ANNUAL REPORT 2011

MBARI

Monterey Bay Aquarium Research Institute


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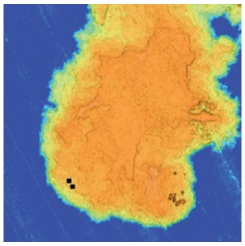

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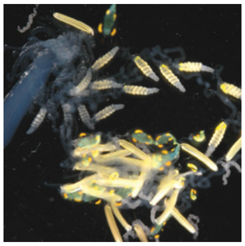

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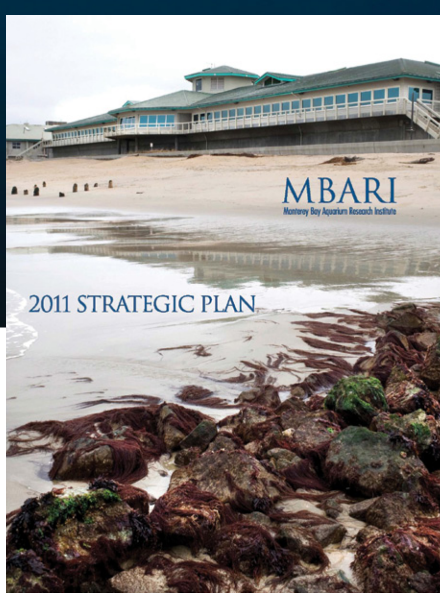
View From the Masthead

As 2011 began we set our sights on meeting a number of institutional milestones for the year ahead. The first of these was the adoption of a new strategic plan. Second, we set out to solve a vexing problem of how best to reconfigure our fleet of research vessels in the face of current economic challenges. Finally, we wanted to begin work on a technology roadmap—a vision for guiding engineering and technological developments at MBARI over the coming decade. Of course, these activities were to take place alongside another year of ambitious projects that included a number of expeditions both local and afar.



The 2011 Strategic Plan will guide MBARI's research efforts for the coming decade.

The 2011 Strategic Plan was formally adopted in March after much input from MBARI's Board of Directors and a cross-section of MBARI staff. Over the coming decade we foresee our research and development programs centering on documenting the state of the ocean against the backdrop of global change. Four interrelated themes are to be emphasized: exploration and discovery, ocean visualization, ecosystem dynamics, and ocean biogeochemistry. Our work under those broad themes will highlight MBARI's unique relationship with our primary benefactor, the David and Lucile Packard Foundation, and be reflective of the foundation's larger programs and goals. The plan showcases our enduring commitment to technical innovation, the merger of science and engineering, and flexibility in the face of changing priorities and circumstances. In addition, we look to create more strategic partnerships that will allow us to undertake a larger suite of activities and connect with a broader audience than would be possible with support from the Packard Foundation alone. I am very proud of the course we have charted.

With the new strategic plan in place, we turned our attention to defining the mix of ships that will be necessary for MBARI's future marine operations. In past years, unfettered access to the sea and the ability to alter ship schedules throughout the year as needed proved to be instrumental in allowing us to rapidly hone our research programs, thereby stimulating a host of new discoveries and novel engineering developments. Traditionally our operations have rested in large part on two types of ships: a regional class expeditionary vessel for extended missions and coastal class vessels to support shorter missions and facilitate technology development. Those needs were met by a three-ship fleet, with the *Western Flyer* serving as our regional vessel and both the *Point Lobos* and *Zephyr* often operating closer to home. The *Point Lobos*, MBARI's first ship, was highly effective at supporting a wide array of operations, primarily using the remotely operated vehicle (ROV) *Ventana* within Monterey Bay, but could not easily go beyond local waters. The *Zephyr*, acquired in 2001, proved to be central to the development of our autonomous underwater vehicle (AUV) program and for operating the AUVs locally and farther afield. However, unlike the *Point Lobos*, the *Zephyr* was not well suited for wet-lab work and had limited lift capacity for deploying and recovering moderately sized science equipment. Nonetheless, when those two vessels were combined with the *Western Flyer*, the three-ship fleet proved to be a powerful cohort instrumental in bringing to fruition a host of novel

The R/V *Rachel Carson* sailed from its former home in Louisiana, through the Panama Canal, up the West Coast to arrive in California in December.

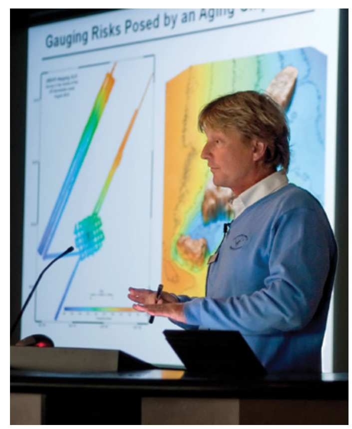
developments and studies that have made MBARI world renowned. Looking beyond 2011, how could we maintain that core capability now that budgetary pressures made continued operation of all three ships impossible?

Our solution was to retire the *Point Lobos* and the *Zephyr* in favor of a single ship that is in effect a hybrid of its predecessors—a new coastal class vessel that would support both AUV and ROV operations locally as well as elsewhere along the western shores of North America. After a long search, we found and acquired a ship that met our needs: an offshore supply vessel located in the Gulf of Mexico. Renamed the R/V *Rachel Carson*, the ship sailed from Louisiana, transited the Panama Canal, and arrived in San Francisco Bay December 23, 2011. That journey harkened back to the early days of our operating the *Point Lobos*, another offshore supply vessel that was purchased from the oil fields of the Gulf of Mexico and brought to Monterey Bay via the same route in 1987.

The *Carson* is currently being outfitted as a research vessel and is scheduled to begin its ocean science service in 2012. The *Point Lobos* officially ended its storied career at MBARI with a final science mission on December 1st after 3,697 missions and 3,668 ROV dives, ironically the very same day that the *Carson* set sail from Louisiana on its transit to San Francisco. In turn, we expect the *Zephyr* to cease its operations during the summer of 2012. The retirement of the *Point Lobos* and the *Zephyr* marks the end of a very formative and productive period while at the same time ushering in the dawn of a new era for this institution and our staff.

With our overarching research themes captured in the new strategic plan and the fleet-renewal program well under way, we then turned toward the challenge of developing a technology roadmap. This document is ultimately intended to articulate engineering and technological developments to accelerate progress in the research areas outlined in our strategic plan. In keeping with MBARI founder David Packard's passion for innovation, I feel it is essential that the technology roadmap emphasize developments that will uniquely distinguish MBARI. The creation of the roadmap began as 2011 drew to close, thus setting the stage for what promises to be another vigorous discussion over the year ahead. How can we best allocate our limited engineering resources, and what strategic partnerships can we form to enhance progress in particular areas? Once more, we will look to staff throughout the institute and tap the expertise and wisdom of MBARI's Board of Directors. Fittingly, it will take place as we celebrate our 25th anniversary with an eye very much cast to the future.

Aside from the work to position MBARI for the coming decade, the past year also proved to be another one rich in discovery and technical achievement. This annual report was specifically crafted as a tribute to the latter—to all of MBARI's staff whose collective efforts serve to highlight the goals captured in our new strategic plan—in particular the emphasis on merging science, engineering, and marine operations. This year's annual report also highlights examples of how we have extended our reach through partnerships and extramural programs. I am amazed to see how far MBARI has come since its inception, and am inspired to consider the prospects for what we can achieve in the coming decades. I am looking forward to 2012!



Chris Scholin presents MBARI's latest research to visitors at the MBARI Open House.

Chris Scholin
President and Chief Executive Officer

Monterey Bay as a Window to the World

More than two decades of MBARI's focused observation and experimentation in Monterey Bay and contiguous waters have provided novel insights into ocean processes and created opportunities for exporting technology to other regions of the world. By fostering technology development and by giving access to tools that extend the range and scope of previous experimental approaches, MBARI is also making Monterey Bay a prime location for other institutions to engage, test, and collaborate on ocean research.

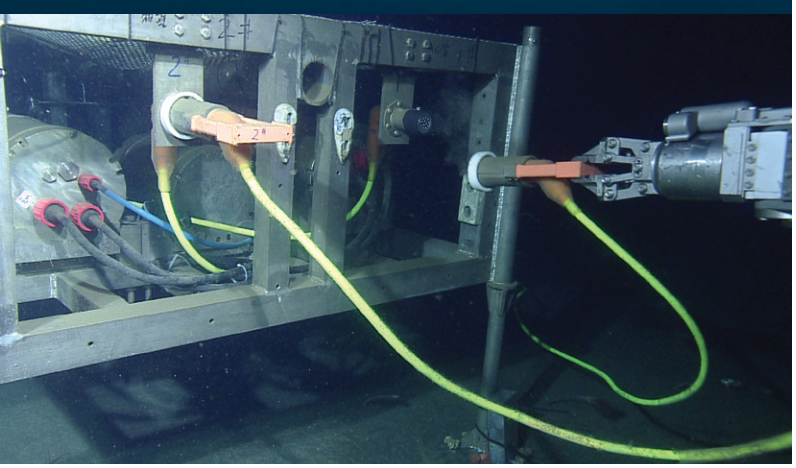


Figure 1: The robotic arm on the ROV *Doc Ricketts* plugs in the cable connecting this component of the Chinese test observatory to the main MARS node.

Deep-sea observatory attracts international use

Scientists have traditionally relied on brief oceanographic cruises and battery-powered instruments to gather data and samples from the deep sea. Now the Monterey Accelerated Research System (MARS), which became operational in 2008, provides uninterrupted ocean access for complicated experiments, allowing research to continue for months at a time, all while being controlled from shore. Worries about battery life are gone with the supply of electrical power directly from shore and researchers can receive data and video from the deep sea in real time, 24 hours a day, from anywhere with an Internet connection.

