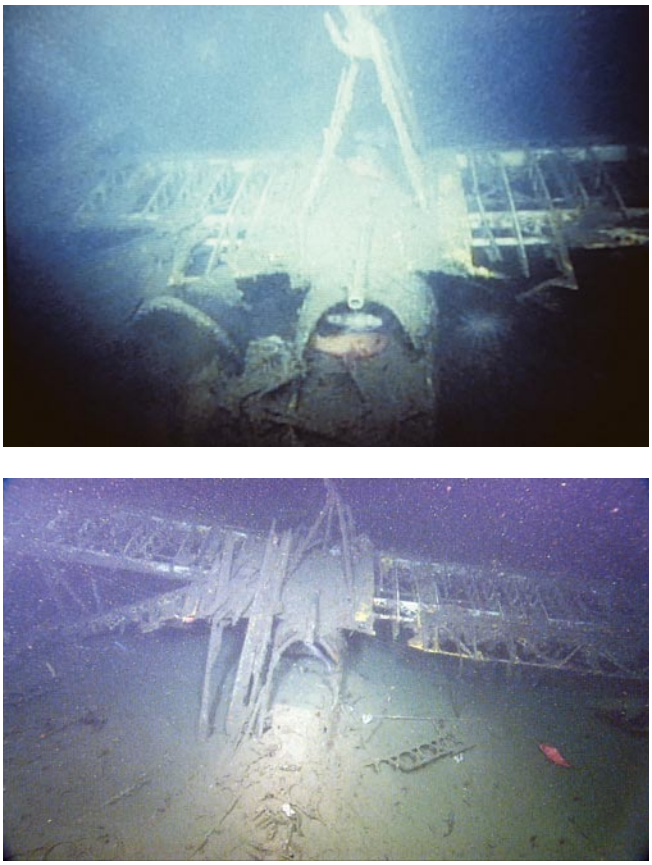


Figure 17: One of the Sparrowhawks that had been carried on the USS *Macon*, photographed in 1991, top, and in 2006, bottom.

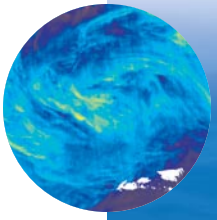
Figure 18: Parts of a star are barely visible on the wing of one of the Sparrowhawk biplanes that were on the USS *Macon*.

The *Macon* expedition created a unique opportunity for MBARI to partner with NOAA in a number of wide-reaching education and outreach efforts. Dozens of public lectures, magazine articles, news stories, and conference presentations resulted. NOAA's Teacher at Sea Program produced a new high school curriculum based on the airship's materials science, aviation history, and deep-sea ecology.

A high point of the expedition was a live broadcast from the deep sea crash site back to MBARI's auditorium allowing a group of distinguished supporters of the Monterey Bay Aquarium to participate remotely in the *Macon* expedition via a two-way link over the Internet. The guests were able to view the same scenes that were being explored by the ROV *Tiburon* in real time and ask questions of the pilots, historians, and scientists aboard the research ship. This technological aspect of the expedition was unique in that it was outside the typical coverage of the MBARI microwave system, involved relays to very remote areas of the Big Sur coastline, and leveraged the Internet. The live link expanded into a five-day national webcast. It was clear from the response to the *Macon* program that it had great appeal to a segment of the population who might not otherwise have been engaged in deep-sea exploration. We are sure that had David Packard still been with us, he would have had a front row seat.

USS *Macon* Expedition

Project lead: Chris Grech
Project managers: Lisa Borok, Chris Grech
Project team: George Badger, Craig Okuda, Steve Rock
Collaborators: Lisa Emanuelson and Dawn Hayes, Monterey Bay National Marine Sanctuary, California; Robert Schwemmer, National Oceanic and Atmospheric Administration Maritime Heritage Program, Monterey, California; Bruce Terrell, National Marine Sanctuary Program, Silver Spring, Maryland; Tim Thomas, Monterey Maritime Museum, California



Seeing the Future in the Stratified Sea

Making useful and accurate predictions about the impact of climate change in the ocean is a very difficult task. To simply state that the oceans will, on average, become warmer is not all that helpful. More useful are forecasts concerning the ecological makeup of the ocean of the future, as such information bears on the productivity of fisheries, the biodiversity of reefs, the microbial load in the coastal ocean, and other factors that matter. A surprising and unexpected shift in the predominant phytoplankton in Monterey Bay, as detected in MBARI time-series data, indicates that simple climate models still have a long way to go before they will be able to capture all of the complexity of ecosystem interactions in the face of environmental change.

Interactions among components of the ecosystem make it challenging to forecast such significant changes, given the magnitude of both the natural and the anthropogenic environmental changes. Fortunately, MBARI's 19-year Monterey Bay time series is illustrating some of the unexpected ecological responses to the Pacific Decadal Oscillation, a natural climate variation that has an amplitude comparable to the expected climate signal in the coming decades. This time series monitors key physical, chemical, and biological oceanographic parameters. The operational components of this program have taken advantage of evolving technologies, originally depending on shipboard surveys and moorings, and now increasingly using autonomous underwater vehicles and drifters. This time-series work is rivaled in the Pacific only by the Hawaii Ocean Time Series program and is a prime example of MBARI's ability to support programs that would be exceedingly difficult

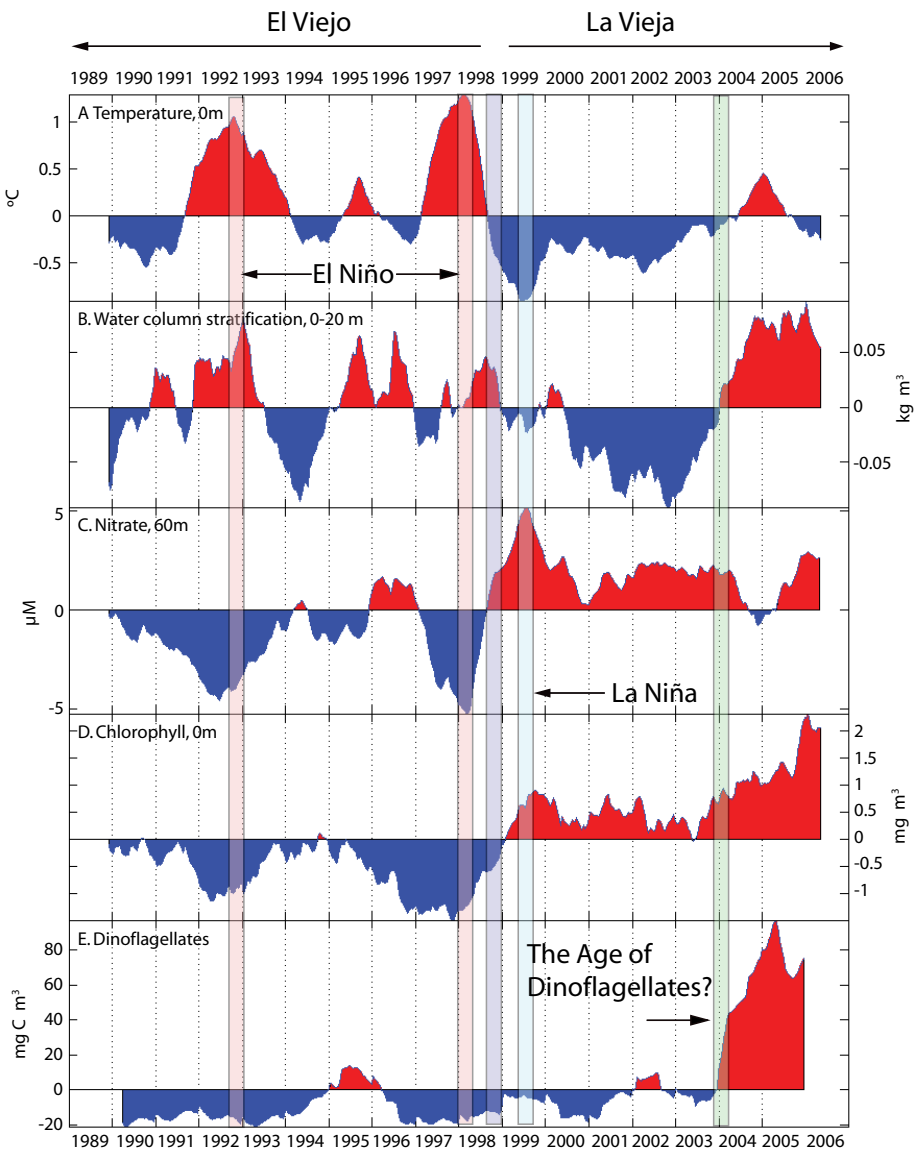


Figure 19: Time series of anomalies, with higher [or lower] than normal values in red [or blue]. (A) Surface temperatures have in general remained cool since 1998, resulting in high (C) 60-meter nitrate and (D) surface chlorophyll (overall phytoplankton biomass) values. However, centric diatoms decreased sharply in 2003 and were apparently replaced by (E) dinoflagellates in 2004. This phytoplankton switch may have been caused by increased (B) near-surface stratification (0-20 meter difference in the water density parameter, sigma-t) which in turn resulted from decreased wind-driven upwelling after 2003.

to sustain with government grants. The time series has grown more valuable with age, and the data collected have resulted in nearly 90 publications in the past five years.

The data (Figure 19) show that the northeast Pacific changed from the warm phase of the Pacific Decadal Oscillation, called "El Viejo," to the cool phase, "La Vieja," following the strong 1997-98 El Niño. However, exploration of this "regime shift" has been confounded by the occurrence of one strong La Niña and two weak El Niño events during the intervening years. El Niño systems are individually complex; when they occur along with seasonal cycles and regime shifts, the thread of causation is easily lost. Nevertheless, due to the potential effects of global climate change, it remains imperative that we learn as much as we can—as quickly as possible—about Earth's climate and ocean system.

In spite of the multiple sources of variability listed above, a number of changes occurred in Monterey Bay after 1998 and have persisted as part of the regime shift to La Vieja. Temperatures have been below normal for most of the past seven years (Figure 19A), and nitrate has been above normal at 60 meters (Figure 19C). As an important local consequence of the increased nitrate, overall phytoplankton biomass has been high (Figure 19D). These changes may indicate stronger upwelling and a faster California Current, which in turn may imply that the entire north Pacific subtropical gyre is rotating more quickly during La Vieja.

In 2003, MBARI researchers noted an unusual anomaly occurring during the recent cool regime. Centric diatoms are often thought of as signature or "keystone" phytoplankton species within upwelling systems, where they flourish and form the base of the food web. As expected, centric diatoms were abundant from 1998-2002, but in spring 2003 became less so—as during the 1997-1998 El Niño. Several months following the centric diatom decrease, dinoflagellates increased instead and their numbers remain high (Figure 19E).

This shift in the dominant phytoplankton taxa may be related to their differing ecological niches. Centric diatoms have high maximum growth rates and thus outcompete other phytoplankton under the high nutrient conditions characteristic of normal upwelling conditions that typically exist in Monterey Bay. Dinoflagellates, on the other hand, have slower maximum growth rates, but can swim and undertake vertical migrations down into higher-nutrient subsurface waters if surface nitrate levels fall (Figure 20). Thus dinoflagellates are favored when near-surface nitrate is low and the thermocline is shallow. Such a switch seems to have occurred in 2004, when the shallow water column became unusually stratified (Figure 19B) due to a reduction in local upwelling-favorable winds. Stratification in the water column restricted mixing of nutrients to the surface from below so that centric diatoms did poorly while dinoflagellates bloomed. The northern portion of Monterey Bay is protected from the prevailing upwelling-favorable winds and has greater water column stability; the typical dinoflagellate blooms that occur in this region every year in late summer greatly increased in area and concentration starting in 2004 (Figure 21). Thus overall phytoplankton biomass remained high, but the dominant organisms changed. This change in phytoplankton must have affected fish and other higher-trophic level organisms in as-yet unexplored ways that are potentially very important for the ecosystem, ecologically and commercially.

A potentially troubling association is the fact that dinoflagellates were geologically prominent 55 million years ago for a brief period of time (220 thousand years). During this period, the Late Paleocene Thermal Maximum, there was a rapid carbon release into the atmosphere and oceans,

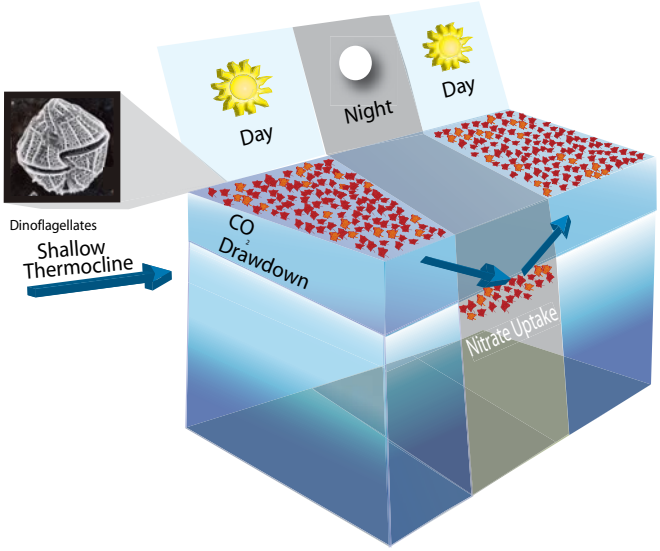


Figure 20: Cartoon describing the nocturnal vertical migration of dinoflagellates to depth. These microscopic organisms swim very slowly but when the thermocline is shallow (~10 meters) and the waters are calm (and stratified) they can reach the thermocline at night, take up nutrients (primarily nitrate) and return to the surface in the daytime to photosynthesize. In doing so they are able to reduce surface carbon dioxide to levels well below what is expected from purely physical processes.

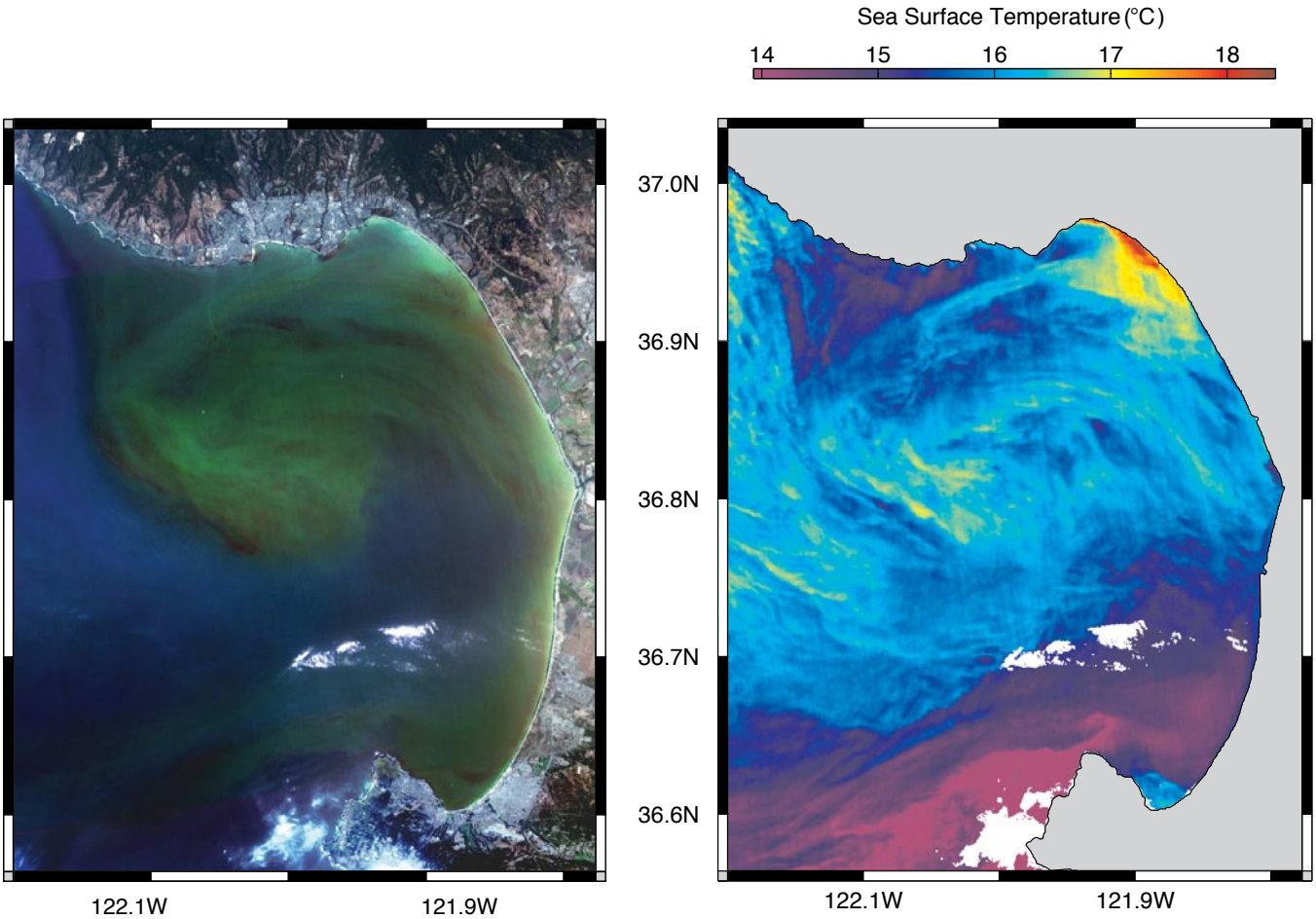


Figure 21: True color and temperature images of Monterey Bay from July 19, 2006 collected with the Moderate Resolution Imaging Spectroradiometer (MODIS) Airborne Simulator sensor on a high-altitude aircraft overflight (resolution is 34 meters). Reddish discoloration, as evident in the true color image in the northeastern corner of Monterey Bay, is often caused by dense accumulations of dinoflagellates. The temperature image shows how the dynamic circulation of the bay can spread dinoflagellate blooms.

rivaling the present anthropogenic release of CO_2, although at that time it was more likely from methane hydrate destabilization. Consequences 55 million years ago included mass extinction of marine benthic organisms. If the sudden onset of the dinoflagellates in Monterey Bay indicates that through the anthropogenic release of CO_2 into the environment, some tipping point has been crossed, this is indeed a serious matter.

It thus appears that we are currently experiencing a cool La Vieja ocean characterized by generally high nutrient levels and high overall phytoplankton abundance, but that increased water column stratification after 2003 reduced near-surface nitrate, which in turn caused a switch in keystone phytoplankton taxa. The cause for the sudden reduction in upwelling remains elusive, as it does not appear to be caused by warming of the surface ocean and deepening of the thermocline as is the case during El Niños. Even with 19 years' experience, the interplay between seasonal, interannual, and decadal change is difficult to unravel. Nevertheless, given that our civilization's continued success will depend on understanding and hopefully mitigating climate change, we must continue to explore the complex relations within the ocean and climate system, both their root causes and their cascading consequences.

Biogeochemical Responses to Climate and Ocean Variability

Project leads/managers: Francisco Chavez, Tim Pennington

Project team: Marguerite Blum, Seth Bushinsky, David Field, Gernot Friederich, Dorota Kolber, Reiko Michisaki, Lionel Pawlowski, Erich Rienecker, Martin Suro

Bringing Real-Time Data into the Classroom

In today's fast-paced world, teachers are always looking for ways to connect what is being taught in the classroom to their students' daily lives. At the same time, with ocean observatories coming on line, the Internet can bring real-time marine conditions from both local and distant environments to any networked computer at the speed of light. The convergence of these two interests is to bring real-time oceanographic data into the classroom, allowing students to check wave heights and water temperature, track bluefin tuna and jumbo squid, or report on seasonal changes in water quality in their local environment. To better equip teachers to access these data and use them in meaningful ways in the classroom, the EARTH (Education and Research: Testing Hypotheses) project, a collaborative effort between MBARI and the Monterey Bay Aquarium has held a series of workshops to educate, excite, and engage teachers.