The MARS hub contains eight ports, which are essentially outlets for plugging in extension cords to various instruments. At times during the past year, seven of the eight MARS science ports were in use testing instruments. These included a Scripps Institution of Oceanography seismometer and a tiltmeter/bottom-pressure recorder for Oregon State University and the National Oceanic and Atmospheric Association—both on the observatory since 2010. Returning to MARS in 2011 after a brief hiatus were MBARI's Free Ocean Carbon Dioxide Enrichment experiment and the Monterey Ocean Broadband (MOBB) seismometer, a collaborative effort between MBARI and the Berkeley Seismological Laboratory. New additions to MARS were a Chinese observatory created by a consortium of five Chinese universities and led by scientists from Tongji University, the Sediment Event Sensor for MBARI's Ken Smith, and a microbial fuel cell for collaborators at Oregon State and Harvard Universities.

Perhaps the most challenging experiment of the year was the installation of the Chinese observatory (Figure 1). Three separate instrument packages were deployed near MARS in a two-ship operation—the crew aboard the R/V *Western Flyer* lowered and released each package while the remotely operated vehicle *Ventana* (launched from the R/V *Point Lobos*), provided guidance to the R/V *Western Flyer* crew for positioning each package with meter-level precision. The packages included a junction box with a video camera that ultimately sent video back to China over the Internet; a chemical-monitoring system measuring in situ anion concentrations, methane, chlorophyll, oxygen, nitrate, and pH; and a system to record salinity, temperature, depth, and current velocity.

Figure 2: ROV pilot Mark Talkovic readies the ROV *Doc Ricketts* mounted to the cable-laying-and-plowing toolsled, which is equipped with wheels to enable controlled transit across the seafloor.

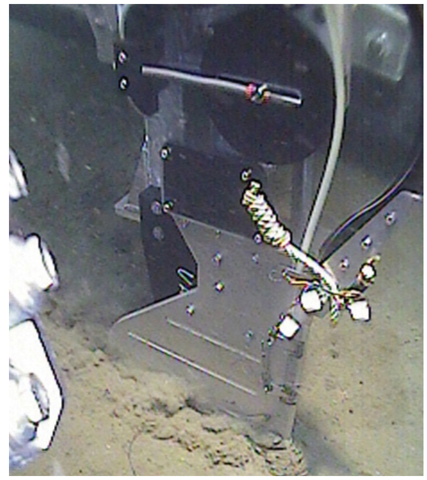


Figure 3: The ROV *Ventana* buries a cable on the seafloor during a test run of the new plow-and-cable-laying toolsled. The toolsled was later installed on ROV *Doc Ricketts* to lay the cable from the MARS node to the seafloor seismometer.

Another big accomplishment for the MARS operation in 2011 was the development of a new tool to bury cables to the various instruments. Three times fishermen had inadvertently trawled the cable connecting MARS to the MOBB seismometer without serious damage, but the fourth time the cable broke. Since the cable lies in an area where fishing is permitted, the best way to avoid such accidents in the future was to bury it. The MARS team, under the leadership of Craig Dawe, devised a plan to attach a plow to the ROV cable-laying toolsled. First, the team had to determine if MBARI's ROVs were powerful enough to drive a plow through the sediment. The first plow blade tested satisfactorily, but it was difficult to maintain a proper angle of attack while the ROV flew over the seafloor. The solution was to add wheels to the toolsled (Figure 2) to better control its path so that the ROV could drive over the seafloor and plow a shallow trough to bury the cable.

These creative solutions came together in June when the ROV *Doc Ricketts* deployed and buried a 3.6 kilometer cable between MARS and the MOBB site. This was the first time an MBARI ROV deployed and buried a cable at the same time. This specialized toolsled was developed using *Ventana* to test the device (Figure 3) before installing it on the *Doc Ricketts* for deployment. The ROV was able to bury 95 percent of the cable length. The MOBB experiment is now less vulnerable to trawling and is once again streaming live data back into the Northern California earthquake-monitoring network.

The successful installation and remote operation of complex experiments on the deep seafloor with MARS ushers in a new era of sustained research on ocean processes, ecosystem dynamics, and climate change, as envisioned by the National Science Foundation's Ocean Observatories Initiative.

Monterey Accelerated Research System (MARS)

Project lead: Steve Etchemendy
Project manager: T. Craig Dawe
Project team: Ken Heller

Development of a Prototype Multi-Sensor Ocean Floor Observatory on the MARS Cable

Project leads: Paul McGill, Barbara Romanowicz
Project manager: Paul McGill
Collaborator: Doug Neuhauser, University of California, Berkeley

Trash in the deep sea: Bringing a hidden problem to light

The impact of anthropogenic marine debris on ocean ecosystems has captured the attention of the scientific community and the public. Most research has focused on cataloguing and quantifying marine debris on beaches, coastal habitats, and surface waters in the open ocean. Due to the technical challenges and prohibitive costs of conducting research in the deep sea, very little is known about the types, sources, and impacts of marine debris on this vast habitat.

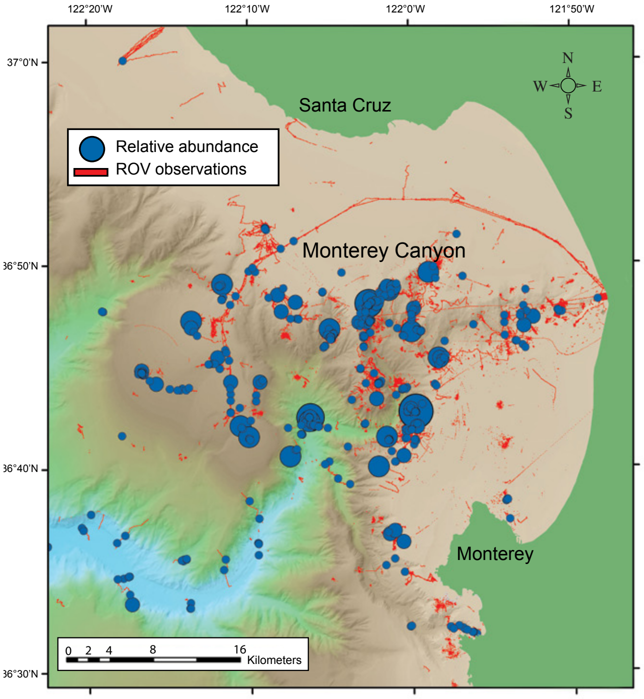


Figure 4: Location of MBARI ROV dive tracks (red) and marine litter observations (blue) in Monterey Bay, California. The size of the circles represents the relative abundance of debris found at each location.

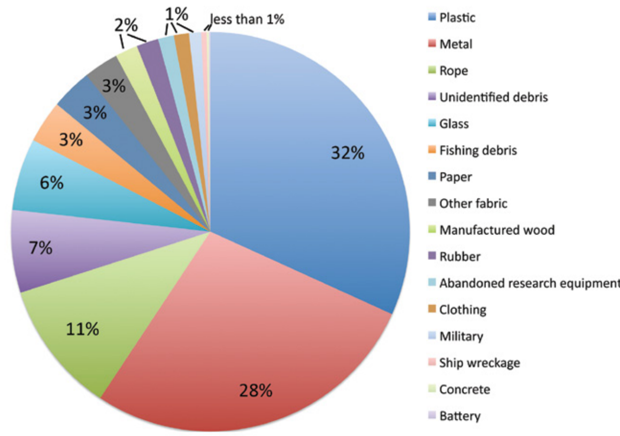


Figure 5: Percentage of total marine debris observations by category.

MBARI's unique video annotation database, a repository of 24 years of observational records, offered the opportunity to take a rare look at marine debris from depths of 40 to 4,000 meters. In 2011, the research staff in MBARI's video lab, led by Nancy Jacobsen Stout, examined the types and distribution of marine debris in the Monterey Bay region.

Using MBARI's Video Annotation and Reference System (VARS), video lab staff analyzed 3.6 million deep-sea observation records from over 18,000 hours of archival video. More than 1,500 observations of marine debris were recorded from the greater Monterey Bay region. Debris types were characterized and mapped (Figure 4). The majority of debris items observed were plastic (32 percent) or metal (28 percent) (Figure 5), with plastic bags and aluminum cans as the most common debris observed. Surprisingly, plastic and metal were most abundant in deeper depths, suggesting that previous studies of marine debris shallower than 500 meters may have underestimated the extent of debris accumulation on the deep seafloor. Trash was more abundant within Monterey Canyon, where items may become lodged on rugged, rocky outcrops or settle within seafloor depressions, than in non-canyon habitats. A similar distribution pattern was observed for naturally occurring debris, such as kelp, seagrasses, and wood, suggesting that most debris of any sort came from nearshore or land-based sources (Figure 6). Some debris, however, appeared to have been discarded or lost overboard from vessels.

The long-term effects of anthropogenic debris on deep-sea life are largely unknown. Animals were associated with the debris in about 40 percent of the observations. A few obvious detrimental impacts upon marine life were observed, such as animals entangled in ghost fishing nets, but the majority of the animal associations appeared to be benign, such as a sea anemone settled on the hard surface of a glass bottle. However, debris may alter ecosystem dynamics by leaching chemicals into the environment or by providing habitat for alien or invasive species. Additionally, an accumulation of debris could alter current flow, obstruct water circulation, or otherwise disturb organisms that live in or on the sediment. The full impact remains an open question that may be quite difficult to determine without sustained observations and experimentation.