The focus of the workshops is on the use of real-time and near-real-time data from observatories that span the water column from the ocean surface to the seafloor. Ocean observatories can range from a sensor with infrequent sampling, such as a tide gauge, to suites of instruments with data streams that must be interpreted jointly, such as conductivity, depth, temperature, and nitrate measurements to monitor biogeochemical cycles. The range in complexity allows participation by all students.

During the EARTH workshops, participants learn about cutting-edge marine science and technology, ocean observatories, and the data that they collect. With the help of active researchers, the teachers explore current scientific studies that use oceanographic data and learn how the data have changed our way of thinking about the oceans (Figures 22 and 23). The teachers develop their own curricula using the research and near-real-time data to teach science content and process (Figure 24). The program also provides the teachers with opportunities for professional networking and for evaluating how real-time oceanographic information might be used for instructional purposes on a national level.

In 2006, MBARI took the EARTH teacher workshops on the road with a weeklong summer workshop hosted by the Jacques Cousteau Coastal Education Center in Tuckerton, New Jersey (Figure 25). Fifteen formal educators and 11 informal educators came together to learn about the Rutgers University Coastal Ocean Observatory Laboratory and the Eye-in-the-Sea (EITS) underwater camera. The scientists who developed the EITS helped the teachers understand the instrument, the scientific questions, the results, and problems with the enormous data sets that will emerge when the EITS is integrated into the Monterey Accelerated

Figure 22: Teachers deploy a glider from a Rutgers University ship as part of the EARTH workshop. Oceanographic data collected with the glider will be available to the teachers upon their return to shore.

Figure 23: George Matsumoto shares the wonders and mess of a midwater trawl sample with teachers at an EARTH workshop.

Education and Research: Testing Hypotheses (EARTH)

Project lead/manager: George I. Matsumoto
Collaborators: Rita Bell, Monterey Bay Aquarium, California; Linda Hagelin, San Jose State University, California; Jennifer Magnusson, Bellingham School District, Washington; Janice McDonnell, Rutgers University, New Brunswick, New Jersey

Research System (MARS) ocean observatory. Classroom activities focus on the concept of "citizen scientists" where students will be tasked with analyzing video clips that have been taken by EITS and posted on the web. Students will mark any clips where they see interesting organisms and provide that information to the researchers (http://www.mbari.org/earth/Observatory/observatory.htm) for further analysis. This project will lead to students being more fully engaged in the scientific process, helping researchers cope with the flood of information, learning from the results, and developing alternative hypotheses, perhaps in concert with the researchers themselves.

Educators at the initial EARTH workshop in 2002 made it clear that they preferred near-real-time data that have been processed for quality and linked with content that puts the data into context. This inspires the students to seek further near-real-time data as they pursue their studies. Use of oceanographic data helps give students an understanding of the importance of environmental research as they take a vested ownership in the challenges—and possible solutions—facing their world. Lesson plans based on real data are effective in a variety of environments, from the most high-achieving schools to less successful learning situations. Projects that provide links to real data allow students to experience science as a process in a fun and motivating way that encourages them to collaborate and communicate which, in turn, utilizes higher order thinking skills. Real data prepares students to think globally when they observe first hand how the ocean, atmosphere, and climate are interconnected.

As MBARI's observatory efforts, such as the undersea MARS cabled observatory and the Land/Ocean Biogeochemical Observatory (LOBO), begin to ramp up, EARTH will serve as a portal to a wealth of data, both archived and near-real-time. The EARTH website (http://www.mbari.org/EARTH) focuses on distributing data with supporting lesson plans. EARTH provides educators with a means to integrate near-real-time data with existing educational standards in an interactive and engaging way. Teachers can use this website to confirm that the near-real-time data activities meet national science education standards, and balance the impact of standardized testing on curricula and instruction. In comparison to the textbooks designed to teach standard science curricula, the EARTH lesson plans are far more engaging because they are inquiry-driven and bring the real world into the classroom. EARTH's success must be

at least partially attributed to the fact that the materials, content, and activities—many developed by educators—are presented in a format familiar to teachers.

As MBARI and the Monterey Bay Aquarium continue working with educators, EARTH teacher workshops will be held in both Monterey and New England in 2007. Teachers have been enthusiastic about the workshops, as one teacher commented, "The workshop has increased my own knowledge of the marine environment, problems facing our ocean and research addressing these issues. I feel I can speak to my students with more authority having participated in the MBARI EARTH workshop!" Another teacher recognized that "classrooms of today can be filled with empowered students, surrounded by the world at their fingertips" as researchers begin to open the taps on the flood of data coming in from ocean observatories.

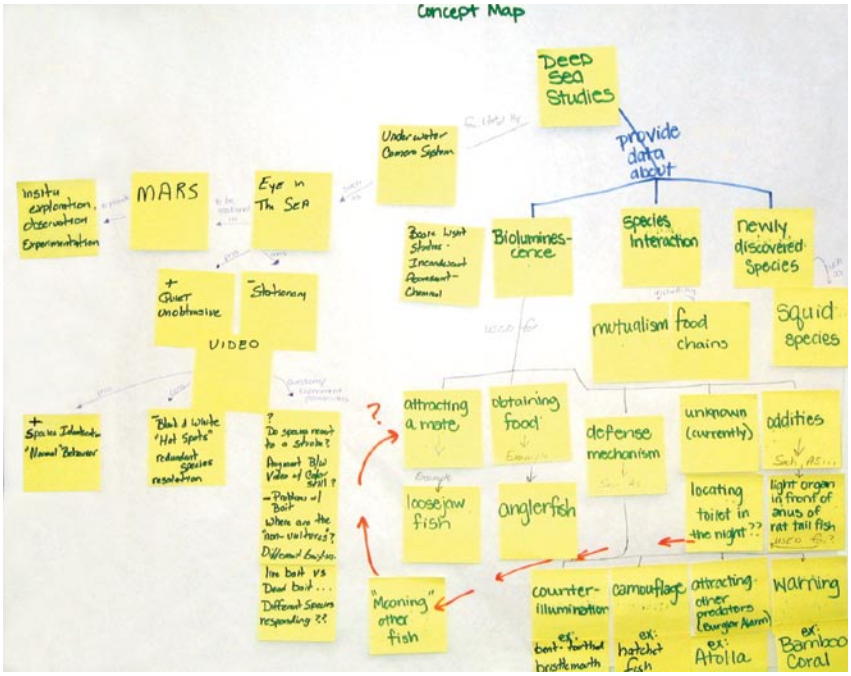


Figure 24: Workshop participants used notes to create a map of the key concepts they wish to convey to students. This particular concept map focuses on deep-sea studies made possible with data collected by underwater camera systems.

Figure 25: Teachers work on inquiry driven lesson plans and activities based on the real online data made available from gliders that they launched the day before. Josh Kohut, director of the Center of Advanced and Sustained Technology at the Rutgers University Coastal Ocean Observation Lab (seated in center of group) helps the teachers interpret the data.

Old-Growth Forests of the Deep Sea

Sailors off the Big Sur coast are awed by the spectacular, natural beauty of that rugged coastline, only lightly touched by the hand of man. Yet most are unaware that a mere 1,250 meters (4,100 feet) beneath them lay the peaks of an extinct undersea volcano that puts even the Big Sur coast to shame. Rising 2,440 meters (8,000 feet) above the surrounding deep seafloor, this undersea mountain, Davidson Seamount (Figure 26), is a stunning oasis of colorful coral gardens that support a rich assemblage of deep-sea animals. This pristine habitat is the deep-sea equivalent of an old-growth forest, and a 2006 expedition of the R/V *Western Flyer* provided an opportunity to share this delightful vista with the public.

Such scenes of natural wonder take a long time to create. The first essential ingredient is a volcanic foundation to produce oceanographic upwelling, which may in turn concentrate nutrients and biological productivity above the feature. Davidson Seamount formed through episodic, explosive eruptions 9 to 15 million years ago along a now-relict seafloor spreading center. It is but one of several seamounts submerged off the Central California coastline. After the volcanic activity died, the biology came alive, carpeting the seamount with some of the slowest growing communities in the ocean. For example, bubblegum coral (*Paragorgia arborea*; Figure 27) could be considered the Giant Sequoia of the deep-sea—reaching nearly three meters in height on Davidson Seamount. One specimen trawled from a New Zealand seamount was nearly 10 meters tall!

Unfortunately, what has taken nature many lifetimes to create can be destroyed by mankind overnight. With the advent of satellite altimetry in 1978, a large number of previously uncharted undersea volcanoes in the southern oceans were detected from space based on centimeter-sized undulations in Earth's sea-level surface. These seamounts proved to be rich fishing grounds and were rapidly exploited as shallow-water resources were depleted. For example, many coral communities on seamount peaks off southeast Australia have been nearly denuded by the bottom-trawling fishery for orange roughy. The recovery of the corals and the fishery resource may require upwards of a century or more. *Paragorgia* and other corals on Davidson are similarly at risk of damage from fishing activities and merit protection from the expanding reach of fisheries into the deep sea.

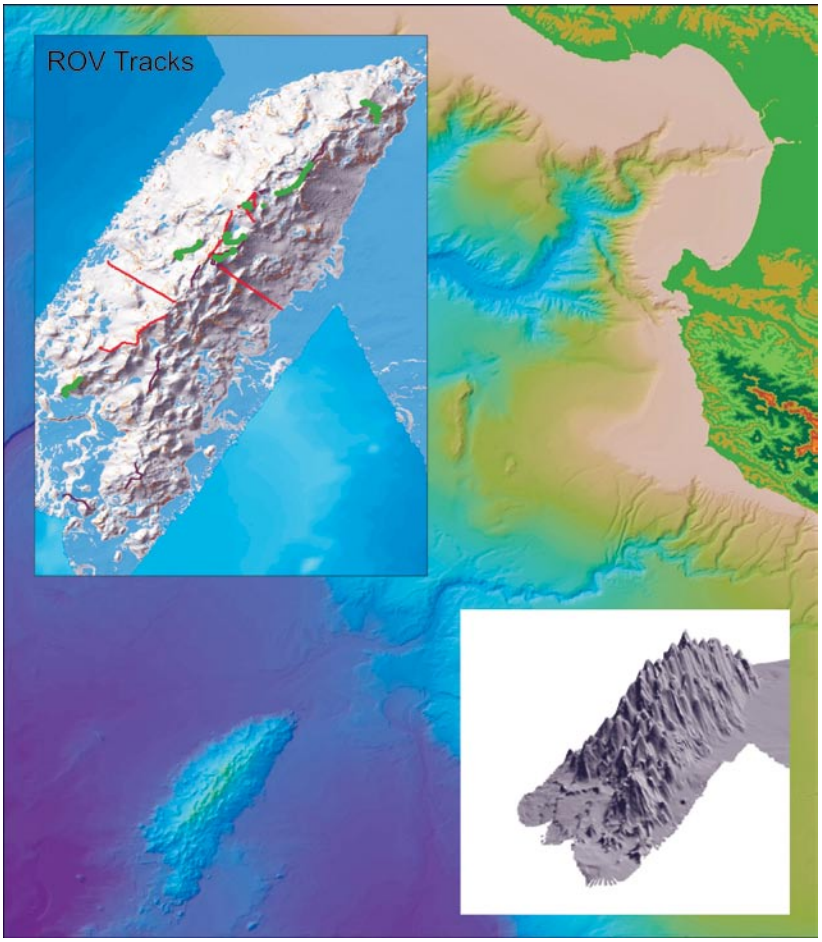


Figure 26: Davidson Seamount is an island habitat amidst the vast sediment-covered abyssal plain, with steep terrain and rocky substrata exposed along current-swept peaks and ridges, steep talus or mixed rubble/sediment slopes, and sediment-filled valleys. Though 8,000 feet tall and 26 miles long, the seamount is only 8 miles wide, with an average slope of over 20 degrees on its flanks and large areas of much steeper, near cliff-like terrain, with multiple small peaks over its summit.

However, we cannot protect what we do not know. For that reason, in early 2006, MBARI, the National Oceanic and Atmospheric Administration's (NOAA) Office of Ocean Exploration (OE), and the British Broadcasting Corporation (BBC) joined forces to sponsor an R/V *Western Flyer* expedition to Davidson Seamount. MBARI's remotely operated vehicle *Tiburon* provided the ideal exploration tool for this expedition. The goals of the cruise included research on the biology of deep-sea corals and seamount geology and biodiversity, as well as public outreach and education concerning the expedition and the seamount resources. Investigators from MBARI, the Monterey Bay National Marine Sanctuary (MBNMS), and Moss Landing Marine Laboratories (MLML) received funding from the OE for those studies.

Figure 27: Bubblegum coral, *Paragorgia arborea*, at the summit of Davidson Seamount. *Paragorgia* colonies reach three meters in height and may be well over 100 years old.

A ship full of investigators spent 10 days over the seamount in late January and early February. Research activities focused on the distribution and abundance of corals and sponges in different habitats, coral age and growth, and the effects of seamount topography and bottom currents on food resources for corals. A welcome observation of this and earlier expeditions was the apparently pristine condition of coral communities on the seamount and minimal evidence of human impact. Corals were found from the base to the peak of the seamount, but the richest coral gardens were found only across peaks and ridges at the seamount summit. These shallowest seamount peaks were covered by a diverse assemblage of large and colorful suspension-feeding animals, including sea fans and gorgonians, soft

Figure 28: A new deep-sea sponge species (*Asbestopluma* sp.) from the peak of Davidson Seamount.

corals, and sponges. At least one new species of sponge was discovered, a beautiful white spiny sponge in the genus *Asbestopluma* (Figure 28). Occurrences of sponge and coral colonies were catalogued using MBARI's Video Annotation and Reference System, and were evaluated in relation to seamount bathymetry using a benthic topographic index, calculated from the slope of a location relative to its surroundings. Large corals were found in dense aggregations on the ridges and peaks of the seamount with high topographic indices, indicating local peaks with adjacent steep slopes, but were far less abundant on nearby valleys or the seamount flanks (Figure 29).

Collections of corals and sponges were made sparingly to minimize damage to these sensitive communities. The samples are being used for studies of the taxonomy, age, growth, and population dynamics of corals, and for analysis of changes in ocean chemistry recorded in cross-sections of coral skeletons. Radiometric techniques are being used to estimate the ages of corals, based on the decay of lead-210 from the center (oldest) to the margin (youngest) of some coral skeletons.

Another element of the science goals was to quantify the relationship between suspended particulate material, current speed, and coral distribution over the seamount, as a test of the hypothesis that acceleration of bottom currents by seamount topography concentrate food for filter-feeding animals. Toward this effort more than 50

small-scale flow measurements were made among the peaks and valleys of the seamount, both near and distant from corals (Figure 30), and analyses of suspended particulate organic carbon were made from water samples collected in standard oceanographic sampling bottles mounted on *Tiburon*. Initial analyses show no clear relationship between coral abundance, flow, and organic carbon in the water column.

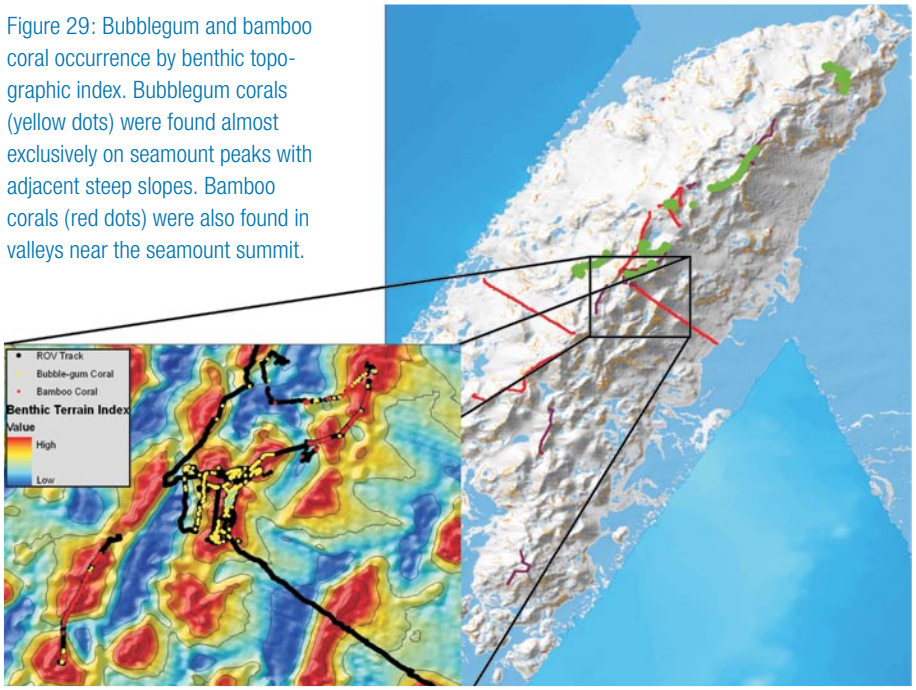


Figure 29: Bubblegum and bamboo coral occurrence by benthic topographic index. Bubblegum corals (yellow dots) were found almost exclusively on seamount peaks with adjacent steep slopes. Bamboo corals (red dots) were also found in valleys near the seamount summit.

Public outreach efforts during and after the cruise are sure to broaden public understanding and appreciation of Davidson Seamount, and of seamount ecosystems in general. MBARI staff created an expedition website (http://www.mbari.org/expeditions/Davidson06/) full of information, daily logs, and educational resources. NOAA's Office of Exploration listed the expedition as one of its "signature cruises" for 2006 and accordingly showcased the Davidson cruise in its education and outreach efforts nationwide. MBARI staff on the ship and on shore contributed essays, images, biographies, and daily updates to the NOAA *Ocean Explorers* education website. Spectacular high-definition video imagery of the corals was collected during the cruise through the combined expertise of the BBC's producer and videographer, and MBARI's top-notch *Tiburon* pilots. Unlike the typical video captured principally for research purposes, careful positioning of lights and orchestrated cinematic techniques were used to maximize the visual drama of flying through the corals. The world of deep-sea coral gardens on Davidson Seamount was introduced to a much broader public audience when the BBC broadcasted its *Planet Earth* series in 2007.

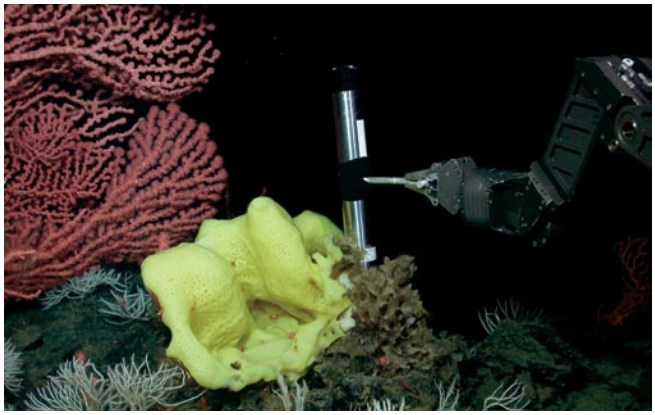


Figure 30: Current measurements were taken near corals using an acoustic doppler current profiler mounted on the remotely operated vehicle.