One opportunity to examine the effects of human-generated debris on seafloor ecosystems was enabled by the serendipitous discovery of a lost shipping container in 2004. While observing the seabed at 1,300 meters depth during a dive with the ROV *Ventana* in the Monterey Bay National Marine Sanctuary (MBNMS), researchers discovered a shipping container resting on the seabed. Based on its serial number, MBNMS (part of the National Oceanic and Atmospheric Administration) and U.S. Customs iden-

Figure 6: Examples of common marine debris observed on ROV video surveys. Clockwise from upper left: plastic bag wrapped around a deep-sea gorgonian, aluminum can, rope and fishing net, glass bottle, plastic bag, and tire with organisms living on and around it. MBARI provided information for a House of Representatives Ocean Caucus briefing on marine debris, a meeting that brought together experts from federal agencies, industry, and non-profit organizations to discuss the impacts of marine debris on the environment and the economy, as well as solutions for mitigating its consequences.

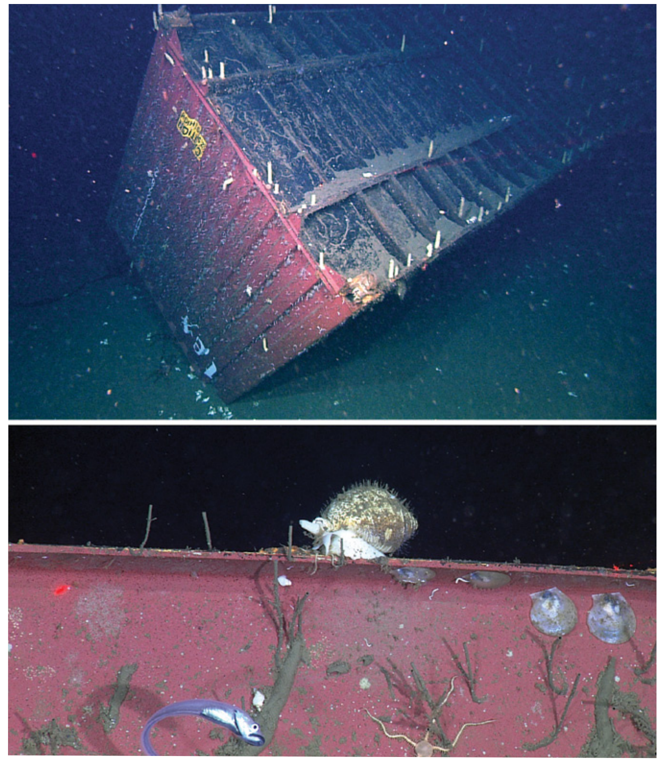


Figure 7: MBARI researchers found this shipping container full of steel-belted tires in the Monterey Bay National Marine Sanctuary. Over time, some seafloor animals settled on the container as it provided a hard surface on an otherwise muddy and sandy seafloor.

tified the source vessel. Investigators determined that the ship, the *Med Taipei*, lost 15 containers off its deck during a storm earlier that year. However, as no one was harmed, there was no legal requirement for the shipping company to report the loss. After a significant legal effort, the shipping company agreed in 2006 to pay NOAA $3.25 million to settle claims relating to the lost containers. Funds from this settlement supported a research expedition to the site in 2011 to investigate any impact the container may have upon the nearby environment.

Together, MBNMS research coordinator Andrew DeVogelaere and MBARI ecologist James Barry are identifying and counting animals on and around the container, and evaluating changes in the sediment and sediment-dwelling fauna in the vicinity of the container (Figure 7). By comparing animal communities at distances radiating away from the container, the researchers hope to determine what effects, if any, the container has had on seafloor life. Initial results indicate that a very different suite of animals lives upon the container compared with the surrounding seafloor. Although most animal species observed on the container are common on rock outcrops in the region, they are unusual in the vicinity of the container because rocky surfaces are fairly rare in the immediate area, where mud and sand are prevalent. According to the U.S. Customs manifest, the container holds more than a thousand steel-belted tires. It does not yet appear to be leaking, but any

Marine Debris Observations

Project leads: Kyra Schlining, Susan von Thun
Project manager: Nancy Jacobsen Stout
Project team: Lori Chaney, Judith Connor, Linda Kuhnz, Lonny Lundsten, Brian Schlining
Collaborators: James Barry, MBARI; Andrew DeVogelaere, Monterey Bay National Marine Sanctuary

compounds released into the marine environment from the container as it degrades may affect the local biological assemblage. This is yet another example of debris creating habitat for organisms, but the long-term effects remain to be seen. Although the research team does not expect large ecological impacts from the single container under study, it is important to consider the combined effects of the many shipping containers lost each year, which eventually accumulate on the deep seabed.

This research effort provides a much-needed snapshot of a worldwide question with vast areas of the deep sea still unexplored. MBARI's ROV videos have recorded evidence of debris as far afield as the waters off Southern California, the Pacific Northwest, Hawaii, and in the Gulf of California. MBARI researchers Ken Smith and Alana Sherman have also observed several pieces of trash on the seafloor using a time-lapse camera at 5,400 meters depth in the Sargasso Sea (in the Atlantic). Though not consistently documented in research studies, reports indicate that few areas of the world ocean are likely untouched by marine debris. MBARI researchers hope that these studies of marine debris will help increase awareness among the public, policy makers, and the scientific community, and inspire action to combat the growing problem of anthropogenic debris in the ocean. Although many do not grasp the consequences of our actions on the ocean, MBARI's consistent access to the deep sea can help enhance understanding of human impacts on the planet.

A new tool in ocean reconnaissance

Five hundred kilometers off the California Coast, a small torpedo-shaped device surfaced, pausing briefly to transmit data to shore and check in for new commands (Figure 8). Launched several days earlier from Moss Landing, *Tethys*,

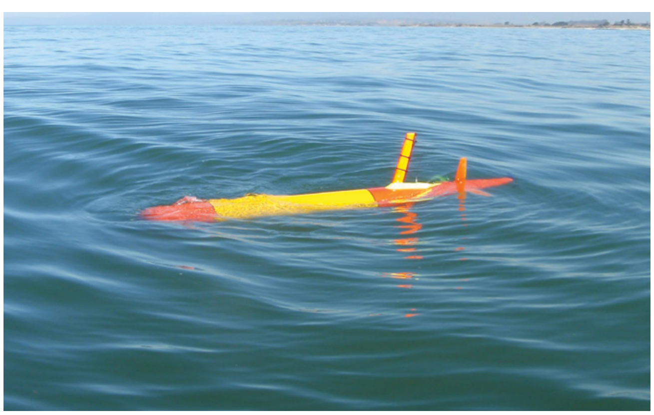


Figure 8: The *Tethys* long-range autonomous underwater vehicle surfaces to transmit data via satellite during a reconnaissance mission in Monterey Bay.

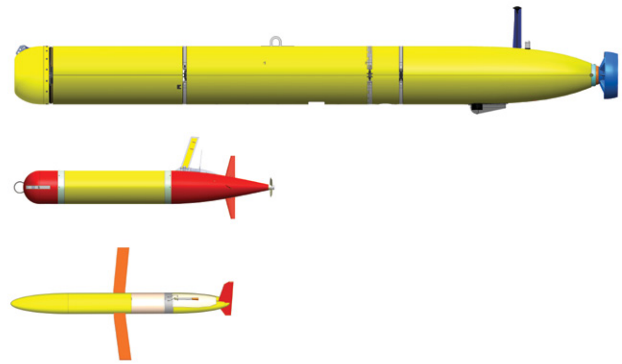


Figure 9: The *Dorado* AUV (top) weighs 500 kilograms and can carry many sensors but can only run day-long missions. The *Tethys* (center) weighs 100 kilograms and can run longer missions. It is capable of running slowly for a long distance or faster for a short distance, or can wait in the water until something interesting happens. The *Spray* glider is the smallest at 48 kilograms, but it has little power for running sensors and travels slowly.

MBARI's newest autonomous underwater vehicle, or AUV, was mapping the variability of the physics, chemistry, and biology of the diverse microbial ecosystems off California as part of the CANON fall field program. CANON, which stands for Controlled, Agile, and Novel Observing Network, is an institute-wide initiative bringing together many research groups to learn more about ocean ecosystems and their processes through new tools and techniques.

Once *Tethys* completed its offshore reconnaissance mission, its next objective was to rendezvous with the research vessel *Western Flyer* 275 kilometers to the east. The vehicle mapped variability around the ship, providing background information about what was going on in the water to help guide the shipboard microbiologists from MBARI and the University of Washington who were taking water samples for later chemical and genomic analyses onshore. From there the AUV motored around Monterey Bay for nearly a week measuring ocean processes to complement measurements from instruments installed on the seafloor by Moss Landing Marine Laboratories and the Naval Postgraduate School. By the time the vehicle was recovered, it had spent 23 days at sea, covered more than 1,800 kilometers, and was growing barnacles. *Tethys* had proven itself as an important element of a complex observing capability to characterize microbial ecosystems and their interactions with the environment.

Although MBARI has operated AUVs for more than a decade, the *Tethys* AUV represents a new generation of robotic systems that greatly extends MBARI's reach offshore. Developed by MBARI Chief Technologist Jim Bellingham and his team of engineers, *Tethys* fills a gap between the prior generation of propeller-driven AUVs, which can carry large payloads but operate for less than a day or so at a time, and buoyancy-driven AUVs (gliders) that operate for months at a time, but at slow speeds and with small payloads (Figure 9). *Tethys* operates four times as fast as gliders, and carries a much larger payload, while at the same time traveling 10 times as far as commonly used propeller-driven AUVs. *Tethys* has capabilities unique from propeller-driven AUVs, such as the ability to adjust buoyancy to reorient for vertical profiles of the ocean or drift at a selected depth without active propulsion.

AUVs are usually designed around their payloads, and *Tethys* was designed so that advanced, small-scale, low-power payloads can be accommodated. The first generation of

A new technological approach

What allows the *Tethys* AUV to travel distances 10 times greater than existing propeller AUVs? Factors include an extremely efficient propulsion system, a low-drag hull, low-power electronics, and control strategies that minimize energy expenditure. The vehicle is also tightly integrated, and thus small, with a dry weight of 110 kilograms (about 240 pounds). Small size normally works against vehicle performance, in that energy capacity scales with the vehicle volume while drag scales with vehicle surface area. If all other factors are equal, small vehicles have lower range and endurance than large vehicles. However, when cost of operations is a factor, small is beautiful. For a large vehicle the cost of single-use primary batteries, with high energy density, is typically prohibitive. In contrast, for smaller vehicles, the correspondingly smaller battery capacity makes using primary batteries economically viable. So a small vehicle has a smaller battery, which allows use of a higher energy density battery should that be desired.

Tethys was created to enable quantitative observations of the dynamics of ecological processes in the ocean. This goal motivates its endurance, range, and payload characteristics. The endurance requirement stems from the need to observe biological communities, such as phytoplankton, over their natural life, from bloom to bust. This drives a desire to carry out observations over weeks or even months. At the same time, understanding oceanic ecosystems requires moving beyond the nearshore environment. For example, off California the temperature, chemistry, and microbial communities change dramatically as one moves from the upwelling zone out to the California Current and on into the central Pacific. Although these regions can be accessed by ships today, such field programs are expensive. This motivates the long range of the vehicle. However, while great endurance and long range are important, it's the availability of a new generation of chemical and biological sensors that will turn the *Tethys* from an impressive technical achievement to a transformational tool for science (Figure 10).

Figure 10: *Tethys* can be launched down a boat ramp, left, and towed with a small boat, center. Its mission can be initiated from a smart-phone, right.

instruments designed specifically to take advantage of the long-range AUV is already in the works. With MBARI scientist Alexandra Worden's group and colleagues at the University of Washington, the *Tethys* team is championing the development of a *Tethys*-capable flow-cell cytometer, an instrument for examining and counting microscopic particles. In addition, a small version of the Environmental Sample Processor for sampling is in development by the ESP team. A turbulence-measuring instrument developed at the Naval Postgraduate School is being integrated. In short, *Tethys* is one part of a gathering arsenal of tools for an assault on the secrets of microbial ecosystems.

Microbes play a pivotal role in determining ocean responses to disturbances, including human impacts, such as increased ocean temperatures and absorption of atmospheric carbon dioxide, nutrient runoff from aquaculture, and pollution. Open ocean phytoplankton populations respond quickly to episodic upwelling of nutrients, occasionally producing spectacular algal blooms, whereas normal conditions are characterized by low productivity. Blooms provide a natural laboratory where carbon, nitrogen, and phosphorus cycles manifest themselves through microbial populations. Little is known about the mechanisms underlying how blooms form and decay and how climate changes will alter the frequency and magnitude of such episodic events. Why is understanding the dynamics of marine ecosystems so challenging? The difficulty arises partly from limitations of shipboard-, mooring-, and satellite-based observations that do not capture microbial population dynamics that change over the course of hours and on spatial scales of tens to hundreds of meters. A second challenge stems from the paucity of in situ sensors for characterizing marine microbial ecosystem and their chemical environment.

AUVs are now capable of actively following and repeatedly characterizing microbial populations, opening a window on how microbial assemblages develop and influence biogeochemical cycles. Long endurance allows the *Tethys* system to be there in situ, so that episodic events that produce biological responses can be studied. This information is essential for developing effective ecosystem models and predictors of natural and human-mediated ecosystems changes.

The development and application of *Tethys* is central to the CANON team's vision of an array of instruments collecting data in a remote environment, while being controlled from shore. In this way, it will be possible to direct biological process experiments from shore without the strict need for ships. Blooms or eddies, identified from satellite-sensed sea-surface height anomaly or ocean-color data, would be investigated by mobile vehicles that follow, study, and sample the water mass for months. The CANON suite of sensors will allow us to address both episodic blooms and the dynamics of the more persistent and enigmatic picophytoplankton populations (organisms that are less than two micrometers in diameter) that dominate open ocean waters. The high-resolution sampling afforded via CANON is perfectly suited to addressing these issues, and for determining if rare organisms contain genetic information that allowed them to thrive under changing conditions.

Long-Range AUV

Project lead: James G. Bellingham
Project manager: Brett Hobson
Project team: Jon Erickson, Michael Godin, Thomas Hoover, Brian Kieft, Dennis Klimov, Rob McEwen, Ed Mellinger, Yanwu Zhang

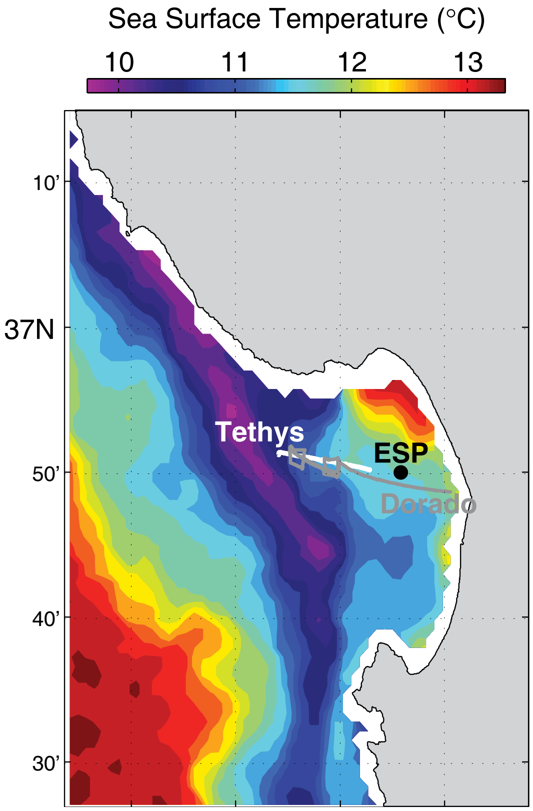
Ecology and Dynamics of Picophytoeukaryotes

Project lead: Alexandra Z. Worden
Project managers: Sebastian Sudek, Alexandra Z. Worden
Project team: Tracy Campbell, Valeria Jimenez, Alexander Limardo, Darcy McRose, Emily Reistetter, Melinda Simmons, Jeltje van Baren, Jeremy Yan
Collaborators: Andrew Allen, J. Craig Venter Institute, San Diego, California; Francisco Chavez and Ken Johnson, MBARI; Connie Lovejoy, University of Laval, Quebec City, Canada; Jon Zehr, University of California, Santa Cruz

Learning to dance the robotic ballet

Intelligent choices regarding the composition, design, and operation of ocean observing systems can greatly improve their utility and the amount of useful information collected. The systems can be made much more effective through coordinated operations of ships, vehicles, moorings, and sensors and by enabling autonomous platforms or robots to react to real-time data and make intelligent decisions without human intervention. Beyond informing an individual robot's activities, instructions and data can be passed between robotic vehicles and instruments to further coordinate operations.

The CANON team made significant advances in 2011 toward these intelligent coordinated operations. During the first



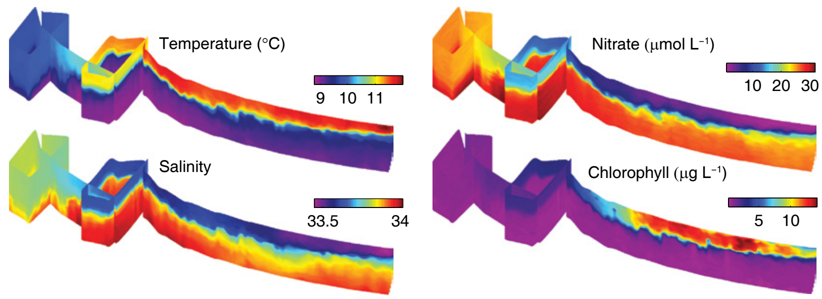


Figure 11: Cooperative robots. During the April CANON experiment, the *Tethys* and *Dorado* AUVs worked together to provide detailed observations of a frontal zone "upstream" of the ESP mooring. The map (left) shows a filament of cold, upwelled water extending across the mouth of Monterey Bay. The boxes in the track of AUV *Dorado* indicate frontal locations identified by AUV *Tethys* (frontal position changed with time). Vertical sections of water column properties (above) are shown for the upper 40 meters along the *Dorado* survey track.