The stunning video from the expedition visually illustrates how biological communities on Davidson Seamount differ markedly from the surrounding abyssal plain. Unlike the monotonous, relatively featureless expanse of mud with few sightings of large animals (although the mud is teeming with life), the seamount, especially its shallower peaks, are home to dense assemblages of large cold-water corals, sponges, and a plethora of associated smaller animals (Figure 31). Deep-sea coral gardens found on seamounts are some of

Davidson Seamount Expedition

Project leads/managers: James Barry, Lisa Borok
Project team: Lonny Lundsten, George I. Matsumoto
Collaborators: Penny Allen and Warwick Sloss, British Broadcasting Corporation Natural History Unit, Bristol, United Kingdom; Allen Andrews, Moss Landing Marine Laboratories, California; Erica Burton, Andrew DeVogelaere, Chad King, and Huff McGonigal, Monterey Bay National Marine Sanctuary/National Oceanic and Atmospheric Administration

the most visually stunning and paradoxical biological assemblages in the ocean. The accumulated biomass of corals, sponges, and other animals of these communities is anomalously high for their depth in the deep-sea, and must be related to the high rates of survival and great longevity of corals (some known to live for hundreds of years), in addition to the apparently low rates of physical disturbance on the seamount.

The data and images gathered on this expedition are important to the Monterey Bay National Marine Sanctuary's current effort to incorporate Davidson Seamount into the sanctuary. Bringing the seamount under the auspices of the sanctuary would assure the protection and conservation of this unique habitat and its "old-growth forest" of the deep sea.

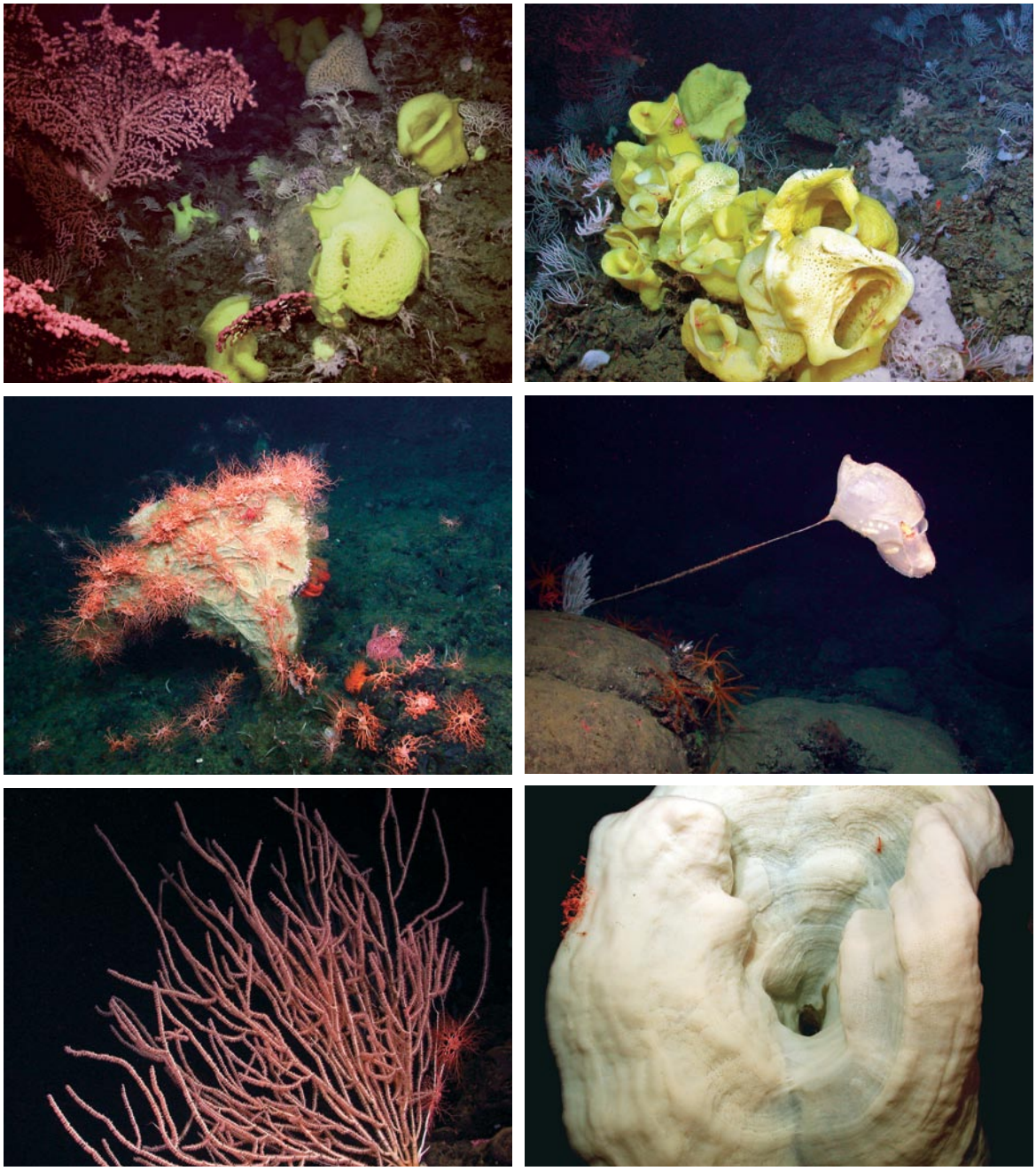


Figure 31: *(clockwise from top left)* Coral gardens on Davidson Seamount; yellow Picasso sponge; solitary tunicate (*Culeolus* sp); massive sponge species; bamboo coral (*Keratoisis* sp.); goiter sponge with basket stars.

A Pioneer Ocean Observatory

Ocean observing seems to be in everyone's plans. The National Science Foundation (NSF) will invest more than $300 million in a research system to catch important, but unpredictable, ocean events when they happen. The National Oceanic and Atmospheric Administration (NOAA) wants to build a large integrated observing system, based on its prediction that data from ocean observatories will be as important as weather forecasts to decisions that affect our daily lives by impacting our health, safety, economic competitiveness, and quality of life. The Department of Homeland Security views ocean observing as a weapon for counter-terrorism. But all of these plans were either in their embryonic stages or non-existent seven years ago. It was thus with nearly oracle-like vision that in 1999 MBARI began investing in the Monterey Ocean Observing System (MOOS), an advanced mooring design that provides power and bi-directional satellite communications from the sea surface to clusters of instruments on the seafloor through an optical-electrical-mechanical cable. All of the design work, prototyping, manufacturing, and testing culminated in 2006, when the MOOS mooring was installed outside of Monterey Bay in support of a major

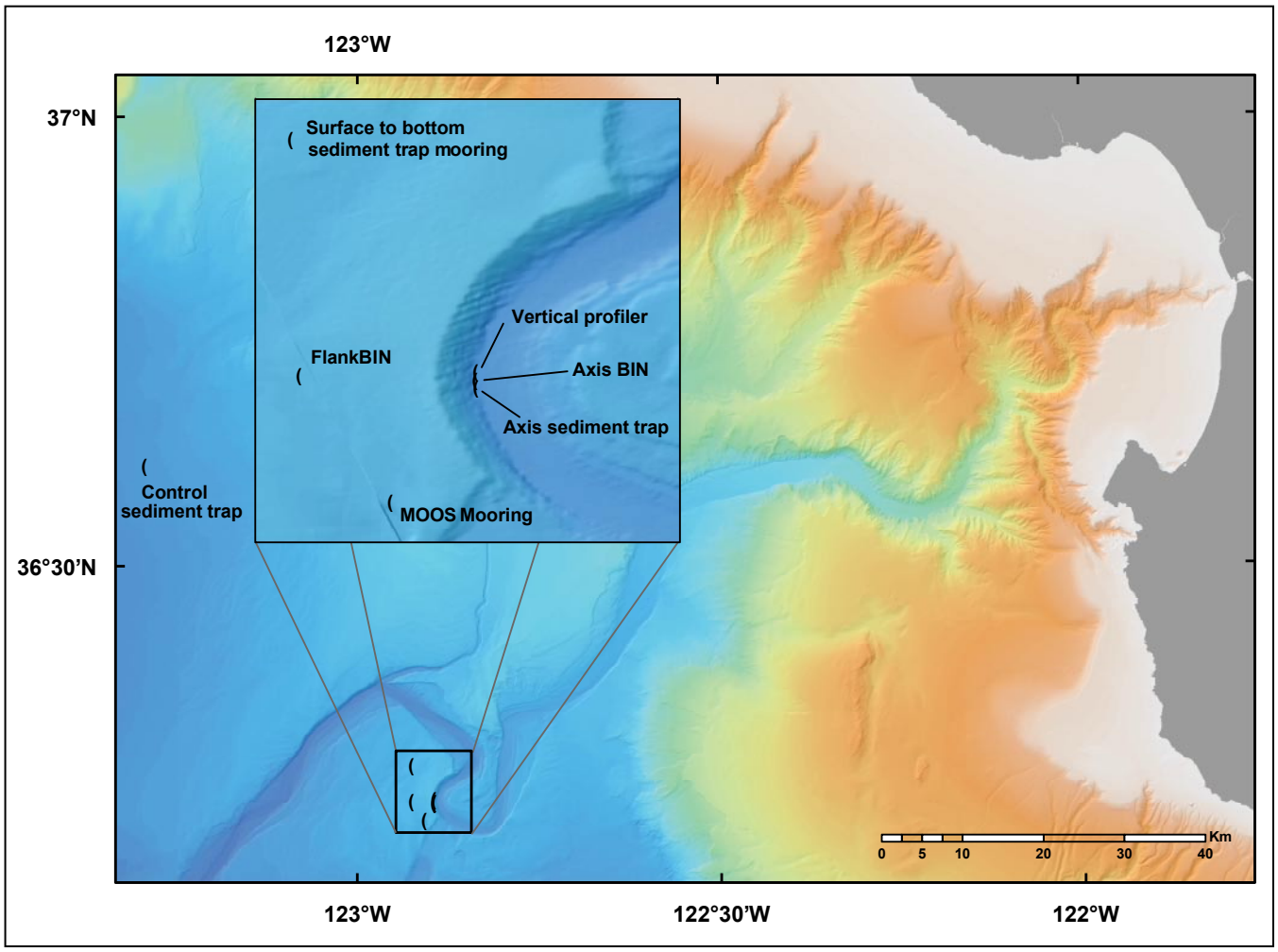


Figure 32: The MOOS science experiment is located about 100 kilometers west of Moss Landing, at the Shepard Meander, an active channel of Monterey Canyon at a depth of 3,450 meters.

experiment to measure carbon transport to the deep sea via submarine canyons.

This deployment of the MOOS infrastructure was the completion of a multiyear engineering development effort. It required close coordination across a broad section of MBARI, including the MOOS mooring team, other engineering teams, the machine shop, marine operations, and science groups. The Software Instrument Applications for MOOS (SIAM) team developed the systems software and wrote "instrument services" to adapt the unique command set of each instrument to the experiment protocol. The Shore Side Data System team provided archive services and tools for science users to access data from all the deployed instruments. Multidisciplinary science groups coordinated the deployment and collected and analyzed the scientific data.

The Shepard Meander Experiment, chosen as the first full field test of MOOS technology, was designed to identify and quantify the processes causing sediment to move into the deep sea. The existing paradigm is that deep-sea organisms live off organic matter that was produced in the overlying surface water and has settled vertically to the seafloor. In contrast, recent investigations have shown that organic matter produced on land and transported off the continent

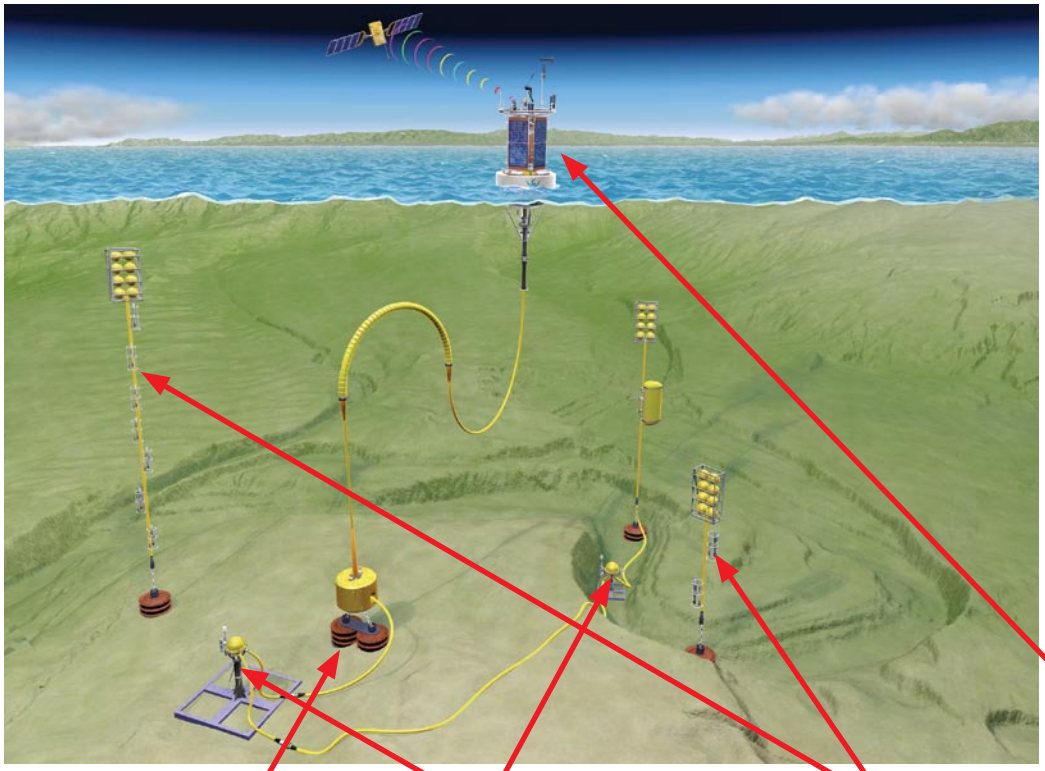
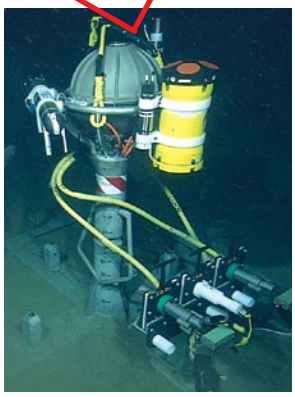


Figure 33: An artist's rendition of the MOOS observatory, along with photos of several observatory components. The surface mooring transmits power to seafloor instruments by way of a four-kilometer-long cable, which also transmits data from the seafloor back to the surface. The data are relayed from the surface buoy to shore via satellite. The instruments on the seafloor are actually located further from the main cable than depicted in this artist's rendition.

Mooring anchor and float



Instrument node

Sediment trap

Mooring

into deep-sea canyons and fan channels may be much more important than previously realized for the nourishment of benthic communities.

The site selected for the experiment was in the Shepard Meander, which lies about 100 kilometers west of Moss Landing, at 3,450 meters depth in the active channel of Monterey Canyon (Figure 32). This site was selected for three reasons. First, the site is far enough offshore to test the entire self-contained, yet portable, MOOS mooring technology, including over-the-horizon satellite communications technology. Secondly, recognizing that the Shepard Meander Experiment is also an engineering test with some risk, the site was selected to be easily reachable from Moss Landing by ship in case of technical problems. Finally, the site is located on the southern flank and in the axis of a channel that extends out from lower Monterey Canyon onto Monterey Fan, far enough down the canyon system to be disturbed less frequently by energetic sediment transport events that are now known to be common within the upper canyon. Given the amount of scientific equipment that has been sacrificed to extreme canyon-forming events further upslope, a more benign environment was deemed desirable for this first real application of MOOS technology.

Completing the field deployment of the experiment required three phases. In the first phase, the observatory support group launched the surface mooring and the specialized anchor cable from the R/V *Point Sur* on June 29, 2006. The designs of both the fiber-optic riser cable, which extends from the buoy on the surface to the seafloor, and the midwater flotation, which supports the cable, had been improved to make the system more robust based on the results from earlier test deployments and destructive testing in an MBARI laboratory test facility.

After testing verified that this operation was successful, the R/V *Western Flyer* and ROV *Tiburon* with the MBARI cable-laying sled were used to connect a combined fiber-optic and power cable to the base of the mooring and to lay it approximately 2.5 kilometers along the seafloor to the first benthic instrumentation site on the canyon shelf, about 2 kilometers back from the edge of the cliff. This mission was more challenging than expected when the benthic cable formed "slinky-like" coils on the seafloor as it was laid. Due in large part to the perseverance and maneuvering skills of the *Tiburon* pilots, the job was completed in spite of the poor cable performance, a good example of the unique capabilities of MBARI, where all participants are united in achieving the mission objectives. The twisting of the cable was ultimately traced to a manufacturing defect in the cable construction.

Once the benthic cable was in place, the flank instrument package was lowered by "benthic elevator" to the seafloor and connected using *Tiburon*, and electrical power was switched on from the mooring. In November the R/V *Western Flyer*/*Tiburon* completed the third phase of the installation with a redesigned benthic cable. *Tiburon* laid another 2.5 kilometers of cable from the flank instrument site, down the wall of the canyon to the second instrument site located in the center or axis of the canyon floor. This axis instrument node was then connected and powered. The Shepard Meander Experiment was the first successful installation of a seafloor observatory consisting of an interconnected

Continental Margin and Submarine Canyon Processes

Project leads: Charles Paull, Bill Ussler
Project manager: Bill Ussler
Project team: Larry Bird, David Caress, Doug Conlin, Gary Greene, Brett Hobson, Rendy Keaten, Hans Thomas, Duane Thompson
Collaborators: Scott Dallimore, Geological Survey of Canada; Angela Hessler, Chevron; Tessa Hill, University of California, Davis; Steve Holbrook, University of Wyoming, Laramie; Joel Johnson, University of New Hampshire, Durham; William Normark, United States Geological Survey, Menlo Park, California

Monterey Ocean Observing System (MOOS) Science Experiment

Project leads: Mark Chaffey, Andrew Hamilton
Project manager: Mark Chaffey
Project team: James Barry, Larry Bird, Francisco Chavez, Jon Erickson, John Ferreira, Kevin Gomes, John Graybeal, Kent Headley, Mike Kelley, Brian Kieft, Ed Mellinger, Tom O'Reilly, Charles Paull, Wayne Radochonski, John Ryan, Karen Salamy, Brian Schlining, Bill Ussler
Collaborators: Norm Farr and Dan Frye, Woods Hole Oceanographic Institution, Massachusetts

array of benthic instruments (Figure 33).

The full payload enabled testing at the maximum design level for all of the hardware and software systems including the power system, the SIAM data collection and telemetry-to-shore system and the shoreside data processing and archival systems. Since the observatory installation, about two megabytes of data are downloaded each day via satellite, processed, and served up on the world wide web: http://ssdspub.mbari.org:8080/mse/index.jsp.

Figure 34: MOOS lead engineer Mark Chaffey finalizes preparation of a seafloor instrument node just before deployment from the R/V *Western Flyer*. Science instruments are attached to the titanium sphere, which contains the computer, power system, and other electronics. The yellow cables wrapped around the base will be plugged into the seafloor cable by *Tiburon*.