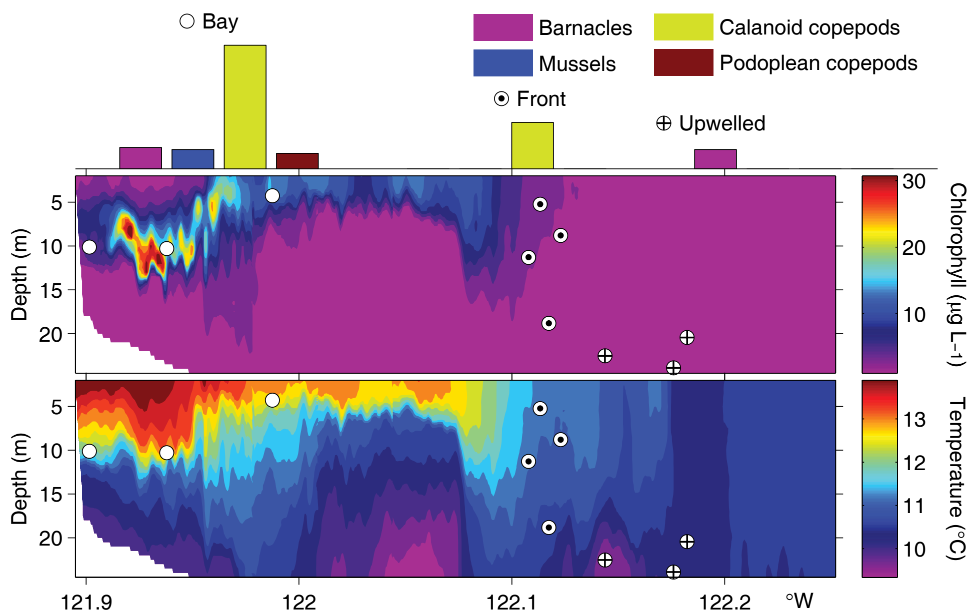


Figure 12: Integration of autonomous feature recognition, signal localization, and molecular analyses allowed CANON researchers to conduct "surgical sampling" of patchy coastal waters. This example of a *Dorado* AUV mission illustrates autonomous recognition and sampling of different coastal domains (active upwelling, upwelling shadows in the bay, and the fronts between them). Bars indicate the abundance of zooplankton molecular signatures from all samples within each water type.

experiment of the year, in April, the mobile robot *Tethys* was deployed to monitor conditions near the stationary robot Environmental Sample Processor. The ESP was moored in northern Monterey Bay where oceanic fronts that separate different water masses, each with its own characteristic biological community, are known to come and go. One of *Tethys*' jobs was to monitor the arrival of the fronts moving into the bay so that the ESP could be programmed to sample the different biological communities accordingly (Figure 11). The type of front that develops most frequently in Monterey Bay occurs between cold waters brought to the surface by wind-driven coastal upwelling and warmer waters that have been heated by the sun over many days. Coastal upwelling of cool, nutrient-rich deep water creates strong gradients and patchiness in the physical environment and plankton communities. The frequently observed upwelling front was active during the April experiment. When *Tethys* detected the frontal region, it sent that information to the *Dorado* AUV, which carried out higher-resolution surveys. *Dorado*'s onboard intelligence, in turn, used that information in real-time to carefully target where it would collect water samples within patches of water.

Dorado's ability to acquire water samples with surgical precision was further advanced during the June CANON experiment. *Dorado* flew 31 kilometers from relatively warm waters in northern Monterey Bay, through an upwelling front, and into a cold upwelling filament. An onboard algorithm detected the region of active upwelling; the warmer, more stratified waters; and the frontal region, and autonomously acquired water samples from all three domains. Further, a "peak" detection algorithm identified high levels of chlorophyll below the sea surface in the stratified waters, which triggered the collection of water samples there. Molecular analyses of the AUV water samples revealed different zooplankton community composition and abundance in the three domains (Figure 12).

These "robotic ballets" were made possible by complementary engineering development programs of the labs of Kanna Rajan and Jim Bellingham, in close coordination with the other CANON researchers.

Marine life in the "future ocean"

As researchers become more aware of the impact of ocean acidification on marine life, new tools and techniques are being devised to predict the consequences of a lower pH ocean in the future. The Intergovernmental Panel on Climate Change and a number of scientific reports have emphasized the need for research concerning the potential effects of ocean acidification on marine organisms and ecosystems, and related impacts on society. Progress in understanding the effects of ocean acidification on marine life has come mostly from using small-scale laboratory

Autonomous Ocean Sampling Networks

Project lead/manager: James G. Bellingham
Project team: Sergey Frolov, Michael Godin, Dorota Kolber, Yanwu Zhang
Collaborators: Rob Fatland, Microsoft Research, Redmond, Washington; Erika McPhee-Shaw, Moss Landing Marine Laboratories, California; William Shaw and Tim Stanton, Naval Postgraduate School, Monterey, California

Compact Ocean Models Enable Onboard AUV and Decentralized Adaptive Sampling

Project lead/manager: James G. Bellingham
Project team: Sergey Frolov, Michael Godin, Yanwu Zhang
Collaborators: Michael Cook and Jeffrey Paduan, Naval Postgraduate School, Monterey, California

Controlled, Agile, and Novel Observing Network

Project leads: James G. Bellingham, Francisco Chavez, Kanna Rajan, Steve Ramp, John Ryan, Chris Scholin, Ken Smith, Robert Vrijenhoek, Alexandra Z. Worden
Project manager: Francisco Chavez
Project team: Danelle Cline, Duane Edgington, Kevin Gomes, Mike McCann, Tom O'Reilly, Thom Maughan, and members of all the research groups associated with the project leads

Cooperative Oceanography and Virtual Experiments

Project lead/manager: James G. Bellingham
Project team: Michael Godin, Dorota Kolber

Distributed Autonomy

Project lead: Kanna Rajan
Project manager: Thom Maughan
Project team: Rishi Graham, Tom O'Reilly, Frederic Py, Hans Thomas
Collaborators: Daniel Borrajo, University Carlos III de Madrid, Spain; Mandar Chitre, National University of Singapore; Timothy Chung, Naval Postgraduate School, Monterey, California; Maria Fox, King's College, London, United Kingdom; Javier Gilabert, Polytecnica Universitat Cartagena, Spain; Joao Sousa, University of Porto, Portugal; Gaurav Sukhatme, University of Southern California, Los Angeles

Using Learned Models to Improve Decision Support in CANON

Project lead: Maria Fox, Kanna Rajan
Project manager: Thom Maughan
Project team: Mike Godin, Frederic Py, Yanwu Zhang
Collaborators: Derek Long and Daniele Magazzeni, King's College, London, United Kingdom

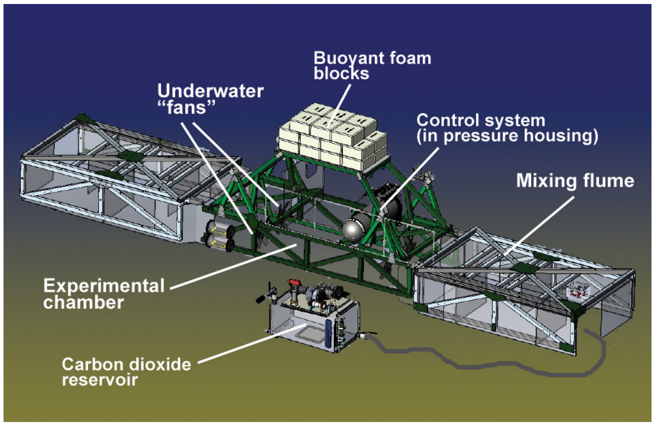


Figure 13: This diagram shows some of the main components of the deep-water FOCE system.

experiments exposing animals to the ocean conditions expected in the future. Such studies are usually limited to laboratory settings and very short time periods that may not represent species' responses to acidification under field conditions. The need for innovative methods to study ocean acidification in situ and over longer time periods led to MBARI development of the Free Ocean Carbon Dioxide Enrichment (FOCE) system.

The FOCE system provides a chamber in which different concentrations of carbon dioxide can be injected while the apparatus is resting on the seafloor (Figure 13). Seawater mixed with carbon dioxide is released at one end of the flume and is pulled through the flume by small thrusters. The acidified seawater flows slowly through a series of baffles, allowing it to completely mix before it enters a central experimental chamber in the center of the flume. By placing marine animals into the chamber, researchers can compare the reaction of the animals receiving the CO_2-enriched water with animals living just outside the chamber or in chambers with no added CO_2. This provides the means to assess how these deep-sea animals will fare in the ocean conditions of the future.

In 2011 scientist Jim Barry used the FOCE system to evaluate the effects of high CO_2 conditions on the behavior of the deep-sea urchin *Strongylocentrotus fragilis*. The ability of

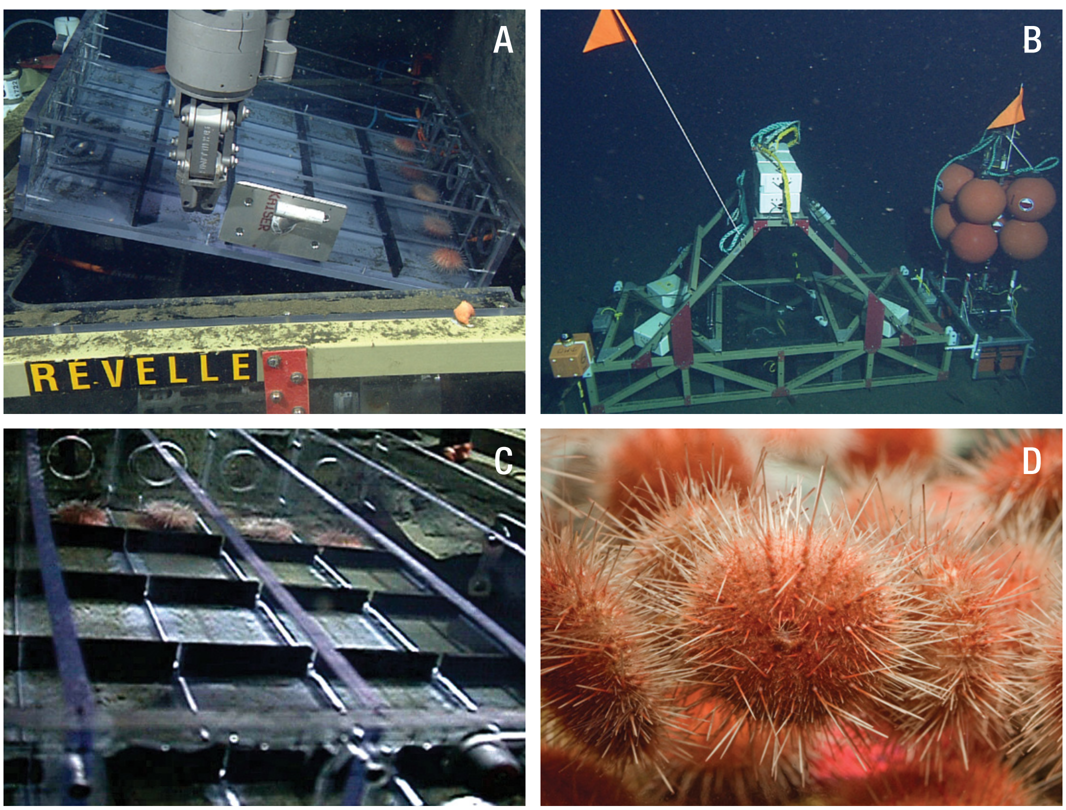


Figure 14: (A) The five-lane urchin "raceway" in which sea urchins were placed at one end and kelp at the other, (B) the FOCE frame and time-lapse camera control site, (C) in situ real-time camera view of urchin movements, and (D) sea urchins *Strongylocentrotus fragilis*.