The MOOS science experiment was designed to take full advantage of the number and diversity of instruments the observatory can support. Seventeen separate science instruments on the surface gather data to help estimate the biological productivity and vertical export of carbon from surface waters to the deep sea in response to variations in atmospheric forcing and ocean circulation. On the seafloor, the flank and axis instrument packages (Figure 34) each contain five instruments measuring suspended biological and inorganic matter, as well as two current meters for estimating the lateral transport of carbon and the influence of the submarine canyon. Two traditional sediment trap moorings were also deployed as part of the experiment for measuring vertical carbon flux and a lower water-column vertical profiler.

The data collected by this project (including the composition of the organic material, tracers like DDT residues, and vertical sediment fluxes provided by traditional sediment-trap moorings) indicate that relatively large volumes of organic-carbon-rich sediment have penetrated out onto Monterey Fan in historical times. While it has long been known that canyons are the conduits for sediments to reach the deep sea, the importance of canyon systems in bringing organic material to nourish deep-sea organisms may have been significantly underestimated.

The MOOS observatory continues to monitor the large abyssal channel, to determine the relative importance of submarine canyons as conduits for transporting fresh organic-carbon-rich sediment. It is likely, however, that most of the material moves through the canyon in episodic, energetic sediment transport events, rather than being carried along continuously in small amounts. Geologists know little about the magnitudes and frequencies of these episodic events, even though evidence from the channels on Monterey Fan indicates that episodic sediment transport events have dominated sedimentation in the last 2,000 years. No significant sediment transport events have been observed since the Shepard Meander Experiment began. But should such an event happen, the MOOS observatory will be there, waiting, monitoring, measuring, sampling, recording, and speeding the information shoreside in a way that no ship-based or manned expedition could ever hope to. The age of observatory science has arrived.

MBARI's AUV Operations Group: New Science through New Technology

At MBARI's inception, founder David Packard outlined the institute's first goal: to adapt a commercial remotely operated vehicle (ROV) for science. To achieve the full return of Packard's investment in the new vehicle that would be christened *Ventana*, MBARI immediately built teams across the institute to share the responsibility for its success. By mid-2007 *Ventana* will have over 3,000 dives to its credit, making it the most scientifically successful ROV ever, thanks to the pilots, marine operations technicians, engineers, and scientists who work together to keep it a well-equipped, state-of-the-art vehicle used to solve important problems.

More recently, MBARI has focused attention on developing missions and payloads for autonomous underwater vehicles (AUVs). AUVs are attractive for replacing some routine ROV missions and vessel-based time series as they are less expensive to build and operate. Although other institutions had previously developed and deployed AUVs to aid in ocean science, AUVs had yet to make the transition to proven workhorses for scientific data collection. Jim Bellingham, MBARI's chief technologist, transplanted his AUV program to MBARI from the Massachusetts Institute of Technology nine years ago, acknowledging that a big draw was the capable marine operations team at MBARI. This AUV Operations Group frees Bellingham's research and development engineers from the day-to-day demands of operating the vehicles in support of a growing cadre of scientific users. The MBARI AUV program provides an excellent example of how this support has translated into a world-class program of ocean science and technical development.

Led by Hans Thomas and supported by Duane Thompson and Doug Conlin, the AUV group in the Marine Operations Division maintained two AUVs at sea 116 days in 2006, with one vehicle for upper-water column surveys and the other specialized for seafloor mapping. The group has virtually adopted researcher David Caress, the driving force behind the mapping AUV (Figure 35). An expert in the challenges of deep-sea acoustics, Caress has taught the group that precision mapping and the requisite precise underwater navigation are a science and an art in and of themselves.

The AUV group reflects a sense of accomplishment that is achieved when a team develops new technology and then operates that technology at sea to unravel mysteries of the ocean. In many ways, ocean science is more challenging than space exploration. For example, humans are, by their very nature, dependent on sight, but because light is attenuated within meters in the ocean, underwater cameras impart a limited sort of "tunnel vision." Fortunately, this problem that has plagued us for years is being overcome by high-precision acoustics providing resolution that can be measured in centimeters. We can see again, and not just a few meters, but the panorama of kilometers of seafloor, or great three-dimensional chunks of ocean. The ocean puzzle that was previously presented to us as dynamic, scattered pieces can now be seen as a whole.

Even at this early stage in AUV operations for science, the small, but dedicated group has been instrumental in enabling new science discoveries. Some of the newest discoveries include sediment waves in Monterey Canyon that seem similar in both topography and movement to glaciers (Figure 36), new hydrothermal vents on Axial Seamount, and gas hydrate fields flanking Barkley Canyon.

The AUV operations team faces a broad set of tasks. The vehicles require sophisticated autonomous control, data management, and storage for a diverse set of sensors, precision acoustic navigation, and complex mechanical functions for propulsion and control. The AUVs also include two-way

Figure 35: *(From left)* Doug Conlin, Hans Thomas, David Caress, and Duane Thompson

satellite communications technology so that the vehicles can communicate with shore personnel when deployed unattended for extended periods. The operations team continues to refine both the mapping AUV (christened the *D. Allan B.* after MBARI's late, long-time board member, D. Allan Bromley) and the upper-water-column AUV by extending their battery power for more endurance, and developing the acoustic modem to provide a safety recall capability and to aid navigation. In addition, they support scientists across the spectrum of disciplines and engineers on projects including the *Gulper* (a discrete water-sampling system) and artificial intelligence (Figure 37).

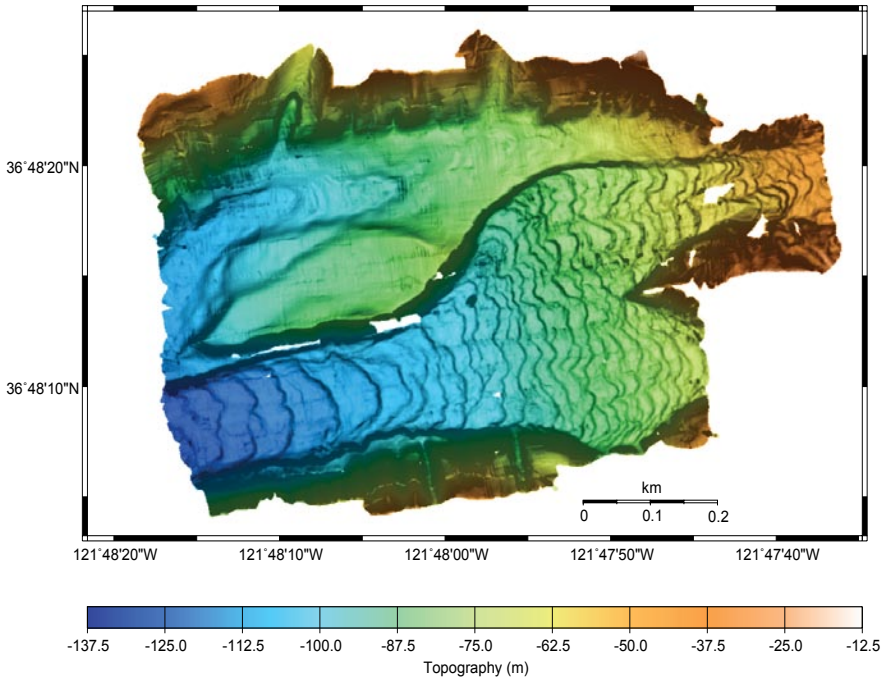


Figure 36: Geologist Charlie Paull uses maps such as this one created with AUV data to study the dynamics of Monterey Canyon. In this image, the sediment transport waves seems to resemble glacier tracks.

The next challenge for the AUV operations team is to fully exploit our abilities to conduct vehicle operations on vessels of opportunity. By making AUV operations portable, our scientists can venture into new interesting territories beyond Monterey Bay and explore exciting new targets around the globe. This capability will support either the mapping or basic instrument AUVs, therefore the possible applications for these systems will be far reaching. Missions such as event response, surveys, or polar work will become feasible. By extending the AUV team's reach, we will be sharing our MBARI assets with the larger scientific community, which is central to MBARI's goals. To prepare for this capability, the team will be specifying and purchasing new equipment in 2007, including a large portable knuckle boom crane with a custom docking head, and shipping vans configured for the AUVs, maintenance supplies, and tools. The AUV group will be integral to the 2008 Gulf of California Expedition, as the AUV takes on the role of a scout, surveying 14 square kilometers every eight hours, in the weeks preceding the ROV expedition. The plan is for the mapping AUV to survey large chunks of seafloor at sub-meter resolution and locate specific targets of interest for the ROV teams to investigate.

AUVs have now taken their place as dynamic operational tools in MBARI's quest to understand ocean processes. As was the case for MBARI's investment with ROVs, the main contribution was not necessarily in MBARI's design of the vehicle itself, but in building the team to operate the equipment in support of ever-changing science missions, day in, day out and week in, week out, with high reliability, in challenging environments and circumstances. MBARI is very proud of its AUV Operations Group, and looks forward to the new scientific discoveries this group will enable.

Figure 37: The AUVs must be launched and recovered by cranes operating from the ship's deck, which limits operations to periods of very low sea states.

Project Teams

Application of Novel Sensor Technology to Studies of the Marine Nitrogen Cycle

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Steve Fitzwater, Hans Jannasch, Joe Needoba, Josh Plant, Carole Sakamoto
Collaborators: Steve Riser and Dana Swift, University of Washington, Seattle

Work has focused on developing and demonstrating new scientific applications for nitrate and ammonia chemical sensors that were developed at MBARI. The In Situ Ultraviolet Spectrophotometer (ISUS) was integrated into a profiling float. The feasibility of making eddy correlation measurements of nitrate flux across the sediment/water interface using the ISUS optical nitrate sensor was demonstrated. A benthic flux chamber with an integral ISUS sensor has been developed for muddy sediments to validate these measurements.

Automated Visual Event Detection (AVED)

Project lead: Danelle Cline
Project manager: Duane Edgington
Project team: Andrew Chase, Kevin Gomes, Ishbel Kerkez, Linda Kuhnz, Jerome Mariette, Bruce Robison, Susan Von Thun, Edith Widder
Collaborator: Erika Raymond, Ocean Research and Conservation Association, Fort Pierce, Florida

This system for detecting events of interest in underwater video was enhanced for processing video from fixed observatory cameras. Hours of archival video from the Eye-in-the-Sea camera were processed and analyzed, verifying the ability of the AVED system to filter out video segments containing only marine snow or other artifacts and to detect events of interest even in low-contrast, noisy video. The AVED hardware and software were upgraded to enable processing of high definition video at full resolution and capture at full frame rate.

Autonomous Ocean Sampling Network (AOSN)

Project lead: James G. Bellingham
Project team: Francisco Chavez, Michael Godin, Thomas Hoover, Yanwu Zhang
Collaborators: Yi Chao, Jet Propulsion Laboratory, Pasadena; Russ Davis, Scripps Institution of Oceanography, La Jolla, California; David Fratantoni, Woods Hole Oceanographic Institution, Massachusetts; Naomi Leonard, Princeton University, New Jersey; Sharan Majumdar, University of Miami, Florida; Jerrold Marsden, California Institute of Technology, Pasadena; Steve Ramp, Naval Postgraduate School, Monterey, California; Allan Robinson, Harvard University, Cambridge, Massachusetts; Igor Shulman, Naval Research Laboratory, Stennis Space Center, Mississippi

For two months, oceanographers from a dozen institutions collaborated in the unique Monterey Bay 2006 experiment. Four major field experiments examined coastal processes: the use of real-time data in models to predict and adapt daily sampling; studies of biological layers in the coastal ocean; the effects of subsurface features on currents, eddies and heat transfer; and the effects of ocean layers and currents on sound, electrical, and magnetic signal transmissions. MBARI developed and provided data systems to enable sharing of data and real-time operations during the field program, including a web-based portal to enable participants to collaboratively control the observation system and share models and information without leaving their home institutions. MBARI researchers also developed methods to predict and evaluate observational performance, extending previous observation metrics to describe performance observations.

AUV Docking

Project lead: James G. Bellingham
Project manager: Brett Hobson
Project team: Jon Erickson, Thomas Hoover, Lance McBride, Rob McEwen, Steve Rock, Farley Shane, Hans Thomas
Collaborators: P. Edgar An, Florida Atlantic University, Boca Raton; Tim Stanton, Naval Postgraduate School, Monterey, California

Tremendous headway was made with the demonstration of a fully functioning prototype of the AUV docking system. AUV docking offers the unique capability to perform oceanographic surveys without a ship and allows for immediate deployment of an AUV in response to an event. The team developed subsystems for homing, capture, self-leveling, power-recharge, and data transfer. The subsystems were integrated and tested in the MBARI test tank, then deployed in successful ocean tests.

AUV *Gulper*

Project lead: John Ryan
Project manager: Alana Sherman
Project team: Larry Bird, Brian Kieft, Chris Scholin, Farley Shane
Collaborators: Steven Haddock, Joe Jones, and Robert Vrijenhoek, MBARI

The *Gulper* water sampler prototype was refined to capture two liters of water in only a few seconds, to accommodate pressure changes between the sample water and seawater, and to prevent samples from leaking. The prototype was tested on remotely operated vehicle (ROV) *Ventana* and on the AUV. The project team also built an oil-filled housing for a new type of actuator for sample triggering.

Benthic Biology and Ecology

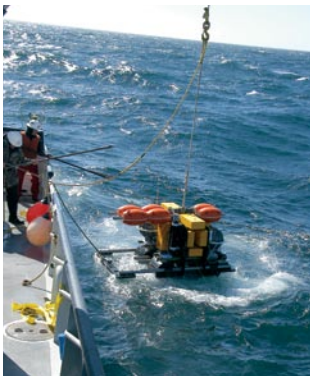
Project lead/manager: James Barry
Project team: Larry Bird, Kurt Buck, Linda Kuhnz, Chris Lovera, Craig McClain, Eric Pane, Kris Walz, Patrick Whaling
Collaborators: Kevin Carman, Louisiana State University, Baton Rouge; Katsunori Fujikura, Japan Agency for Marine-Earth Science and Technology; Jacqueline Grebmeier, University of Tennessee, Knoxville; Charles Paull, MBARI; Dave Thistle, Florida State University, Tallahassee; Patricia Yager, University of Georgia, Athens

Research on the effects of rising ocean carbon levels indicate that shallow communities are far more tolerant of acidification than those in deep waters. Laboratory studies showed a shallow Dungeness crab is quite tolerant to hypercapnia (high levels of carbon dioxide), while a deep-living Tanner crab is relatively intolerant. Sediment traps and optical sensors moored within and outside of Monterey Canyon showed that levels of organic carbon and suspended sediment in the canyon exceed those outside of the canyon by roughly a factor of 10. Studies of benthic faunal patterns in Monterey Canyon indicate that frequent turbidity flows in the upper canyon lead to lower animal diversity on the seafloor there, while increasing animal densities at deeper depths.

Benthic *Rover*

Project leads: Paul McGill, Ken Smith
Project manager: Paul McGill
Project team: Andrew Chase, Rich Henthorn, Brett Hobson, Doug Pargett, Alana Sherman

Development continued on the benthic *Rover*, an autonomous seafloor-transecting instrument for estimating the impact of phytodetritus on seafloor communities. Engineers at Scripps Institution of Oceanography completed the vehicle frame and propulsion system, then pressure housings and instruments were added at MBARI. Following *Rover's* successful first deployment at 1,000 meters depth in Monterey Bay, its propulsion system and basic instrumentation were tested at a depth of 4,100 meters during a cruise on the R/V *Atlantis*. A respirometer was integrated onto the vehicle, allowing for the study of oxygen consumption within the sediments.



Bioluminescence and Zooplankton

Project lead/manager: Steven Haddock
Project team: Lynne Christianson, Rebecca Hoover
Collaborators: William Browne, University of Hawaii, Honolulu; Casey W. Dunn, Brown University, Providence, Rhode Island; Rebeca Gasca, El Colegio de la Frontera Sur, Mexico; Richard Harbison, Woods Hole Oceanographic Institution, Massachusetts; Philip R. Pugh, National Oceanography Centre, Southampton, United Kingdom; Bruce Robison, MBARI; Brad Seibel, University of Rhode Island, Kingston; Erik Thuesen, Evergreen State College, Olympia, Washington

Progress was made in the study of four principal groups of organisms: ctenophores, siphonophores, radiolarians, and hyperiid amphipods. On two cruises off the Central California coast and one cruise to the Gulf of California, dozens of new species were collected, demonstrating how little we know about the inhabitants of the vast deep sea. Molecular work on these groups has produced several surprising results, including discovery of new families with member species that have never been described. Extensive characterization of planktonic pigments revealed classes of fluorescent and absorbent materials which give plankton their unique colors. A new green-fluorescent protein was discovered from only the third phylum known to possess these important genes.

Biophysical Oceanographic Sensor Array (BiOSA)

Project lead/manager: Zbigniew Kolber
Project team: Denis Klimov, Wayne Radochonski

The mechanical design and most of the electronic design have been completed for BiOSA, a multifunctional, reconfigurable sensor platform capable of operating as a network object in an ocean observatory. The mechanics were pressure tested at the equivalent of 4,000 meters depth. The fluorescence sensor for the BiOSA has been implemented and tested in a benchtop fast-repetition-rate fluorometer instrument.

Center for Microbial Oceanography: Research and Education (CMORE)

Project leads/managers: Zbigniew Kolber, Chris Scholin
Project team: Scott Jensen, Doug Pargett, Kevin Wheeler
Collaborators: Ed DeLong and Jon Zehr, MBARI; David Karl, University of Hawaii, Manoa; Ricardo Letelier, Oregon State University, Corvallis; Craig Taylor, Woods Hole Oceanographic Institution, Massachusetts

The CMORE center, sponsored by the National Science Foundation, was established to improve our understanding of how microorganisms drive biogeochemical cycles in the global ocean, and to project how environmental change may affect microbial communities and the processes they mediate. The center is a joint effort of researchers at the University of Hawaii, Massachusetts Institute of Technology, Oregon State University, Woods Hole Oceanographic Institution, and MBARI.

Center of Integrated Marine Technologies (CIMT)

Project lead/manager: Francisco Chavez
Project team: Seth Bushinsky, Paul Coenen, Gernot Friederich, Ken Heller, Mike McCann, Reiko Michisaki, Craig Okuda, Mark Pickerill, Martin Suro
Collaborators: Don Croll and Raphael Kudela, University of California, Santa Cruz

MBARI has supported CIMT with the development and deployment of the M0 mooring in Monterey Bay. The M0 mooring is located in an area of highly stratified waters and increased algal bloom formation relative to the more open-circulation conditions at moorings M1 and M2. New data collected from the M0 location show that dinoflagellates may influence carbon dioxide dynamics in Monterey Bay by migrating to depth at night, harvesting nutrients and then migrating to surface during the day and consuming carbon dioxide.