animals to function in activities such as feeding, moving, escaping predators, or chasing prey is often critical to their growth and survival. Echinoderms are important components of benthic marine ecosystems occupying diverse roles as predators (sea stars), grazers (sea urchins), detritus feeders (sea cucumbers, brittle stars, sea urchins), and filter feeders (sea lilies, crinoids), and as prey for higher trophic levels. They also reshape and reprocess seafloor sediments. Echinoderms in general are thought to be highly sensitive to ocean acidification driven by increased atmospheric CO_2. Several reports on shallow habitats have noted the impacts of high CO_2 levels on sea urchins—from a reduction in the growth, survival, and calcification of larvae to reduced growth and higher mortality in adults. The FOCE test bed at MARS presented an ideal platform for Barry's long-term study of the sub-lethal effects that may become evident as changes in normal movement, posture, and feeding rates (Figure 14). Based on previous laboratory experiments, Barry had expected the urchins to cease normal activities. But

Figure 15: Diver George Matsumoto helps situate the shallow-water FOCE system for experiments off Hopkins Marine Station in 15 meters of water in a joint project with the Center for Ocean Solutions.

even after three weeks in the chamber at 900 meters deep, they were moving back and forth inside the FOCE system. Barry's team will analyze videos of urchins in both acidified and normal seawater and look for differences in their activity levels—how fast and how far they moved. This particular species of sea urchin may be relatively tolerant to somewhat acidic conditions, but will likely show somewhat less activity in acidified seawater than in normal seawater.

The FOCE system can serve the needs of researchers initiating studies of ocean acidification with limited resources and technical expertise. The concept is designed to allow an upgrade path so that, once the system is operational, researchers can add elements specific to their research needs. A number of experiments are planned or under way for in situ ocean acidification research at locations around the world. The MBARI team began the transfer of FOCE technology for use on coral reefs by collaborating with the University of Queensland, Brisbane, Australia. The team is now helping to design and demonstrate FOCE technology in France, England, and Antarctica. MBARI is also installing a shallow-water FOCE at Stanford University's Hopkins Marine Station in collaboration with the Center for Ocean Solutions (Figure 15). MBARI's development efforts and contributions toward understanding climate change and ocean acidification are transforming research and conservation on state, national, and international levels.

Free Ocean CO_2 Enrichment

Project leads: James Barry, Peter G. Brewer, William Kirkwood
Project manager: William Kirkwood
Project team: Kent Headley, Bob Herlien, Chad Kecy, George Matsumoto, Thom Maughan, Tom O'Reilly, Ed Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborators: Tony Fountain, Peter Shin, and Sameer Tilak, University of California, San Diego; Jean-Pierre Gattuso, Frederic Gazeau, and Paul Mahacek, Villefranche-Sur-Mer Oceanological Observatory, France; David Kline, University of Queensland, Australia; Vladimir Prodanov, California Polytechnic State University, San Luis Obispo; Donna Roberts, University of Tasmania, Australia; Stephen Widdecombe, Plymouth Marine Laboratory, England; Brock Woodson, Center for Ocean Solutions, Stanford University, California

The Ocean in a High CO_2 World

Project leads: James Barry, Peter G. Brewer, William Kirkwood
Project manager: Edward Peltzer

Expeditions

Expeditionary missions took MBARI research and development teams away from Monterey Bay in various directions in 2011. MBARI's research vessels *Western Flyer* and *Zephyr* carried the ROV *Doc Ricketts* and the mapping AUV, the *D. Allan B.*, north off Oregon, Washington, and Canada (Figure 16), whereas ships from other institutions provided research opportunities in Hawaiian waters and the Bahamas.

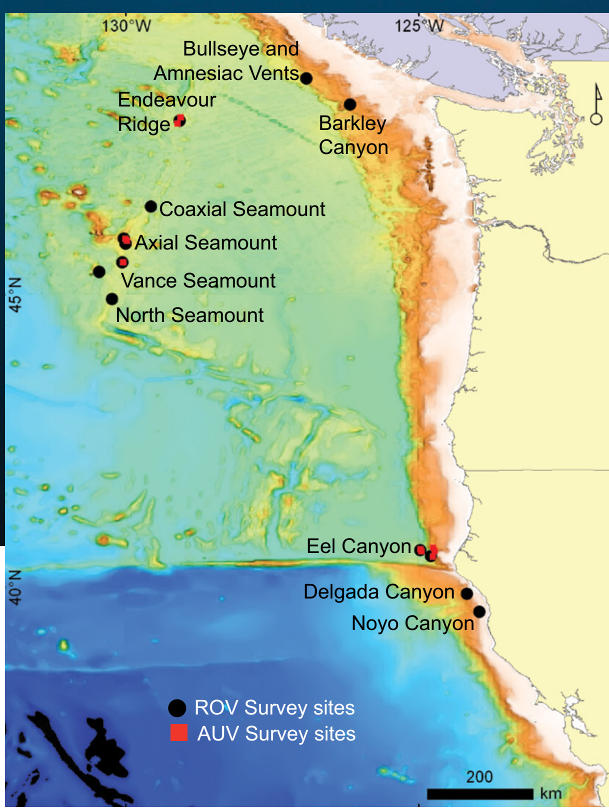


Figure 16: AUV survey and ROV dive sites during the 2011 Northern Expedition.

Seafloor mapping on the fly

MBARI's Submarine Volcanism Group, led by David Clague, discovered a recent volcanic eruption that changed the focus of their cruise during MBARI's Northern Expedition. First they noted turbid water during one of their early dives at Axial Seamount on the Juan de Fuca mid-ocean ridge. While seeking an extensive old lava flow to sample, they found the bathymetry did not conform to their map, which was made with AUV data collected as recently as 2009. The depression that had marked the old lava flow could not be found. Noting how the flow was covered with soupy reddish-brown hydrothermal deposits, the team discussed the diffuse hydrothermal activity surrounding the known nearby hydrothermal field.

Serendipitously, Clague then received an email from Bill Chadwick of Oregon State University, who was nearby aboard another research vessel, the *Atlantis*. Chadwick reported discovering that a volcanic eruption on Axial's southern caldera had occurred sometime during the previous year, as evidenced by the disappearance of several instruments he had left on the seafloor. At one site, his team observed that instruments they had deployed the previous summer were now frozen in lava. The MBARI researchers then realized that the turbid water, bathymetry that didn't match their map, and soupy hydrothermal deposits they had observed were almost surely related to the new eruption as well.

The Clague team adjusted their original plans to provide as much support as possible to the Oregon State researchers without interfering with the Oregon group's equipment or sampling program. The R/V *Zephyr* had just arrived at the Endeavour segment of the Juan de Fuca Ridge farther north and was about to start mapping with the AUV *D. Allan B.* Clague's team prepared for the AUV to come back to the Axial caldera to gather data for a new map.

Communications flew back and forth between Chadwick on the *Atlantis*, the science party on the *Western Flyer*, AUV group leader Hans Thomas on the *Zephyr*, and mapping software engineer Dave Caress back in California. A survey was quickly designed to cover the numerous sites where Chadwick and Clague had observed the new flow. Visual identification of this newest flow at Axial was challenging because the previous eruption in the same area occurred just 13 years earlier and both flows were still young and glassy. The AUV team ran a mapping survey at Axial and

Figure 17: The amount of data collected by the mapping AUV was so large, that the only practical way to transfer it was on a hard drive. Crew member Perry Shoemake carefully paddles from the R/V *Zephyr* to the R/V *Western Flyer* to deliver the data.

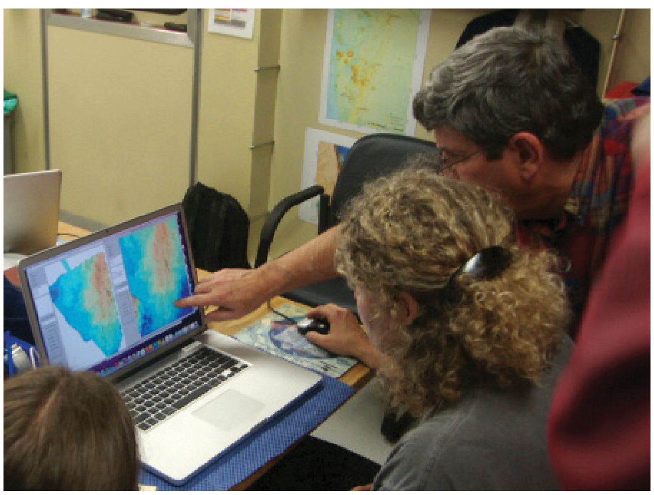


Figure 18: Jenny Paduan and David Clague comparing the new AUV survey data showing the 2011 lava flow to the pre-eruption map. Within a short time, a difference map that clearly defined the new flows was produced and an ROV dive and an additional AUV survey were being planned.