Central and Northern California Ocean Observing System: Leadership in Coordination of Ocean Observing (CeNCOOS)

Project leads: Francisco Chavez, Heather Kerkering
Project manager: Heather Kerkering
Collaborators: Sarah Allen, Point Reyes National Seashore; Kenneth Coale, Moss Landing Marine Laboratories; Michael Connor, San Francisco Bay Estuary Institute; Newell Garfield, San Francisco State University; Pat Coulston, California Department of Fish and Game; Karen Garrison, Natural Resources Defense Council; Zeke Grader, Pacific Coast Federation of Fishermen's Associations; Gary Griggs, University of California, Santa Cruz; Churchill Grimes, Southwest Fisheries Science Center; John Largier, University of California, Davis; Laura Pederson, CODAR Ocean Sensors; Steve Ramp, Naval Postgraduate School; Jeff Robinson, Humboldt Bay Harbor Recreation and Conservation District; Sheila Semans, California State Coastal Conservancy

CeNCOOS assisted with recovery efforts after the largest oil spill drill in California history, providing scientists and hazardous materials specialists with historical and real-time biological and physical data, geographic information system data for ecological monitoring and decision-making, global positioning-equipped surface drifters, and high-frequency radar technologies. Observatory experts recognized CeNCOOS and its local partners as one of the two groups in the nation to develop an inventory of observing assets that provide data in near real-time and a map of existing assets which can be queried for details. CeNCOOS, along with its southern California counterpart, developed a well-received exhibit for the California and World Ocean Conference.

Chemical Sensor Program

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Steve Fitzwater, Hans Jannasch, Todd Martz, Josh Plant, Carole Sakamoto
Collaborator: Zanna Chase, Oregon State University, Corvallis

Sensors to detect ammonia, total inorganic carbon, and copper have been developed into prototypes that were deployed in the Elkhorn Slough. Data collected with the ammonia sensor were validated by independent laboratory measurements. Work continues on the development of in situ iron analytical systems and a benchtop analytical method for dissolved carbonate ion. Field work was completed on a project to demonstrate the utility of the In Situ Ultraviolet Spectrophotometer (ISUS) for in situ sulfide measurements. An ISUS was integrated with a benthic flux chamber and deployed at the Extrovert Cliff cold-seep site.

Continental Margin Processes Self-Triggering Event Detector

Project lead: Larry Bird
Project manager: Bill Ussler
Project team: Brett Hobson, Charles Paull

The Self-Triggering Event Detector (STED) was developed to provide a means for detecting the occurrence of energetic sediment transport events within submarine canyons. STEDs were placed in the axis of the Monterey Canyon at locations known to experience frequent sediment transport events. When a STED platform experiences currents in excess of 200 centimeters per second at one meter above the sea bed, a positive buoyant science package is released to the surface. This science package includes a pop-off satellite transmitter that will time-stamp the event and can be adapted to provide essential scientific data. Significant testing proved the STED concept with one such instrument reporting an event in June.

Core Conductivity-Temperature-Depth (CTD) Data

Project lead: David Caress
Project manager: Mike Burczynski
Project team: Doug Conlin, Gernot Friederich, Reiko Michisaki, Bruce Robison, Rich Schramm, Patrick Whaling

Support continued on the maintenance, calibration, and configuration of core CTD instruments, electronics, and related hardware. Development of the new user interface for real-time ROV data display was completed and integrated onto both vehicles. In addition, the ROV data processing and auto-archival software underwent a much-needed major overhaul. One of the end products was a more user-friendly web interface to view and plot archived data.

Core Mooring Data

Project lead: David Caress
Project manager: Brian Schlining
Project team: Francisco Chavez, Mike McCann
Collaborator: Fred Bahr, Naval Postgraduate School, Monterey, California

Data from the M1 and M2 moorings continued to be archived and monitored. The mooring data streams were manually edited and quality controlled by an external contractor. Automated systems detected when additional mooring data became available and posted them to the appropriate repositories. Hourly and daily averages of the core data streams were produced.

Core Navigation Data

Project leads: David Caress, Dale Graves
Project manager: David Caress
Project team: Jennifer Chase, Jane Curtner, Mike McCann, Rich Schramm

Staff from almost every division worked together to maintain the integrity of navigation data collected by the ships and remotely operated vehicles. Software was developed to automate data processing and archiving and the data were monitored to assure consistent quality.

Creating the Essential Science and Technology for Knowledge of the Ocean in a High CO_2 World

Project leads: James Barry, Peter Brewer, Bill Kirkwood
Project manager: Edward Peltzer

As a scoping proposal, the objective of this project was to define the scientific problem of ocean acidification and MBARI's role within it, and identify a team of interested individuals to serve as collaborators for a multi-institutional approach to the problem. Experimental work began with in situ experiments on midwater organisms by exposing them to the high-CO_2/low-pH seawater approximating conditions expected in the later part of this century. The first short-term attempts at this were successfully made on the jelly *Solmissis*. New designs have been created for Free Ocean CO_2 Enrichment experiments that incorporate simpler delivery of CO_2-enriched seawater and delay lines sufficient for equilibrium to be reached based upon fundamental kinetic models and data.

Deep-Water Salps in Monterey Bay

Project lead/manager: Lawrence Madin

Two days of R/V *Point Lobos* and ROV *Ventana* time were used to continue collection of samples and data on particle transformation by midwater pelagic tunicates, particularly *Vitreosalpa gemini* and the doliolid *Doliolinetta intermedia*. These data will contribute to the larger study on the role of these organisms in the collection, compaction, and sedimentation of particulate material in the mesopelagic zone.

Deep-Water Sample Module for the Environmental Sample Processor (ESP)

Project leads: Scott Jensen, Chris Scholin
Project managers: Doug Pargett, Kevin Wheeler
Project team: Mark Brown, Jon Erickson, Christina Preston, Brent Roman
Collaborator: John Delaney, University of Washington, Seattle

A prototype pressure housing and a sample collection module were designed to allow deployment of the ESP at depths to 1,000 meters. The prototype was built, then deployed using the ROV *Ventana*.

Development of an Eddy Flux System for Benthic Flux Measurements

Project leads: James Barry, Ken Johnson
Project manager: James Barry
Project team: Luke Coletti, Andrew Hamilton, Chris Lovera, Patrick Whaling

Deployments of the eddy flux system on the continental shelf yielded several reliable estimates of benthic fluxes of nitrate and oxygen. Recent measurements of nitrate flux using the eddy correlation technique were very near the values indicated in the scientific literature. For oxygen, eddy correlation estimates were nearly identical to those obtained from benthic chambers, and somewhat higher than oxygen microprofiles at the same site. Measurements of biogeochemical fluxes through the seabed are important for understanding elemental cycles and rate processes for the benthic biological assemblage, particularly oxygen and carbon consumption.

Equatorial Pacific Moorings

Project lead/manager: Francisco Chavez
Project team: Gernot Friederich, Martin Suro
Collaborator: Chris Sabine, National Oceanic and Atmospheric Administration/Pacific Marine Environmental Laboratory, Seattle, Washington

For a decade, MBARI has maintained instrumentation on moorings in the equatorial Pacific as part of the Tropical Atmosphere Ocean array. The MBARI-maintained database of chlorophyll and nutrients that spans over 25 years continues to be updated, allowing for analysis of biological-physical coupling in the equatorial Pacific and long-term trends in ecosystem processes.

Feasibility of Biofuel-Cell Powered Deep-Ocean Sensors

Project lead/manager: Peter Girguis
Project team: Lance McBride
Collaborator: Clare Reimers, Oregon State University, Corvallis

A variety of instruments—including commercially available pH and optical density sensors, transmissometers, and high brightness light-emitting diodes—have been identified that may be powered by in situ microbial fuel cells. Additionally, a new design of microbial fuel cell (a device that harnesses energy from microbial metabolism) was deployed in the Monterey Canyon to study both "power production" as well as microbial community composition. These designs produced more power than previously described, and fostered the growth of numerous bacterial species on the electrodes.

Integrated Ocean Drilling Program (IODP) Boreholes

Project leads: Charles Paull, Bill Ussler
Project manager: Bill Ussler
Project team: Larry Bird, Knute Brekke, T. Craig Dawe, Jon Erickson
Collaborators: Kevin Grigar, Gene Pollard, and Derryl Schroeder, Texas A&M University, Austin

Efforts continued toward the establishment of an IODP borehole research facility in Monterey Bay, which will eventually be connected to the MARS cable. Activities centered on finalizing designs for the science payload modules that are integral to the overall ROV-serviceable, submarine cable-connected wellhead design. Conceptual designs were completed for an ROV-installed permanent borehole sealing system that would preclude contamination of borehole fluids and collect temperature and pressure conditions inside the borehole.

Investigation of Unobtrusive Observation Techniques

Project lead/manager: Edith Widder
Project team: Steven Haddock, Gene Massion, Kim Reisenbichler, Bruce Robison
Collaborators: Lee Frey, Harbor Branch Oceanographic Institution, Fort Pierce, Florida; Erika Raymond, Johns Hopkins University, Baltimore, Maryland

The unobtrusive autonomous deep-sea observatory, Eye-in-the-Sea (EITS), was deployed in Monterey Canyon. A hydrophone fitted to the system recorded the acoustic signatures of the ROV *Ventana* and ROV *Tiburon* at incremental distances away from the sensor. Presence or absence of animal activity around EITS was also recorded and compared during vehicle-present and vehicle-free recording periods. Initial results

indicate a species-specific aversion to ROV activity around the study site. Experiments with white and red illuminators were also conducted in the absence of ROV noise.

Joint Projects Committee

Project leads: Chris Harrold, George I. Matsumoto
Project manager: George I. Matsumoto
Project team: Lisa Borok, Judith Connor, Kim Fulton-Bennett, Lonny Lundsten, Craig Okuda, Kyra Schlining, Susan von Thun
Collaborators: Rita Bell and Cynthia Vernon, Monterey Bay Aquarium; Janice McDonnell, Rutgers University, New Brunswick, New Jersey

MBARI and the Monterey Bay Aquarium continued to strengthen their unique collaboration. MBARI provided AUVs and staffing for a two-day *Deep-Sea Days* event and began working with aquarium staff to plan a permanent exhibit about MBARI. MBARI staff regularly contributed to the aquarium newsletter, interpreted the *Exploring Monterey Canyon* program in the aquarium auditorium, and provided high-definition video to update this program.

Juan de Fuca Boreholes

Project lead/manager: Hans Jannasch
Project team: Josh Plant, Geoff Wheat
Collaborators: Keir Becker, University of Miami, Florida; Earl Davis, Pacific Geoscience Center, Canada; Andy Fisher, University of California, Santa Cruz

During a cruise aboard the R/V *Atlantis* with the *Alvin* submersible, an effort was made to better seal one of the boreholes in the eastern flank of the Juan de Fuca Ridge. The expedition also permitted the exchange of several seafloor OsmoSamplers. Work progressed on the planning, design, and building of OsmoSampler packages, including newly developed seafloor samplers that can be easily exchanged during submersible or ROV visits.

Land/Ocean Biogeochemical Observatory (LOBO)

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Steve Fitzwater, Hans Jannasch, Joe Needoba, Josh Plant, Carole Sakamoto
Collaborators: Marc Los Huertos, California State University, Monterey Bay; Steve Monismith and Adina Paytan, Stanford University, California; Kerstin Wasson, Elkhorn Slough Estuarine Research Reserve, California

The LOBO network of chemical sensors was expanded by adding a new mooring in the Parson's Slough portion of Elkhorn Slough, which is near MBARI. These sensors monitor the concentration of nutrient chemicals, such as nitrate and ammonia, which influence plant growth in the coastal ocean. In order to make this development available to the broader community, the LOBO system design was licensed to Satlantic, Inc. for commercial distribution. The Satlantic system will provide a complete plug-and-play observing system.

Long-Term Broadband Seismic Observatory in Monterey Bay

Project leads: Paul McGill, Barbara Romanowicz
Project manager: Paul McGill
Collaborators: David Dolenc and Doug Neuhauser, University of California, Berkeley

Data from the Monterey Ocean Bottom Broadband (MOBB) seismic station were processed to reduce the long-period noise due to infragravity waves as well as shorter period, signal-generated noise, due to the reverberation of seismic waves in the near surface sediment layers. Work began on plans to add an interface from MOBB to the Monterey Accelerated Research System cabled observatory in Monterey Bay.

Marine Metadata Interoperability Project

Project lead: Luis Bermudez
Project manager: John Graybeal
Collaborators: Philip Bogden, Gulf of Maine Coastal Observing System; Matthew Howard and Stephanie Watson, Texas A&M University, Austin; Andrew Maffei, Woods Hole Oceanographic Institution, Massachusetts; Stephen Miller and Karen Stocks, Scripps Institution of Oceanography, La Jolla, California; and many national and international members of the marine data management community

The project team developed a draft ontology for observing platforms, hosted a major workshop on sensor metadata interoperability, held a two-day strategic planning meeting, and initiated a major technical collaboration on an end-to-end data infrastructure. By securing a three-year grant from the National Science Foundation the project is now positioned to become a major contributor to the development of effective, sophisticated oceanographic data systems and data access capabilities.

Midwater Ecology

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Karen Osborn, Rob Sherlock
Collaborators: Stephanie Bush, Steven Haddock, William Hamner, Larry Madin, George I. Matsumoto, Ken Smith, and Edith Widder, MBARI; Jeff Drazen, University of Hawaii, Honolulu; Kevin Raskoff, California State University, Monterey Bay; Brad Seibel, University of Rhode Island, Kingston; Tim Shaw, University of South Carolina, Columbia; Maria Vernet, Scripps Institution of Oceanography, La Jolla, California; Lou Zeidberg, Hopkins Marine Station, Stanford University, Pacific Grove, California

Research focused on quantifying the routes and rates of nutrient energy transfer through the ecosystem, in terms of energy flow and organic carbon flux. On about a monthly basis, samples of key mesopelagic species were collected for proximate and elemental carbon, hydrogen, and nitrogen analyses. This allowed the calculation of how much organic carbon is tied up in each link of the web, and the measurement of carbon flux through the system. On the same monthly time scale, specimens were collected for respiration studies as a measure of metabolism, or how much nutrient energy is consumed at each major step in the web.

Midwater Respirometry System

Project leads: Kim Reisenbichler, Bruce Robison
Project manager: Kim Reisenbichler
Project team: Jon Erickson, Brett Hobson, Craig Okuda

A respirometry system was developed to enable midwater researchers to conduct in situ oxygen consumption measurements on animals that do not survive capture and transport to the surface. The system will also be used in situ with more robust animals that can also be respired in the laboratory to determine the effects of pressure and decompression on the respiration rates of midwater animals. The new system was assembled using samplers and electronics previously developed for MBARI's benthic respirometer system. Two successful midwater deployments provided the first in situ measurements of midwater animal oxygen consumption taken in the oxygen minimum layer.

Midwater Time Series

Project lead/manager: Bruce Robison
Project team: Karen Osborn, Kim Reisenbichler, Rob Sherlock
Collaborators: Stephanie Bush, Steven Haddock, William Hamner, Laurence Madin, George I. Matsumoto, and Edith Widder, MBARI; Jeff Drazen, University of Hawaii, Honolulu; William Gilly and Lou Zeidberg, Hopkins Marine Station, Stanford University, Pacific Grove, California; Kevin Raskoff, California State University, Monterey Bay; Brad Seibel, University of Rhode Island, Kingston

Regular video transects of the midwater continued, providing an unparalleled time series measuring the identity, abundance, and vertical distribution of the constituents of the midwater fauna at specific sites in the Monterey Bay region. An example of the application of the data provided by the time series is the investigation of the invasion of central California waters by the large, aggressive Humboldt squid, *Dosidicus gigas*, reflecting a significant change in the composition and structure of the pelagic community along the entire coast of California.

Mining the Video Annotation and Reference System (VARS) for Science Insights

Project leads: Charles Paull, Bill Ussler
Project manager: Bill Ussler
Project team: Andrew Chase

New software tools were developed to mine and analyze historical data in the VARS database to advance the understanding of the relationship between seafloor geology and benthic ecology, and to identify factors that control the patterns and patchiness in the distribution of benthic organisms on the seafloor of Monterey Bay.

Molecular Ecology of Marine and Aquatic Organisms

Project lead: Robert Vrijenhoek
Project manager: Joe Jones
Project team: Caren Braby, David Clague, Katharine Coykendall, Scott Jensen, Shannon Johnson, Roman Marin III, Gene Massion, Chris Scholin, Alana Sherman, Curtis Young
Collaborators: Melissa Duhaime, Max-Planck-Institut für Marine Mikrobiologie, Germany; Shinzou Fujio, University of Tokyo, Japan; Shana Goffredi and Victoria Orphan, California Institute of Technology, Pasadena; Ana Hilario, University of Santiago, Portugal; Enrique Macpherson, Centro de Estudios Avanzados de Blanes, Spain; Peter Moller, University of Copenhagen, Denmark; Vicki Pearse, University of California, Santa Cruz; Fred Pleijel, Göteborg University, Sweden; Steve Rock, MBARI; Greg Rouse, Scripps

Institution of Oceanography, La Jolla, California; Michel Segonzac, Institut Francais de Recherché pour l'Exploitation de la Mer, France; Craig Smith, University of Hawaii, Manoa; Peter Smith, National Institute of Water and Atmospheric Research, New Zealand; Nicole Stroncik, University of Kiel, Germany; Paul Tyler, National Oceanographic Centre, United Kingdom; Cindy van Dover, College of William and Mary, Williamsburg, Virginia; Anders Waren, Swedish National Museum; Yong-Jin Won, Ewha Womans University, South Korea; Craig Young, University of Oregon, Eugene

Surveys of whale-falls in Monterey Bay have now revealed 12 species of *Osedax* bone-eating worms that segregate partially according to depth. The carcass of a 10-meter-long grey whale at 1,700 meters depth in Monterey Canyon revealed that *Osedax rubiplumus* larvae densely colonize a whale carcass in less than three months. Time-series analyses of *Osedax* clearly showed that the microscopic males colonize later than females and then accumulate gradually in number, which is consistent with the hypothesis that the male sex is determined environmentally. *Osedax* research has been extended into the areas of systematics and reproduction, symbiosis and microbiology, developmental biology, and paleontology.

Monterey Accelerated Research System (MARS) Cabled Observatory

Project manager: Keith Raybould
Systems engineer: Gene Massion
Project team: Mandy Allen, Aaron Marburg, Ed Mellinger, Kevin Sullivan, Greg Voogd
Partners: University of Washington, Seattle; Woods Hole Oceanographic Institution, Massachusetts; industrial partners Nautronix MariPro and Alcatel Submarine Networks

Final environmental and construction permits were acquired for the MARS cable installation and shore-landing construction. The subsystem integration and testing of the low-voltage power system, the data communication system, the housings, and the science harnesses proceeded at MBARI. Alcatel designed and fabricated the medium-voltage converters. The horizontal directional drilling for the cable landing on shore, the shore landing facility, and connection to the utilities were all completed.

MARS Toolsled and Port Testing Tool

Project lead/manager: T. Craig Dawe
Project team: Larry Bird, Knute Brekke, D.J. Osborne, Kevin Sullivan, Mark Talkovic

A remotely operated vehicle toolsled was built for the launch and recovery of the MARS electronics module. Development also progressed on a tool to test the individual science ports on the MARS node while deployed at sea.

Mooring Maintenance

Project leads: Francisco Chavez, Mike Kelley
Project manager: Mike Kelley
Project team: George Badger, Paul Coenen, Ken Heller, Eric Nelson, Craig Okuda, Mark Pickerill, Mike Risi
Collaborators: Curtis Collins, Naval Postgraduate School, Monterey, California; Mary Silver, MBARI

The local M1 and M2 moorings underwent annual refurbishment and redeployment and the M0 mooring (part of the CIMT project) was also refurbished and deployed for another year. MBARI moorings represent state-of-the-art systems for the collection of concurrent time series of physical, chemical, and biological properties and are considered model systems for the developing network of coastal observatories planned for U.S. coastal waters.