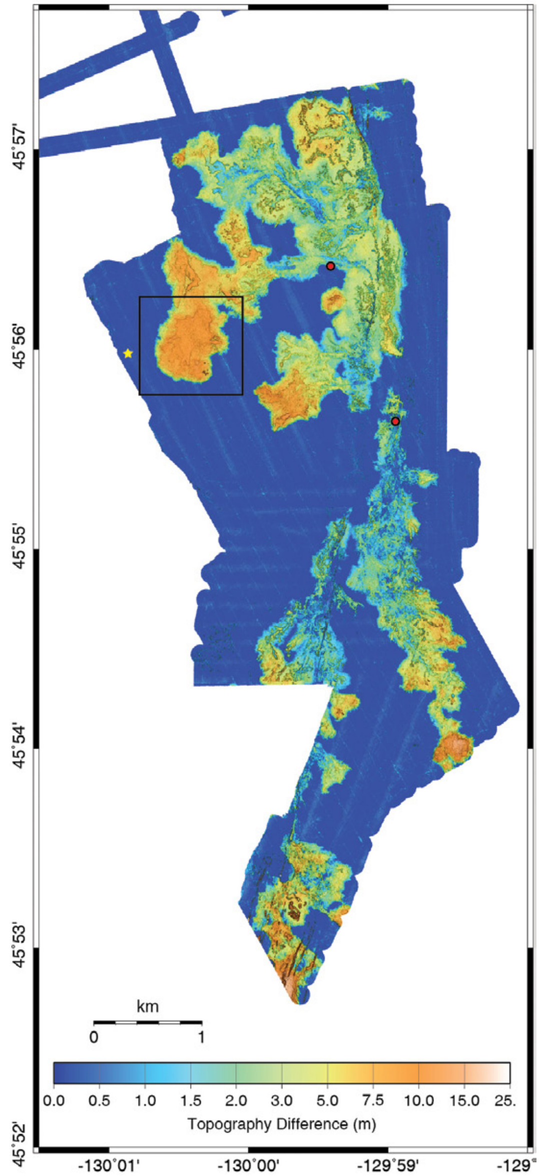


Figure 19: Difference map showing the 2011 lava flows near the summit at Axial Volcano. The two red dots are the locations of bottom photographs in Figures 21 (northern dot) and 22 (southern dot). The box shows the extent of the flow lobe nearest the Ashes hydrothermal vent field (yellow star).

transferred the data to the science team aboard the *Western Flyer* (Figure 17).

Clague's team made a map showing the changes from the previous maps (Figures 18, 19, and 20) and planned an ROV dive to sample and observe several of the new lava lobes, eruptive fissures, and flow channels. It was evident that the new survey did not cover the entire flow as some lobes exited the mapped area. A second AUV survey was needed.

Once again, emails flew back and forth, Caress set about creating an additional mapping mission, and the *Zephyr* team was advised that another plan would be sent while the AUV batteries recharged overnight. The AUV team prepared for the just-designed new mission to map the rest of the new flow and the ROV pilots readied the ROV for launch early the following morning.

Once the ROV was on the bottom, the team quickly found contacts between the new and old flows (Figure 21), and flew the ROV down a channel that fed the largest lobe that crossed the entire caldera and ended in a thick ponded flow near Ashes hydrothermal field. They explored several parts of the fissure system and found the flows close to the vents covered in thick, light-colored, fluffy bacterial deposits, which gave way to more colorful yellow and orange hydrothermal sediment farther from the vents. Along the central and northern fissures, they found low-temperature hydrothermal vents, lined with thick white bacterial mats and venting shimmering water. Some of these spewed white bacterial particles in keeping with their descriptive name "snowblower" vents (Figure 22). By the end of the ROV dive, 15 rock samples had been collected and the team had seen much of the area. The area mapped by the AUV showed 7.8 square kilometers and 27 million cubic meters of new lava with distal lobes about 17 meters thick. This 2011 eruption reused the same fissures and covered a significant portion of the 1998 flow, which would now be difficult to map had we not collected bathymetry data between the 1998 and 2011 eruptions.

Another research vessel, the *Thompson*, was soon to depart to plan cable routes for the National Science Foundation's (NSF) Ocean Observatory Initiative cable installation at Axial, so the maps were quickly revised to show the extent of the new flows and the locations of the new MBARI samples. Colleagues from the University of Washington used the maps and data to plan dives with their ROV. They also used the *Thompson's* ship-mounted multibeam sonar system to run a repeat mapping survey at lower resolution of the entire summit and south rift zone, and mapped a large ridge of pillow lava that had erupted since the MBARI ship-mounted multibeam survey in 1998. The data sharing and coordination among the three research groups led to a rapid assessment of the eruption and allowed for quick redesign of the cable routes for the NSF observatory.

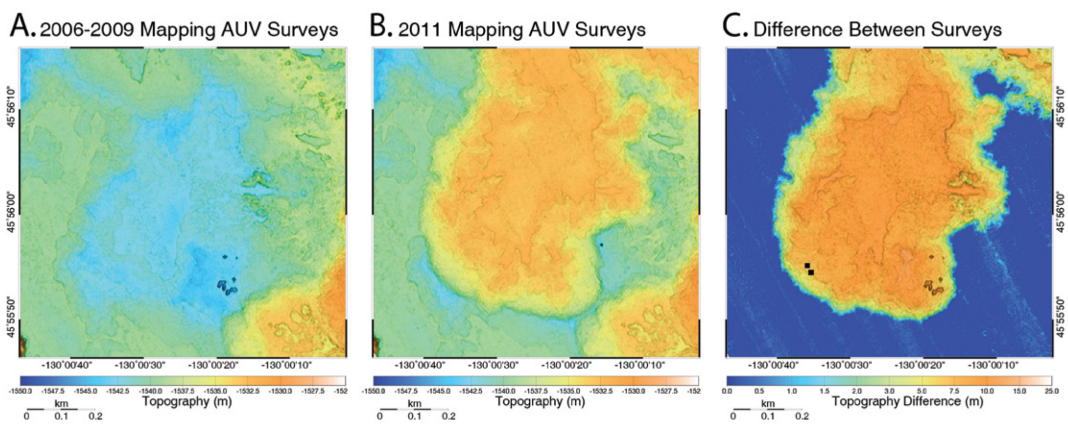


Figure 20: A) Pre-2011 eruption AUV map of area framed by box in Figure 19. B) Post-2011 eruption AUV map of the same area. C) Difference map showing the flow lobe reaches about 15-meter thickness. Black squares are the locations of two lava samples collected on an early dive.

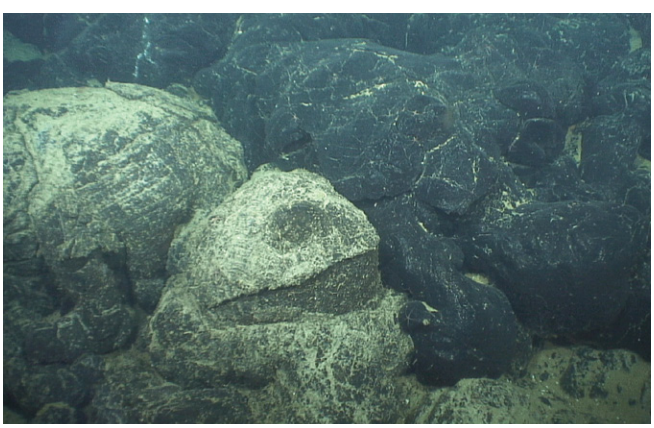


Figure 21: Frame grab from ROV *Doc Ricketts* video showing the contact of the 2011 lava flow on an older one.

Figure 22: Frame grab from ROV *Doc Ricketts* video showing new "snowblower" hydrothermal vents within the 2011 lava flows.

The repeat high-resolution AUV surveys revealed a wealth of information about where the eruptive fissures were located and how the lava was emplaced. The team was surprised to see the extent to which eruptive fissures from previous eruptions were used again, and the extent to which the 2011 flows mimic the underlying 1998—and even earlier—flows, including lava ponds near the vents, channels leading away from the vents, and even distal lobes.

The synergistic use of the AUV and ROV to map and sample the seafloor proved to be a powerful capability. The rapid response capitalized on the remarkable opportunity presented by the 2011 Axial eruption and demonstrated the flexibility called for in the institute's newly adopted strategic plan.

Massive scours hint at deep-flowing rivers

The combined capabilities of the mapping AUV deployed from the R/V *Zephyr* and the ROV *Doc Ricketts* on the R/V *Western Flyer* also proved valuable for investigating largely unexplored deepwater areas around Eel Canyon, offshore of Northern California. Charlie Paull and his team set out to learn about sediment transport and possible gas plumes emanating from the seafloor.