The Next Challenge: Observing the Effects of the Anthropogenically Induced pH Shift in the Upper Ocean

Project lead/manager: Zbigniew Kolber
Project team: Arlene Haffa, Denis Klimov

The oceans absorb the majority of the anthropogenically produced CO_2, which increases the pH in the upper ocean. Researchers performed a series of experiments on cultures of green algae and diatoms as well as on natural phytoplankton populations, which showed growth rates decreased in periods of low pH. These results contradict the notion presented in the Royal Academy of Science report on Ocean Acidification, that ocean productivity is assumed to increase by 20 to 30 percent under the conditions of increased dissolution of CO_2 in the upper ocean.

Observations of Open Ocean and Coastal Upwelling Systems in Ocean Process and Climate Research and Education

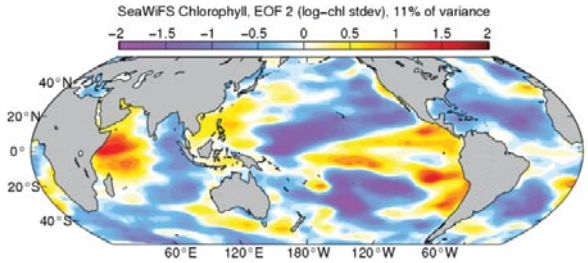
Project leads: Francisco Chavez, John Ryan
Project manager: John Ryan
Collaborator: Annette de Charon, Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine

Researchers used concurrent satellite and in situ ecosystem time series to probe how local ecosystems are strongly influenced by the large-scale oceanographic background cycles. Analysis of global chlorophyll distributions on the ocean surface show a trend of increasing chlorophyll concentrations of all major upwelling systems of the eastern Pacific.

Observing Complexity in the Coastal Ocean

Project lead: John Ryan
Project manager: Erich Rienecker
Project team: Andrew Fischer, Mike Kelley, Hans Thomas
Collaborators: Francisco Chavez, Chris Scholin, and Mary Silver, MBARI; James Gower, Institute of Ocean Sciences, Canada; Raphael Kudela, University of California, Santa Cruz

Researchers explored topographic influences on circulation and plankton ecology over Davidson Seamount and the oceanographic conditions influencing the development of thin, concentrated layers of plankton. Investigations of red-tide ecology in Monterey Bay led to the discovery of a distinct environment within a relatively small region of the



northeastern bay that regularly hosts dense populations of red-tide forming phytoplankton. This region is important to understand because it hosts a number of potentially harmful phytoplankton species, and bay-wide red-tide blooms have followed the spread of a seed population from this region.

Oceanic Carbon, Nitrogen, and Redox Cycling in the 21st Century

Project leads: Francisco Chavez, Ken Johnson
Project manager: Francisco Chavez
Project team: James G. Bellingham, Kevin Gomes, Andrew Hamilton, Brett Hobson, Zbigniew Kolber, Gene Massion, Chris Scholin
Collaborators: Yi Chao, National Aeronautics and Space Administration/Jet Propulsion Laboratory, Pasadena, California; Russ Davis, Scripps Institution of Oceanography, La Jolla, California; Jon Zehr, MBARI

This scoping study defined a new institutional initiative focused on direct and indirect impacts of human alteration of the marine nitrogen cycle. In the nearshore regions of the world ocean, human production of fixed nitrogen has doubled or tripled the loads of nitrate flowing to the coastal zone, leading to significant ecosystem impacts. In offshore waters, nutrient supply rates are limited by nitrogen fixation and vertical and horizontal mixing. This program focuses on three locations (nearshore, upwelling, and offshore) that represent globally important regions in the cycling of nitrogen.

Pelagic-Benthic Coupling and the Carbon Cycle

Project lead/manager: Ken Smith
Project team: Jacob Ellena, Paul McGill, Henry Ruhl, Michael Vardaro

Time-series studies continued along the continental slope at depths of greater than 4,100 meters. The research focused on particulate organic matter that passively falls to the seafloor and use of that food supply by deep-sea communities. Measurements of the spatial and temporal variability of food and resultant benthic community responses on long time scales are critical to understanding the oceanic carbon cycle with respect to climate change. Recent results showed significant agreement between climate indices and the fluxes of food supply to the deep-sea benthic community.

Precision Control Technologies for ROVs and AUVs

Project leads: Rob McEwen, Steve Rock
Project manager: Steve Rock
Project team: James Barry, David Caress, T. Craig Dawe, Brett Hobson, Mike Risi, Bruce Robison, Brian Schlining, Robert Vrijenhoek

A new technique was demonstrated to enable autonomous navigation and control of an ROV relative to the terrain. The system is unique in that it eliminates the drift errors normally associated with odometer-based techniques. This system was used to fly ROV *Tiburon* over the entire debris field of the USS *Macon* (see page 13). In other work, the feasibility of using an automated system to enable a single ROV pilot (instead of the usual two) to service moored or tethered instruments was demonstrated.

Research Engineering Sensor Program

Project lead/manager: Zbigniew Kolber
Project team: Arlene Haffa, Denis Klimov, Ke Wang
Collaborators: Joseph Berry, Stanford University, California; Jack DiTullio and Walker Smith, Virginia Institute of Marine Science, Gloucester Point; David Hutchins, University of Delaware, Newark; Mak Saito, Woods Hole Oceanographic Institution, Massachusetts; Philippe Tortell, University of British Columbia, Canada

Construction was completed on three benchtop flow-through sea-monitoring systems for studying photosynthesis in the marine environment. The instruments were tested on several cruises including an investigation of cumulative effects of iron, light, and CO_2 levels on photosynthetic performance and algal assemblages in the Ross Sea of Antarctica. Researchers also deployed the LIDAR-based sensor for monitoring photosynthesis in terrestrial environments, began work on the long-period grating based sensors, and initiated efforts to reduce the effects of biofouling on the performance of optical instruments.

ROV Video Outline Annotation

Project leads: David Caress, Steven Haddock
Project manager: Lonny Lundsten
Project team: Lori Chaney, Linda Kuhnz, Kyra Schlining, Nancy Jacobsen Stout, Susan von Thun

Outline video annotations continued, bringing the number of observations in the Video Annotation and Reference System (VARS) database close to two million. MBARI scientists, interns, and collaborators have produced numerous presentations, theses, posters, and publications using these valuable annotation data. The VARS software system has been successfully released as an open-source project for use by other institutions (see http://vars.sourceforge.net/). In addition, non-embargoed video annotations continue to be available to external audiences via the VARS Public Query.

Seafloor Mapping

Project lead/manager: David Caress
Project team: Doug Conlin, Rich Henthorn, Bill Kirkwood, Rob McEwen, Hans Thomas, Duane Thompson
Collaborator: Dale Chayes, Lamont-Doherty Earth Observatory, Palisades, New York

MBARI's seafloor mapping autonomous underwater vehicle (AUV), the *D. Allan B.,* was employed on seven expeditions in Monterey Canyon, Santa Monica Basin, Barkley Canyon, offshore of Point Conception, and at the summits of Axial and Davidson Seamounts. Software updates were released as part of the National Science Foundation-supported development of MB-System (http://www.mbari.org/data/mbsystem), an open-source software package for the processing and display of swath mapping sonar data. The MBARI Seafloor Mapping Database, which supports research efforts of a number of different science groups, includes over 35,000 swath data files (371 gigabytes) from more than 20 types of multibeam, side-scan, and interferometric sonars.

SENSORS: Ocean Observing System Instrument Network Infrastructure

Project leads: Dan Davis, Kevin Gomes
Project manager: Duane Edgington
Project team: John Graybeal, Kent Headley, Tom O'Reilly

Addressing key technology issues of ocean observatories, engineers demonstrated plug-and-work technology by interfacing an instrument to the Monterey Ocean Observing System (MOOS) network and to an environmental monitoring system. The MOOS software interface was also demonstrated on a MARS cabled observatory test system in the laboratory, and a web-service interface was shown to successfully work with the MOOS software to provide distributed data access and control.

Shore Side Data System (SSDS)

Project lead: Kevin Gomes
Project manager: John Graybeal
Project team: Andrew Chase, Francisco Chavez, Mike McCann, Rich Schramm

SSDS provided data management and access for the MOOS Science Experiment while continuing its transition from a development project to an operational data system. A significant architectural overhaul, completed mid-year, provided a framework for many advanced capabilities, including web-accessible navigation through data, metadata, and provenance.

Simulations of Coastal Ocean Physics and Ecosystems

Project lead/manager: Francisco Chavez
Project team: Dorota Kolber, Reiko Michisaki, Lionel Pawlowski
Collaborators: Richard Barber, Duke University, Durham, North Carolina; James G. Bellingham, MBARI; Fei Chai, University of Maine, Orono; Yi Chao, Jet Propulsion Laboratory, Pasadena, California; Niki Gruber and Jim McWilliams, University of California, Los Angeles; John Kindle, Naval Research Laboratory Stennis Space Center, Mississippi; Mat Maltrud, Los Alamos National Laboratory, New Mexico

Ecosystem models were integrated with three-dimensional physical circulation models to test our understanding of basic nutrient, phytoplankton, and zooplankton interactions. A high-resolution coastal model nested within regional and basin-scale models, simulated the observed seasonal and interannual variations in physical oceanographic forcing and the chemical and biological consequences of that variation. The rich historical database and excellent matrix of real-time ocean observing systems available at MBARI have provided a

unique environment for the development of the next generation of coupled coastal physical-biological models.

Studies of Biogeochemical Dynamics of Upwelling Systems Using Drifters

Project leads/managers: Francisco Chavez, Gernot Friederich
Project team: Dorota Kolber, Martin Suro
Collaborators: Gilberto Gaxiola and Ruben Lara, Centro de Investigación Cientifica y de Educación Superior de Ensenada, Mexico; Jesus Ledesma, Instituto del Mar de Perú; Osvaldo Ulloa, Universidad de Concepcion, Chile

MBARI researchers have trained scientists in Mexico, Peru, and Chile in the use of ocean drifters that make ongoing measurements of the flux of carbon dioxide between the ocean and the atmosphere. Data collected by this NASA-funded project are being synthesized to create an accurate estimate of the coastal carbon cycle along the entire length of the eastern Pacific.

Submarine Volcanism

Project lead: David Clague
Project manager: Alicé Davis
Project team: Jenny Paduan
Collaborators: Nicky Allison, University of St. Andrews, Scotland; Bruce Applegate and Chris Kelley, University of Hawaii, Manoa; John Barron, Dave Bukry, Andy Calvert, Jim Hein, Larry Mastin, Mary McGann, Jim Moore, Bill Normark, and Stephanie Ross, United States Geological Survey; Juan Carlos Braga, University of Grenada, Spain; Dave Butterfield and Bob Embley, National Oceanic and Atmospheric Administration; Pat Castillo, Peter Lonsdale, and Jerry Winterer, University of California, San Diego; Bill Chadwick, Oregon State University, Corvallis; Brian Cousens, Carleton University, Canada; Jackie Dixon, University of Miami, Florida; Fred Frey and Guangping Xu, Massachusetts Institute of Technology, Cambridge; Christina Gallup and Kristen Riker-Coleman, University of Michigan, Ann Arbor; Jim Head, Brown University, Providence, Rhode Island; Ken Hon, University of Hawaii, Hilo; Shichun Huang, Florida State University, Tallahasee; Marv Lilley, University of Washington, Seattle; Kathie Marsaglia, California State University, Northridge; Jim McClain and Rob Zierenberg, University of California, Davis; Bill McIntosh, New Mexico Tech, Socorro; Juli Morgan, Rice University, Houston, Texas; Michael Perfit, University of Florida, Gainesville; Don Potts, Christina Ravello, and Eli Silver, University of California, Santa Cruz; Willem Renema, Leiden Natural History Museum, Netherlands; Jennifer Reynolds, University of Alaska, Fairbanks; Warren Sharp, Berkeley Geochronology Laboratory, California; John Stix, McGill University, Canada; Ed Stolper, California Institute of Technology, Pasadena; Karen von Damm, University of New Hampshire, Durham; Jody Webster, James Cook University, Australia; Lionel Wilson, University of Lancaster, England

Work on giant submarine landslides around Hawaii was completed, and studies progressed on ROV *Tiburon* dives to the northern Gorda Ridge. New research began on formation of calderas and clastic deposits on the Vance and Axial Seamounts. Preliminary results indicated that collapse of each caldera on each seamount was accompanied by voluminous explosive eruptive activity that deposited abundant pyroclastic fragments and by discharge of large amounts of hydrothermal fluids that precipitated abundant low-temperature deposits of iron-rich clay and manganese-oxides. Studies of active volcanic processes entered a new phase this year with the deployment of the mapping AUV *D. Allan B.* on Axial and Davidson Seamounts.

Using MBARI Video Archives to Investigate Behavior of Midwater Invertebrates

Project manager/lead: William Hamner
Project team: George I. Matsumoto, Bruce Robison
Collaborator: Jane Lee, University of California, Los Angeles

MBARI video archives were used to investigate the biology of midwater invertebrates. Research focused on the species compositions of krill swarms at the shelf break, the dynamics of siphonophore (*Praya* and *Apolemia*) behavior, feeding behavior and distribution of the ctenophore *Thalassocalyce inconstans*, and predator-prey interactions of *Sergestes similis* in the water column.

Awards and Degrees

Awards

James G. Bellingham

K. D. Woods Colloquium, University of Colorado Aerospace Engineering Sciences

Bruce Robison

University Distinguished Lecturer, Texas A & M University

Steinbach Visiting Scholar, Massachusetts Institute of Technology/Woods Hole Oceanographic Institution

Edith A. Widder

Wings Worldquest Sea Award

The MacArthur Fellowship

Degree awarded

Curtis R. Young

Ph.D., University of California, Santa Cruz

Invited Lectures

Mandy Allen

International Workshop on Scientific Use of Submarine Cables and Related Technologies, Dublin, Ireland

James Barry

Petrobras International Seminar on Carbon Sequestration and Climate Change, Rio de Janeiro, Brazil

Stanford University, Stanford, California

California Coastal Commission, San Francisco, California

Monterey Bay Aquarium, Monterey, California

James G. Bellingham

Woods Hole Oceanographic Institution, Massachusetts

Massachusetts Institute of Technology, Cambridge

K. D. Woods Colloquium, University of Colorado Aerospace Engineering Sciences, Boulder

Coastal Observatories Workshop, Liverpool, United Kingdom

Conference on Manoevring and Control of a Marine Craft, Lisbon, Portugal

University of Washington-Microsoft Summer Institute, Blaine

Luis Bermudez

Open Geospatial Consortium Web Services Meeting, Reston, Virginia

Global Organization for Earth System Science Portal Workshop, Lawrence Livermore National Laboratory, Livermore, California

Interoperability Workshop on Automated Harvesting of Data and Metadata, Scripps Institution of Oceanography, La Jolla, California

Southeast Coastal Ocean Observations Regional Association, Chapel Hill, North Carolina

Peter G. Brewer

University of California, Santa Barbara

U.S. Department of Energy International Methane Hydrates Meeting, Kauai, Hawaii

Yale University, New Haven, Connecticut

Future Ocean Symposium for German National Day of Unification, Kiel, Germany

Gussenhoven Distinguished Lecture, University of North Carolina, Chapel Hill

Turkish Chamber of Petroleum Engineers, Middle Eastern Technical University, Ankara, Turkey

American Geophysical Union, San Francisco, California

Francisco Chavez

Keynote Speaker, Biannual Mexican Oceanography Conference, Manzanillo, Mexico

Second Institute of Oceanography, Hangzhou, China

Woods Hole Oceanographic Institution, Massachusetts

Keynote Lecture, International Seminar on Global Climate Change: Perspectives for Peru, Lima, Peru

Week of the Anchoveta Meeting, Lima, Peru

David Clague

American Geophysical Union, San Francisco, California

Judith Connor

Monterey Bay Aquarium, Monterey, California

Hopkins Marine Station of Stanford University, Pacific Grove, California

Modesto Junior College, California

Virginia Aquarium and Marine Science Center, Virginia Beach

Duane Edgington

Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan

Steve Etchemendy

International Marine Technician Conference, Woods Hole Oceanographic Institution, Massachusetts

David B. Field

Bodega Marine Laboratory, Bodega Bay, California

Peter Girguis

University of Massachusetts, Boston

Ridge Interdisciplinary Global Experiments Theoretical Institute, Mammoth Lakes, California

American Society of Microbiology, Orlando, Florida

Berea College, Kentucky

Boston University, Massachusetts

University of South Florida, Tampa

Sonoma State University, California

University of California, Irvine

Skidmore College, Saratoga, New York

John Graybeal

Keynote Lecture, International Association of Aquatic and Marine Science Libraries and Information Centers Conference, Portland, Oregon

Chris Grech

Moffett Field Historical Society, Mountain View, California

Maritime Museum of Monterey, California

Monterey Bay National Marine Sanctuary, Point Sur Lighthouse, California

Dianne I. Greenfield

Eastern Pacific Ocean Conference, Timberline Lodge, Oregon

Florida Gulf Coast University, Fort Myers

Steven Haddock

Monterey Peninsula College, California

California State Summer School for Mathematics and Science, University of California, Santa Cruz

Moss Landing Marine Laboratories, Moss Landing, California

Rutgers University, New Brunswick, New Jersey

Hawaii Pacific University, Honolulu

Rebecca Hoover

Monterey Bay Aquarium, Monterey, California

Cabrillo College, Aptos, California

Ken Johnson

National Science Foundation, Tuskegee University, Alabama

Maurice Lamontagne Institute, Mont Joli, Quebec, Canada

Darling Marine Center, University of Maine, Walpole

American Chemical Society, Anaheim, California

Hopkins Marine Station of Stanford University, Pacific Grove, California

Joe Jones

University of South Carolina, Columbia

California State University, Monterey Bay, Marina

Judith T. Kildow

Restore America's Estuaries Conference, New Orleans, Louisiana

Keynote Speech, Coastal Conference on Ecosystem-Based Approaches to Management in the Southeast Region, Wilmington, North Carolina

Gulf of Mexico Summit, Corpus Christi, Texas

Katoomba Conference, Portland, Oregon

Keynote Speech, Coastal Conference, New South Wales, Australia

Australian Department of Environment and Heritage, Canberra

Bill Kirkwood

Ocean Observatory Workshop, Commonwealth Scientific and Industrial Research Organisation, Tasmania, Australia

Olin College, Needham, Massachusetts

Zbigniew Kolber

International Symposium on Microbial Ecology, Vienna, Austria

George I. Matsumoto

Keynote Speech, Lego League Regional Competition, San Jose, California

American Society of Limnology and Oceanography, Victoria, British Columbia, Canada

Geological Society of America, Philadelphia, Pennsylvania

Craig McClain

International Biogeography Society, Puerto De La Cruz, Tenerife, Spain

Monterey Bay Aquarium, Monterey, California

Marcia McNutt

Monterey Bay Aquarium Travel Dynamics Expedition, East Antarctica

University of Minnesota, Minneapolis

Palo Alto Research Center, California

International Conference on Space Mission Challenges for Information Technology, Pasadena, California

U.S. House of Representatives Committee on Science, Washington, D.C.

California and the World Ocean Conference, Long Beach, California

Symposium on the Anniversary of the International Geophysical Year, American Geophysical Union, San Francisco, California

Maritime Museum of Monterey, California

Joe Needoba

Stanford University, Stanford, California

Tom O'Reilly

Oceans 2006, Boston, Massachusetts

Karen Osborn

Loma Linda University, California

Charles K. Paull

Elkhorn Slough Foundation, Moss Landing, California

Chevron Research Division, San Ramon, California

Plenary Address, U.S. Department of Energy Workshop, Kauai, Hawaii

Keynote Address, European Geosciences Union, Vienna, Austria

Bodega Marine Laboratory, Bodega Bay, California

Gordon Conference on Permeable Sediments, Waterville, Maine

Keynote Lecture, International Sedimentological Congress Meeting, Fukuoka, Japan

Virginia Institute of Marine Science, Gloucester Point

Edward T. Peltzer

Inter-Laboratory Hydrate Workshop, Colorado School of Mines, Golden

National Methane Hydrate Advisory Committee Meeting, Houston, Texas

Bruce Robison

University Distinguished Lecture, Texas A & M University, College Station

Marine Sciences Research Center, Stony Brook University, New York

Bermuda Underwater Exploration Institute, Hamilton, Bermuda

Woods Hole Oceanographic Institution, Massachusetts

Steinbach Visiting Scholar Lecture, Massachusetts Institute of Technology/Woods Hole Oceanographic Institution Joint Program, Woods Hole, Massachusetts

New Yorker Festival, New York

Steel Lecture, Scoliosis Research Society, Monterey, California

Japan Agency for Marine-Earth Science and Technology, Yokosuka, Japan

San Francisco State University Romberg Tiburon Center for Environmental Studies, California

Steve Rock

National Aeronautics and Space Administration Ames Research Center, Moffett Field, California

Henry Ruhl

National Science Foundation Long-Term Ecological Research Science Meeting, Estes Park, Colorado

John Ryan

Woods Hole Oceanographic Institution, Massachusetts

Long Marine Laboratory of the University of California, Santa Cruz

Brian Schlining

Australian Society for Fish Biology Workshop, Hobart, Australia

Chris Scholin

Hopkins Marine Station of Stanford University, Pacific Grove, California

Oceans 2006, Boston, Massachusetts

Agilent Technologies, Santa Clara, California

Susan Von Thun

United States Geological Survey Coastal and Marine Geology, Santa Cruz, California

Robert Vrijenhoek

Hopkins Marine Station of Stanford University, Pacific Grove, California

University of Southern California, Los Angeles

National Oceanic and Atmospheric Administration/ National Marine Fisheries Service Conservation Genetics Group, Seattle, Washington

Edith A. Widder

Florida Atlantic University, Boca Raton

Florida Natural History Museum, Gainesville

Florida Oceanographic Society, Jupiter

Plenary Lecture, Ocean Sciences Meeting, Honolulu, Hawaii

American Museum of Natural History, New York

Mensa World Gathering, Orlando, Florida

The Kennedy Center Imagination Celebration, Fort Worth, Texas

Kight Center for Emerging Technologies, Fort Pierce, Florida

Explorer's Club, New York City

Curtis R. Young

Neyman Lecture, University of California, Berkeley

Mentorships

James Barry

Craig McClain, postdoctoral fellow (factors influencing the biodiversity of deep-sea communities)

Eric Pane, postdoctoral fellow (impacts of ocean acidification)

James Barry, Linda Kuhnz

Gillian Clague, undergraduate student, Willamette University (comparison of biological communities on lava flows)

James G. Bellingham, Mike Godin

Dustin Carroll, graduate summer intern, Moss Landing Marine Laboratories (a survey planning tool for Monterey Bay 2006)

James G. Bellingham, Brett Hobson

Francois Cazenave, M.S. student, Moss Landing Marine Laboratories (using stand-alone accelerometers to determine impact levels and movement)

Peter Brewer

Rachel Dunk, postdoctoral fellow (laser Raman spectroscopy of seawater and methane gas hydrates; effect of pressure on the kinetics of carbon dioxide hydration kinetics)

Peter Brewer, Peter Walz

Jonathan Scholl, undergraduate summer intern, Princeton University (use of hollow-core waveguides to increase the sensitivity of laser Raman spectroscopy of solutes in seawater)

Francisco Chavez

David B. Field, postdoctoral fellow (foraminifera in sediments as tracers of decade-to-century scale climate change)

Lionel Pawlowski, postdoctoral fellow (simulations of coastal ocean physics and ecosystems)

Christina Tanner, undergraduate summer intern, University of California, Santa Barbara (ecology of the California current system: time-series research in biological oceanography between Cape Mendocino and Point Conception, 1998-2006)

David Clague

Liz Cornejo , M.S. student, Carleton University (isotope geochemistry of the Vance Seamounts)

Iain Faichley, Ph.D. student, James Cook University, Australia (drowned coral reefs around the Maui complex, Hawaii)

Christoph Helo, Ph.D. student, McGill University, Canada (formation of clastic deposits during caldera collapse on Axial Seamount)

Huiyu Li, Ph.D. student, California Institute of Technology (Ni-Mn relations of mantle domains)

Bruce Pauley, Ph.D. student, University of California, Davis (formation of palagonite)

Rachael Wendt, M.S. student, University of Florida (trace element geochemistry of the Vance Seamounts)

Guangping Xu, Ph.D. student, Massachusetts Institute of Technology (petrology of Molokai)

Danelle Cline, Duane Edgington

Ishbel Kerkez, M.S. student, The University of Adelaide, Australia (automated event detection in video of benthic habitat)

Jerome Mariette, M.S. student, University of Poitiers, France (segmentation of objects in underwater video)

Judith L. Connor

Luke Hunt, Ph.D. student, Stanford University (the upper limit of *Endocladia muricata*)

Patrick Martone, Ph.D. student, Stanford University (convergent evolution of genicula in articulated coralline algae)

Dan Davis, Duane Edgington

Joshua Kroll, undergraduate summer intern, Harvard University (robust classification for the Automated Visual Event Detection system)

Duane Edgington

Julien Barde, postdoctoral fellow (metadata-driven data management system)

David B. Field

Renato Salvatecci, M.S. student, Centro de Investigacion Cientifica y Educacion Superior de Ensenada, Mexico (flux and preservation of scales and other fish remains in the oxygen minimum zone in front of Pisco, Peru in the last 400 years)

Kim Fulton-Bennett

Hugh Powell, graduate summer intern, University of California, Santa Cruz (research, design, and production of a web site describing the MARS ocean observatory for the general public)

Peter Girguis

Erik Cordes, Harvard University postdoctoral fellow (population dynamics of microbial communities at vents)

Geoffrey Dilly, Ph.D. student, Harvard University (establishment of animal-microbial symbiosis)

Rebecca Helm, undergraduate student, Eckerd College (microbial ecology of estuarine sediments)

Spencer Nyholm, Harvard University postdoctoral fellow (gene expression of chemoautotrophic symbiosis)

Vignatha Reddy, high school student, Kennedy High School (microbial ecology of fuel cells)

Annelys Roque, B.S. student, Harvard University (microbial ecology of Monterey Bay seeps)

Sonam Sharma, B.S. student, Harvard University (microbial ecology of fuel cells)

Daniel Stolper, B.S. student, Harvard University (microbial ecology of International Ocean Drilling Program sediments)

Scott Wankel, Harvard University postdoctoral fellow (analytical approaches to quantifying microbial activity)

Helen White, Harvard University postdoctoral fellow (microbial ecology of fuel cells)

Chris Grech

Noah Doughty, educator, Mission College Preparatory High School (NOAA Teacher at Sea Program participant in USS *Macon* expedition, assisting the crew and gathering information to create high school curriculum)

Steven Haddock

Nicholas Beck, undergraduate summer intern, University of Pennsylvania (plankton pigments)

Alison Henden, high-school student, Harker School (web development)

Rebecca Hoover, postdoctoral fellow (zooplankton ecology, amphipod-host interactions)

Brian Johnson, undergraduate student, California State University, Monterey Bay (dietary origins of luciferins)

Dan Swezey, undergraduate student, University of California, Santa Barbara (red fluorescence in the deep sea)

Ken Johnson

Todd Martz, postdoctoral fellow (CO_2 chemistry, sensor development)

Judith T. Kildow

Scott Norris, undergraduate student, California State University, Monterey Bay (economic indicators for Elkhorn Slough)

Alicia Vieira, M.S. student, California State University, Monterey Bay (political and legal organizational structure influencing restoration options in Elkhorn Slough)

Alana Rivadeneya, undergraduate student, California State University, Monterey Bay (aquaculture indicators for a time series for the National Ocean Economics Program)

Caitlin Moehrke, undergraduate student, California State University, Monterey Bay (analysis of federal ocean expenditures)

Kirstin Csik, undergraduate student, California State University, Monterey Bay (creating a framework for community-based socio-economic indicators for coastal vulnerability, resiliency, and sustainability)

Bill Kirkwood, Paul McGill

Alison LaBonte, graduate summer intern, Scripps Institution of Oceanography (a new temperature probe for determining flow rates at cold seeps)

Zbigniew Kolber

Donovan Carillo, high school intern, Monterey High School, Monterey Academy of Oceanographic Science (selection and implementation of the pH monitoring system for laboratory pH-stats)

Jimin Radochonski, high school student, York High School (effect of temperature and pH changes on the photosynthetic properties of phytoplankton)

Ke Wang, postdoctoral fellow (long period grating fiber sensor and waveguide sensor for seawater pH sensing)

Roman Marin, Christina Preston, Chris Scholin

Shawn Meredyk, undergraduate summer intern, University of New Brunswick, Canada (analysis of different array printing techniques)

Charles K. Paull

Tzvetie Erohina, Ph.D. student, Stanford University (benthic foraminifer assemblages as indicators of recent seafloor disturbance in submarine canyons)

John Polhmann, Ph.D. student, Virginia Institute of Marine Science (sedimentary biogeochemistry of Northern Cascadia Margin gas hydrate system)

Tim Pennington

Joel Steinmetz, high school student, Monterey High School (exposure to cruise and lab work associated with the Monterey Bay time-series cruises)

Kanna Rajan

Shuonan Dong, graduate summer intern, Massachusetts Institute of Technology (introducing model-based autonomy on autonomous underwater vehicles)

Bruce Robison

Stephanie Bush, Ph.D. student, University of California, Berkeley (the role of ink in the defenses of deep-sea squids)

Jane Lee, Ph.D. student, University of California, Los Angeles (biomechanics and ecology of the giant siphonophore *Praya dubia*)

Karen Osborn, Ph.D. student, University of California, Berkeley (ecology and systematics of deep-sea, pelagic munnopsid isopods)

Steve Rock

Sean Augenstein, Ph.D. student, Stanford University (servicing tethered instruments and moorings)

Jinwhan Kim, Ph.D. student, Stanford University (vision-based AUV docking)

Peter Kimball, Ph.D. student, Stanford University (terrain-based navigation for ROVs and AUVs)

Debbie Meduna, Ph.D. student, Stanford University (terrain-based navigation for ROVs and AUVs)

Kiran Murthy, Ph.D. student, Stanford University (benthic mosaicking and navigation)

Aaron Plotnik, Ph.D. student, Stanford University (servicing tethered instruments and moorings; jellyfish tracking)

Kristof Richmond, Ph.D. student Stanford University (benthic mosaicking and navigation)

Stephen Russell, Ph.D. student, Stanford University (servicing tethered instruments and moorings)

Dan Scheinfeld, Ph.D. student, Stanford University (servicing tethered instruments and moorings)

Henry Ruhl

J. Ashley Booth, undergraduate student, Connecticut College (size distribution dynamics of abyssal ophiuroids)

John Ryan

Jane Lee, Ph.D. student, University of California, Los Angeles (krill ecology at the Monterey Canyon rim)

Sarah Rizk, undergraduate summer intern, Stanford University (influence of Davidson Seamount on shallow pelagic ecology)

Andrea Vander Woude, Ph.D. student, University of California, Santa Cruz (retention sites in the Northern California coastal upwelling system)

Chris Scholin

Dianne I. Greenfield, postdoctoral fellow (applications of the second generation Environmental Sample Processor)

Ken Smith

Henry Ruhl, postdoctoral fellow (deep-sea megafauna communities and climate change)

Mike Vardaro, Ph.D. student, University of California, San Diego, Scripps Institution of Oceanography (bioturbation studies by deep-sea megafauna)

Robert Vrijenhoek

Shawn Arellano, graduate summer intern, University of Oregon (molecular detection of marine larvae)

Caren Braby, postdoctoral fellow (molecular characterization of larval invertebrates and whale-fall ecology)

Kristi Erickson, graduate student intern, College of William & Mary (molecular identification of hydrothermal vent organisms)

Philip Hoos, M.S. student, Moss Landing Marine Laboratories (population genetics of an invasive marine species)

Curtis R. Young, Ph.D. student, University of California, Santa Cruz (population genetics of deep-sea marine organisms)

Edith A. Widder

Karen Breitlow, M.S. student, Florida Atlantic University (evidence that the function of bioluminescence in dinoflagellates is concentration dependent)

Miranda Hoover, Ph.D. student, Florida Atlantic University (monitoring bloom dynamics of a common coastal bioluminescent ctenophore)

Erika Raymond, Ph.D. student, Johns Hopkins University (investigations of unobtrusive observation techniques)

Peer-Reviewed Publications

Alendal, G., P. Haugan, R. Gangsto, K. Caldeira, E. Adams, **P.G. Brewer**, **E.T. Peltzer**, G. Rehder, and T. Sato (2006). Comment on "Fate of Rising CO_2 Droplets in Seawater." *Environmental Science and Technology*, **40**: 3653-3654.

Bailey, D.M., **H.A. Ruhl**, and **K.L. Smith Jr.** (2006). Long-term changes in benthopelagic fish abundance in the abyssal northeast Pacific Ocean. *Ecology*, **87**: 549-555.

Baklouti, M., V. Faure, **L. Pawlowski**, and A. Sciandra (2006). Investigation and sensitivity analysis of the mechanistic phytoplankton model implemented in a new modular numerical tool (Eco3M) dedicated to biogeochemical modelling. *Progress in Oceanography*, **71**: 34-58.

Behrenfeld, M.J., K. Worthington, R.M. Sherrell, **F.P. Chavez**, P. Strutton, M. McPhaden, and D.M. Shea (2006). Controls on tropical Pacific Ocean productivity revealed through nutrient stress diagnostics. *Nature*, **442**: 1025-1028.

Bellingham, J.G. (2006). New challenges for ocean technology. *Marine Technology Society Journal*, **40**: 139-140.

Bermudez, L., J. Graybeal, and R. Arko (2006). A marine platforms ontology: Experiences and lessons. In: *Proceedings of the Semantic Sensor Networks Workshop at the Fifth International Semantic Web Conference (ISWC)*, Athens, Georgia.

Bermudez, L. and M. Piasecki (2006). Metadata community profiles for the semantic web. *Geoinformatica*, **10**: 159-176.

Braby, C.E. and G.N. Somero (2006). Ecological gradients and relative abundance of native (*Mytilus trossulus*) and invasive (*M.galloprovincialis*) blue mussels in the California hybrid zone. *Marine Biology*, **148**: 1249-1262.

Braby, C.E. and G.N. Somero (2006). Following the heart: Temperature and salinity effects on heart rate in native and invasive species of blue mussels (genus *Mytilus*). *Journal of Experimental Biology*, **209**: 2554-2566.

Brewer, P.G., B. Chen, R. Warzinski, A. Baggeroer, **E.T. Peltzer**, **R.M. Dunk**, and **P. Walz** (2006). Three-dimensional acoustic monitoring and modeling of a deep-sea CO_2 droplet cloud. *Geophysical Research Letters*, **33**: doi: 10.1029/2006GL027181.

Chase, Z., A. Paytan, **K.S. Johnson**, J. Street, and Y. Chen (2006). Input and cycling of iron in the Gulf of Aqaba, Red Sea. *Global Biogeochemical Cycles*, **20**: GB3017, doi: 10.1029/2005GB002646.

Chen, Y., R. Matsumoto, and **W. Ussler III** (2006). Methane-derived authigenic carbonates from the IMAGES VIII/PAGE 127 Gas Hydrate and Paleoclimate Cruise on the R/V *Marion Dufresne* in the Gulf of Mexico, 2-18 July 2002; Chapter 14. In: *Initial Report of the IMAGES VIII/PAGE 127 Gas Hydrates and Paleoclimate Cruise on the R/V* Marion Dufresne *in the Gulf of Mexico, 2-18 July 2002, U.S. Geological Survey Open-File Report 2004-1358*, edited by W. Winters, T. Lorenson, and **C.K. Paull**.

Clague, D.A., J.B. Paduan, W.C. McIntosh, B.L. Cousens, **A.S. Davis**, and J.R. Reynolds (2006). A submarine perspective of the Honolulu Volcanics, Oahu. *Journal of Volcanology and Geothermal Research*, **151**: 279-307.

Collins, A.G., B. Bentlage, **G.I. Matsumoto**, **S.H.D. Haddock**, **K.J. Osborn**, and B. Schierwater (2006). Solution to the phylogenetic enigma of *Tetraplatia*, a worm-shaped cnidarian. *Biological Letters*, **2**: 120-124.

Davis, A.S. and **D.A. Clague** (2006). Deep submarine explosive basaltic eruptions at vents in the North Arch Volcanic Field. *Journal of Volcanology*, **68**: 294-307.

DeLong, E.F., **C. Preston**, T. Mincer, V. Rich, S.J. Hallam, N.U. Frigaard, A. Martinez, M.B. Sullivan, R. Edwards, B.R. Brito, S.W. Chisholm, and D.M. Karl (2006). Community genomics among stratified microbial assemblages in the ocean's interior. *Science*, **311**: 496-503.

Dierssen, H.M., R.M. Kudela, **J.P. Ryan**, and R.C. Zimmerman (2006). Red and black tides: Quantitative analysis of water-leaving radiance and perceived color for phytoplankton, colored dissolved organic matter, and suspended sediments. *Limnology and Oceanography*, **51**: 2646-2659.

Field, D., T.R. Baumgartner, C. Charles, V. Ferriera-Bartrina, and M.D. Ohman (2006). Planktonic foraminifera of the California Current reflect 20th century warming. *Science*, **311**: 63-66.

Field, D., D. Cayan, and **F.P. Chavez** (2006). Secular warming in the California Current and North Pacific. *California Cooperative Oceanic Fisheries Investigations Reports*, **47**.

Fleeger, J.W., K.R. Carman, P.B. Weisenhorn, H. Sofranko, T. Marshall, D. Thistle, and **J. Barry** (2006). Simulated sequestration of anthropogenic carbon dioxide at a deep-sea site: Effects on nematode abundance and biovolume. *Deep-Sea Research Part I*, **53**: 1135-1147.

Gasca, R., E. Suárez-Morales, and **S.H.D. Haddock** (2006). Symbiotic associations between crustaceans and gelatinous

zooplankton in deep and surface waters off California. *Marine Biology*, doi: 10.1007/s00227-006-0478-y.

Gilly, W.F., U. Markaida, C.H. Baxter, B.A. Block, A. Boustany, **L.D. Zeidberg**, **K.R. Reisenbichler**, **B.H. Robison**, G. Bazzino, and C. Salinas (2006). Vertical and horizontal migrations by the jumbo squid *Dosidicus gigas* revealed by electronic tagging. *Marine Ecology Progress Series*, **324**: 1-17.

Girguis, P.R. and **J.J. Childress** (2006). Metabolite uptake, stoichiometry and chemoautotrophic function of the hydrothermal vent tubeworm *Riftia pachyptila*: Responses to environmental variations in substrate concentrations and temperature. *Journal of Experimental Marine Biology*, **209**: 3516-3528.

Girguis, P.R. and R.W. Lee (2006). Thermal tolerance and preference of alvinellids. *Science*, **312**: 231.

Glazer, B.T., G.W. Luther III, S.K. Konovalov, **G.E. Friederich**, D.B. Nuzzio, R.E. Trouwborst, B.M. Tebo, B. Clement, K. Murray, and A.S. Romanov (2006). Documenting the suboxic zone of the Black Sea via high-resolution real-time redox profiling. *Deep-Sea Research Part II*, **53**: 1740-1755.

Goffredi, S.K., **W.J. Jones**, **C.A. Scholin**, **R. Marin III**, and **R.C. Vrijenhoek** (2006). Molecular detection of marine invertebrate larvae. *Marine Biotechnology*, **8**: 149-160.

Greene, H.G., L.Y. Murai, P. Watts, N.A. Maher, M.A. Fisher, **C.K. Paull**, and P. Eichhubl (2006). Submarine landslides in the Santa Barbara Channel as potential tsunami sources. *Natural Hazards and Earth System Sciences*, **8**: 149-160.

Greenfield, **D.I.**, **R. Marin III**, **S. Jensen**, **E. Massion**, **B. Roman**, J. Feldman, and **C.A. Scholin** (2006). Application of the environmental sample processor (ESP) methodology for quantifying *Pseudo-nitzschia australis* using ribosomal RNA-targeted probes in sandwich and fluorescent in situ hybridization formats. *Limnology and Oceanography: Methods*, **4**: 426-435.

Haddock, S.H.D. (2006). Luminous marine organisms. In: *Photoproteins in Bioanalysis*, edited by S. Daunert and S.K. Deo. Wiley-VCH, pp. 25-47.

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Independent Auditors' Report

The Board of Directors
Monterey Bay Aquarium Research Institute
Moss Landing, California

We have audited the accompanying statements of financial position of the Monterey Bay Aquarium Research Institute (the "Institute") as of December 31, 2006 and 2005, and the related statements of activities and changes in net assets and of cash flows for the years then ended. These financial statements are the responsibility of the Institute's management. Our responsibility is to express an opinion on these financial statements based on our audits.

We conducted our audits in accordance with auditing standards generally accepted in the United States of America. Those standards require that we plan and perform the audit to obtain reasonable assurance about whether the financial statements are free of material misstatement. An audit includes consideration of internal control over financial reporting as a basis for designing audit procedures that are appropriate in the circumstances, but not for the purpose of expressing an opinion on the effectiveness of the Institute's internal control over financial reporting. Accordingly, we express no such opinion. An audit also includes examining, on a test basis, evidence supporting the amounts and disclosures in the financial statements, assessing the accounting principles used and significant estimates made by management, as well as evaluating the overall financial statement presentation. We believe that our audits provide a reasonable basis for our opinion.

In our opinion, such financial statements present fairly, in all material respects, the financial position of the Institute at December 31, 2006 and 2005, and the changes in its net assets and its cash flows for the years then ended in conformity with accounting principles generally accepted in the United States of America.

As discussed in Note 3 to the financial statements, the Institute has significant related-party transactions.

Deloitte + Touche LLP

DELOITTE & TOUCHE LLP

February 21, 2007

Monterey Bay Aquarium Research Institute

Statements of Financial Position
as of December 31, 2006 and 2005

Assets	2006	2005
Cash and Cash Equivalents	$ 9,451,000	$ 2,559,000
Receivables:		
The David and Lucile Packard Foundation	38,950,000	41,815,000
Federal awards and other	887,000	1,258,000
Prepaid Expenses and Other	1,870,000	1,556,000
Property and Equipment—Net	75,660,000	78,269,000
TOTAL	$ 126,818,000	$ 125,457,000

Liabilities and Net Assets		
Liabilities:		
Accounts payable	$ 824,000	$ 998,000
Accrued liabilities	3,031,000	2,613,000
Capital lease obligation	41,000	79,000
Total liabilities	3,896,000	3,690,000
Net Assets:		
Unrestricted	85,922,000	87,917,000
Temporarily restricted	37,000,000	33,850,000
Total net assets	122,922,000	121,767,00
TOTAL	$ 126,818,000	$ 125,457,000

See notes to financial statements.

Monterey Bay Aquarium Research Institute

Statements of Activities and Changes in Net Assets
for the Years ended December 31, 2006 and 2005

	2006		
Revenues:	Unrestricted	Temporarily Restricted	Total
Contributions:			
The David and Lucile Packard Foundation	$800,000	$37,000,000	$37,800,000
Individual gifts	5,000		5,000
Federal awards	5,857,000		5,857,000
Interest income	279,000		279,000
Realized and unrealized gains			
Other	1,070,000		1,070,000
Net assets released from restrictions	33,850,000	(33,850,000)	–
Total revenues	41,861,000	3,150,000	45,011,000
Expenses:			
Research	37,038,000		37,038,000
Management and general	6,818,000		6,818,000
Total expenses	43,856,000		43,856,000
Transfer of Costs to Capital Projects (Note 2)			
(Decrease) Increase in Net Assets	(1,995,000)	3,150,000	1,155,000
Net Assets:			
Beginning of year	87,917,000	33,850,000	121,767,000
End of year	$85,922,000	$37,000,000	$122,922,000

See notes to financial statements.

	2005		
Revenues:	Unrestricted	Temporarily Restricted	Total
Contributions:			
The David and Lucile Packard Foundation	$ –	$33,850,000	$33,850,000
Individual gifts			
Federal awards	5,370,000		$5,370,000
Interest income	530,000		530,000
Realized and unrealized gains	123,000		123,000
Other	1,172,000		1,172,000
Net assets released from restrictions	32,965,000	(32,965,000)	–
Total revenues	40,160,000	885,000	41,045,000
Expenses:			
Research	33,714,000		33,714,000
Management and general	6,436,000		6,436,000
Total expenses	40,150,000	–	40,150,000
Transfer of Costs to Capital Projects (Note 2)	7,243,000		7,243,000
(Decrease) Increase in Net Assets	7,253,000	885,000	8,138,000
Net Assets:			
Beginning of year	80,664,000	32,965,000	113,629,000
End of year	$87,917,000	$33,850,000	$121,767,000

See notes to financial statements.

Monterey Bay Aquarium Research Institute

Statements of Cash Flows
for the Years ended December 31, 2006 and 2005

	2006	2005
Cash Flows from Operating Activities:		
Increase in net assets	$ 1,155,000	$ 8,138,000
Adjustments to reconcile increase in net assets to net cash provided by (used in) operating activities:		
Net realized and unrealized gains on investments		(123,000)
Depreciation	9,063,000	8,474,000
Loss on disposal and abandonment of property and equipment	158,000	259,000
Transfer of costs to capital projects		(7,423,000)
Effect of changes in:		
Receivables	3,236,000	(33,959,000)
Prepaid expenses and other	(314,000)	(654,000)
Accounts payable	(174,000)	(497,000)
Accrued liabilities	418,000	393,000
Net cash provided by (used in) operating activities	13,542,000	(25,212,000)
Cash Flows from Investing Activities:		
Purchases of property and equipment	(6,612,000)	(6,822,000)
Proceeds from disposal of property and equipment		59,000
Proceeds from sales of investments		123,000
Net cash used in investing activities	(6,612,000)	(6,640,000)
Cash Flows from Financing Activities—Payments on capital lease obligation	(38,000)	(38,000)
Net Increase (Decrease) in Cash and Cash Equivalents	6,892,000	(31,890,000)
Cash and Cash Equivalents—Beginning of year	2,559,000	34,449,000
Cash and Cash Equivalents—End of year	$ 9,451,000	$ 2,559,000
Supplemental Disclosures—		
Property and equipment acquired through capital lease	$ –	$ 117,000
Cash paid for federal taxes	$ 4,000	$ 13,000

See notes to financial statements.

Monterey Bay Aquarium Research Institute

Notes to Financial Statements
As of and for the years ended December 31, 2006 and 2005

1. Summary of Significant Accounting Policies

Organization—The Monterey Bay Aquarium Research Institute (the "Institute") is a not-for-profit organization founded in 1987 for the purpose of conducting scientific research in marine biology, oceanography, underwater geology, and other kinds of marine research in and around the Monterey Bay and elsewhere and to educate the scientific community and the general public in regard to such research. The Institute's primary facilities are located in Moss Landing, California.

Since 1994, The David and Lucile Packard Foundation has been the Institute's only member, with the power to elect the Board of Directors. In 2006 and 2005, approximately 84% and 83%, respectively, of the Institute's revenues came from The David and Lucile Packard Foundation. In addition, certain trustees and officers of The David and Lucile Packard Foundation are also directors or officers of the Institute.

Basis of Presentation—The financial statements are presented on the basis of unrestricted, temporarily restricted, and permanently restricted net assets in accordance with accounting principles generally accepted in the United States of America ("generally accepted accounting principles"). The Institute had no permanently restricted net assets as of December 31, 2006 and 2005.

Use of Estimates—The preparation of financial statements in conformity with generally accepted accounting principles requires management to make estimates and assumptions that affect the reported amounts of assets and liabilities and disclosure of contingent assets and liabilities at the date of the financial statements and the reported amounts of revenues and expenses during the reporting period. Actual results could differ from those estimates.

Unrestricted Net Assets—Unrestricted net assets represent unrestricted resources available to support the Institute's operations and temporarily restricted resources, which have become available for use by the Institute in accordance with the intentions of donors.

Temporarily Restricted Net Assets—Temporarily restricted net assets represent gifts that are limited in use by the Institute in accordance with temporary donor-imposed stipulations. These stipulations may expire with time or may be satisfied and removed by the actions of the Institute according to the terms of the gift. At December 31, 2006 and 2005, the temporarily restricted net assets consist entirely of gifts from The David and Lucile Packard Foundation restricted to the subsequent years' operations. Net assets of $33,850,000 and $32,965,000 were released from restrictions due to the expiration of time restrictions during the years ended December 31, 2006 and 2005, respectively.

Concentrations of Credit Risk—Financial instruments which potentially subject the Institute to credit risk consist primarily of cash and cash equivalents and receivables. Cash and cash equivalents are maintained by major financial institutions and include investments in money market funds. At times, such amounts may exceed Federal Deposit Insurance Corporation limits. Receivables consist primarily of funds due from The David and Lucile Packard Foundation (see Note 3). The Institute closely monitors receivables and has not experienced significant credit losses.

Cash and Cash Equivalents—Cash and cash equivalents consist of cash on hand and in banks, plus highly liquid investments purchased with remaining maturity at the time of purchase of three months or less.

Property and Equipment—Property and equipment are stated at cost or at the fair market value at the date of donation and depreciated on the straight-line basis over the estimated useful lives of the assets (3 to 30 years). Capitalized costs for self-constructed assets include direct labor and benefits for employees specifically identified with the project. Long-lived assets are reviewed for impairment whenever events or changes in circumstances indicate that the carrying amount may not be recoverable.

Capital Leases—Capital leases are recorded as an asset and an obligation at the fair market value of the leased property at the inception of the lease. The Institute has leased equipment under long-term capital leases included in property and equipment at December 31, 2006, totaling $117,000, less accumulated depreciation of $66,000. The capital lease obligation of $41,000 at December 31, 2006, is expected to be repaid in 2007.

Revenue Recognition—Contributions are recognized as revenues when they are received or unconditionally pledged. The Institute reports gifts of cash and other assets as restricted support if they are received with donor stipulations that limit the use of the donated assets. When a donor restriction expires, that is, when a stipulated time restriction ends or purpose restriction is accomplished, temporarily restricted net assets are reclassified to unrestricted net assets and reported in the accompanying statements of activities and changes in net assets as net assets released from restrictions. Temporarily restricted contributions are reported as unrestricted support when the restriction is met in the same period as the contribution is received.

Income Taxes—The Institute's principal activities are exempt from federal and state income taxes under Section 501(c)(3) of the Internal Revenue Code ("IRC") and Section 23701(d) of the California Tax Code. To the extent that the Institute carries out activities which are subject to the unrelated business income tax, it is subject to income taxation.

The Institute is a private operating foundation which makes its required charitable expenditures by sponsoring and managing its own programs. Its status as an operating foundation is determined annually by satisfying the income test and certain other numerical tests. Generally, a private operating foundation must make qualifying distributions of 4.25% of the average fair market value of the foundation's investment assets directly for the active conduct of the activities for which it is organized and operating. The Institute has met the requirements for private operating foundation status through December 31, 2006.

Functional Expense Allocations—Expenses, such as salaries and wages, depreciation and amortization and professional fees, are allocated among the Institute's research categories and management and general classifications on the basis of employee and occupancy ratios and estimates made by the Institute's management.

New Accounting Pronouncement—In September 2006, the Financial Accounting Standards Board issued Statement of Financial Accounting Standards ("SFAS") No. 157, *Fair Value Measurements*. This standard establishes a single authoritative definition of fair value, sets out a framework for measuring fair value, and requires additional disclosures about fair value measurements. SFAS No. 157 applies to fair value measurements already required or permitted by existing standards. SFAS No. 157 is effective for financial statements issued for fiscal years beginning after November 15, 2007. The changes to current generally accepted accounting principles from the application of this statement relate to the definition of fair value, the methods used to measure fair value, and the expanded disclosures about fair value measurements. As of December 31, 2006, the Institute does not believe the adoption of SFAS No. 157 will impact the financial statement amounts.

2. Property and Equipment

Property and equipment at December 31, 2006 and 2005, consist of the following

	2006	2005
Land	$4,246,000	$3,522,000
Buildings	49,550,000	49,288,000
Research vessels	41,210,000	40,129,000
Remotely operated vehicles	18,841,000	18,404,000
Equipment, furniture, and fixtures	20,775,000	17,863,000
Capital projects in progress	14,876,000	14,682,000
Total	149,498,000	143,888,000
Less accumulated depreciation	(73,838,000)	(65,619,000)
Property and equipment—net	$75,660,000	$78,269,000

During 2005, it was determined that the Monterey Accelerated Research System research project (the "MARS Project") would result in a tangible asset to be held and used by the Institute. As a result, $7,243,000 in costs related to the MARS Project, which were previously expensed, were transferred to capital projects in progress in 2005.

3. Related-Party Transactions

In December of each year, the Institute receives a grant from The David and Lucile Packard Foundation to support the subsequent year's operations. The Institute received grants of $37,000,000 and $33,850,000 in 2006 and 2005, to be used in 2007 and 2006, respectively. The Institute received an additional $800,000 in 2006 for the purchase of adjacent real property. The receivable from this related party was $38,950,000 and $41,815,000 as of December 31, 2006 and 2005, respectively.

4. Commitments and Contingencies

The Institute leases certain land and facilities under noncancelable operating leases. The terms of these leases expire in 2007 through 2039, with certain options to renew. Certain rental rates are subject to adjustment based on increases in the consumer price index. Future minimum lease payments under noncancelable operating leases as of December 31, 2006, are approximately as follows:

Years Ending December 31:

2007	139,000
2008	112,000
2009	22,000
2010	22,000
2011	23,000
Thereafter	621,000
Total	$939,000

Rent expense was $147,000 and $114,000 for the years ended December 31, 2006 and 2005, respectively.

As of December 31, 2006 and 2005, the Institute has $500,000 on deposit as collateral to guarantee that the Institute will comply with the provisions of a land lease entered into with the State of California, California State Lands Commission to obtain right-of-way use needed for the construction of the MARS Project. Such amount is included in prepaids and other assets in the statements of financial position.

The Institute derives a portion of its revenues from various federally funded programs which are subject to review and audit by governmental oversight agencies. Institute management believes that the Institute is in material compliance with the standards set forth by the federal governmental agencies and that the outcome of reviews and audits conducted by such agencies will not have a significant effect on the financial position or results of activities of the Institute.

6. Minimum Future Rental Revenues

The Institute leases land and facilities to others under noncancelable leases with lease terms expiring in 2007 through 2011, with options to renew. Certain rental rates are subject to annual increases ranging up to 3%.

Minimum future rental receipts from operating leases having noncancelable lease terms in excess of one year are approximately as follows:

Year Ending December 31:

2007	158,000
2008	145,000
2009	136,000
2010	50,000
2011	22,000
Total	$511,000

7. Retirement Plans

The Institute sponsors defined contribution plans under both IRC Section 401(a) and 403(b). The plans cover all employees who meet eligibility requirements. Contributions to the 401(a) plan are made by the Institute at 10% of annual employee salary. Under the 403(b) plan and subject to statutory limits, employees make voluntary deferred salary contributions to the plan. Total expenses related to such plans were $1,676,000 and $1,591,000 in 2006 and 2005, respectively.

Effective December 1, 2004, the Institute established the Monterey Bay Aquarium Research Institute Section 457(b) Qualified Eligible Salary Deferral Plan (the "Salary Deferral Plan") primarily for the purpose of providing deferred compensation for a select group of management or highly compensated employees to accumulate retirement assets. The Salary Deferral Plan enables participants to defer income

on a pre-tax basis and is not funded. As of December 31, 2006 and 2005, $348,000 and $177,000, respectively, has been deferred based on elections made by the participants.

Effective December 1, 2004, the Institute also established the Monterey Bay Aquarium Research Institute Nonqualified Deferred Compensation Restoration Plan (the "Compensation Restoration Plan") primarily for the purpose of providing deferred compensation for a select group of management or highly compensated employees to accumulate retirement assets. The Compensation Restoration Plan provides for the Institute to make contributions to a participant's account equal to the amount in excess of IRC limits that the participant would otherwise have been eligible for in accordance with the Institute's 401(a) plan. The Compensation Restoration Plan is intended to be an unfunded plan. As of December 31, 2006 and 2005, $13,100 and $8,300, respectively, has been accrued by the Institute related to the Compensation Restoration Plan.

The Institute held funds of $361,000 and $185,000, included in prepaid expenses and other, at December 31, 2006 and 2005, respectively. These assets are designated by the Institute to pay future Salary Deferral Plan and Compensation Restoration Plan liabilities.

8. Research Expenses

The Institute's research expenses are classified within the following divisions:

Division of Marine Operations—Division of marine operations is responsible for operating and maintaining the research vessels and remotely operated vehicles.

Research and Development—Research and development encompasses scientists and engineers who develop and manage oceanographic research programs.

Information and Technology Dissemination—Information and technology dissemination is responsible for internal and external communication efforts.

Research expenses, by division, for the years ended December 31, 2006 and 2005, are as follows:

	2006	2005
Division of marine operations	$5,593,000	$5,642,000
Research and development	29,506,000	26,121,000
Information and technology dissemination	1,939,000	1,951,000
Total	$37,038,000	$33,714,000

Credits

On the cover: Artist's rendering of a DNA probe array (left) used to detect different organisms such as barnacle larvae (center) based on their unique genetic codes (right, strand of DNA). The arrays are developed remotely under the sea using the Environmental Sample Processor. See page 5.

Inside front cover: Divers work with the Environmental Sample Processor during trials in the MBARI test tank.

Project manager: Nancy Barr

Project team: Lori Chaney, Judith Connor, Jane Curtner, Patricia Duran, Marcia McNutt

Graphic design: Scott Design Inc.

Page 8, photo of microbead array: Provided by the Walt Laboratory at Tufts University

Page 10, bottom: Courtesy of Colorado School of Mines

Page 13: Courtesy of Naval Air Station, Moffett Field

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http://www.mbari.org/news/publications/2006AnnRpt.pdf

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