Paull was particularly interested in determining the impact of dense, freshwater river flows on submarine canyons and deep-sea fans. Some rivers can carry so much sediment during floods that floodwaters reaching the ocean are hyperpycnal (denser than the ocean water). Instead of spreading over the ocean's surface and readily mixing with seawater, hyperpycnal river water flows downslope along the seafloor. While hyperpycnal flows are believed to be one of the most

Collaborative Research: Data Synthesis for Examination of Magmatic, Tectonic, and Hydrothermal Activity at the Endeavour Segment

Project leads: David Caress, David Clague
Project manager: David Clague
Project team: Julie Martin, Jennifer Paduan
Collaborators: Brian Dreyer and James Gill, University of California, Santa Cruz; Deborah Kelley, University of Washington, Seattle

Fine-Scale Crustal Accretion Processes and Rates of Magma Supply and Replenishment at the Southern Juan de Fuca Ridge Neovolcanic Zone

Project lead/manager: David Clague
Project team: David Caress, Julie Martin, Jennifer Paduan
Collaborators: Julie Bowles, University of Minnesota, Twin Cities; William Chadwick, Oregon State University, Corvallis; Brian Dreyer and James Gill, University of California, Santa Cruz; Robert Embley, Pacific Marine Environmental Laboratory, Newport, Oregon; Kenneth Rubin, University of Hawaii, Manoa

Ocean Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Mike Burczynski, T. Craig Dawe, Rich Henthorn, Brett Hobson, Eric Martin, D.J. Osborne, Steve Rock, Bryan Schaefer, Mark Talkovic, Hans Thomas

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: David Caress, Julie Martin, Ryan Portner
Collaborators: Michael Bizimis, University of South Carolina, Columbia; Juan Carlos Bragam, University of Granada, Spain; Brian Cousens, Carleton University, Ottawa, Canada; Jacqueline Dixon, University of Miami, Florida; Robert Duncan and John Huard, Oregon State University, Corvallis; Fred Frey and Guangping Xu, Massachusetts Institute of Technology, Cambridge; Paul Fullagar, University of North Carolina, Chapel Hill; Jim Hein, Rozalind Helz, James Moore, Stephanie Ross, and David Sherrod, U.S. Geological Survey, Menlo Park, California; Christoph Helo, Ludwig Maximillians Univseritat, Munich, Germany; Tessa Hill, Jim McClain, Peter Schiffman, and Rob Zierenberg, University of California, Davis; David Hilton and Jerry Winterer, Scripps Institution of Oceanography, La Jolla, California; Shichun Huang, Harvard University, Cambridge, Massachusetts; Kathie Marsaglia, California State University, Northridge; Craig McClain, University of North Carolina, Durham; Michael Perfit, Florida State University, Tallahassee; Don Potts and Christina Ravelo, University of California, Santa Cruz; Willem Renema, Leiden University, the Netherlands; John Smith, University of Hawaii, Honolulu; John Stix, McGill University, Montreal, Canada; Jody Webster, University of Sydney, Australia.

important processes responsible for moving sediment over the surface of the Earth, from land to sea, the fate of the suspended sediment in the hyperpycnal water carried into the deep sea is poorly understood. One possibility is that hyperpycnal water descends into submarine canyons and cascades into the deep sea, perhaps forming very energetic turbidity flows that pick up and carry large amounts of sediment across the entire continental margin. The Eel River is especially apt to generate hyperpycnal flows during major floods as it drains an area of steep mountainous terrain and has no large areas of low relief in its basin to temporarily store river sediment. Furthermore, this sediment load can easily make its way into the deep sea since the head of Eel Canyon is very close to the shoreline and the mouth of the Eel River. Thus, the team's objectives were to identify distinctive seafloor morphologies and sedimentary deposits that would reveal evidence of energetic flow events and their frequency, and to document their offshore extent.

To map the seafloor the AUV was programmed to fly missions approximately 50 meters above the bottom. Thus, the surveys of the seafloor morphology within the axial channel of Eel Canyon required the vehicle to dive through the narrow sinuous channel in water depths ranging from 1,400 to 1,700 meters. The surveys show the existence along the axial channel of a repetitive sequence of large depressions spaced about one kilometer apart, with dimensions up to 30 meters deep, 600 meters long, and 500 meters wide (Figure 23 inset A). These kinds of conspicuous features have not been observed within the axes of Monterey Canyon nor in the axes of submarine canyons off Southern California. Subsequent ROV observations confirmed that these are erosional scours, cut into the canyon floor. While the scours on the floor of Eel Canyon are large, similarly shaped but much larger features occur on the fan below.

Indeed, previous lower-resolution bathymetry collected from a ship suggested the presence of at least eight giant elongated asymmetric depressions in the Eel deep-sea sediment fan at a depth of more than 2,500 meters. The higher-resolution AUV surveys conducted over two of these features (Figure 23, inset B) reveal that the distinctive arc-

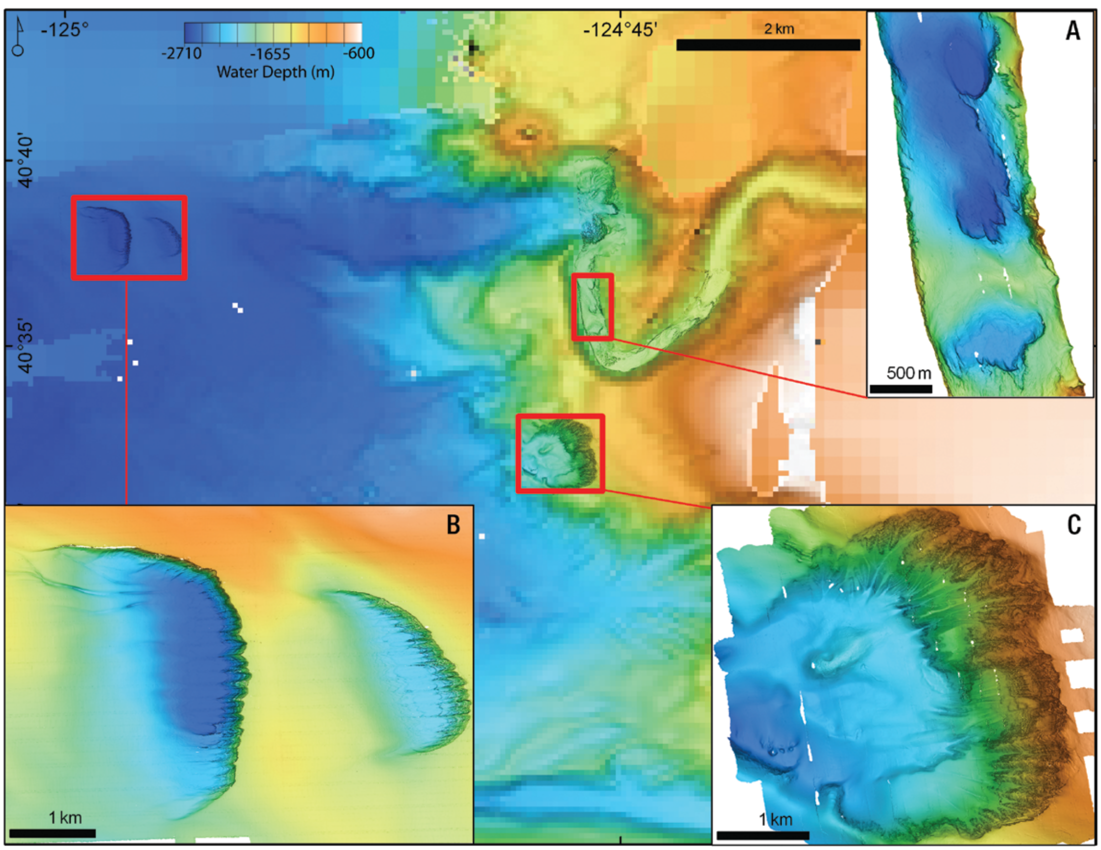


Figure 23: Map showing bathymetry of lower Eel Canyon and outlining areas where AUV surveys were conducted. Inset maps show A) floor of canyon, B) scours on the Eel Fan, and C) oil-and-gas venting mound within a large depression on the seafloor.

Figure 24: Sharp edge of one of the ridges that runs down the face of the arcuate erosional scarps in the Eel Fan. Also shown are the horizontal beds, consisting of repetitions of thin turbidites.

Figure 25: Oil droplets seeping out of the seafloor at 1,850 meters water depth.

shaped scarps that form the eastern (upstream) edge of both depressions display a surprising sawtooth pattern on their faces. Subsequent ROV observations documented that these ridges have very sharp edges (Figure 24). ROV video also showed that the 90-meter-thick, layered section exposed on the face of one scarp is composed of repetitions of one- to 10-centimeter-thick sections of sand deposited by turbidity flows separated by thin sections of more slowly deposited sediments.

Collectively, these observations suggest that the depressions are massive scours that have experienced erosion on their upstream side. These scours appear to be one of the most massive examples documented to date of hydrodynamic features known as cyclic steps. Large energetic marine flows, presumably focused by the Eel Canyon, traveled over the surface of the fan, resulting in alternating deposition and erosional features. Whether the train of scours present on the fan is the composite of numerous events, or was generated in a few enormous events remains an open question. Intriguingly, one interpretation of the exposed stratigraphic section is that each turbidite deposit is associated with a flooding event in the Eel River that resulted in hyperpycnal flows and subsequent turbidity currents extending out to the fan. Alternatively, turbidite sedimentary deposits could also have resulted from failures associated with strong earthquakes. Tests to date these sediments promise to provide a unique constraint on the recurrence frequency of these turbidites and this in turn should shed light on the identity of the triggers for these deposits: major storms and floods or earthquakes?

This leg of the Northern Expedition also gave Paull and his group a chance to map and investigate the source of plumes of gas and oil emanating from the seafloor in Eel Canyon. Plumes that rise as much as 1,400 meters from the seafloor were previously discovered. The larger of two plumes mapped by the MBARI AUV (Figure 23 inset C) appears to emanate from a distinctive topographic mound that is about 650 meters long, 350 meters wide, and stands nearly 60 meters higher than the surrounding seafloor at 1,850 meters depth. Subsequent ROV observations showed droplets of liquid oil as well as intermittent streams of gas bubbles coming from the seafloor on top of this mound (Figure 25). This is the largest and deepest natural hydrocarbon-venting site known on the North Pacific margin. In this case the seepage is naturally occurring and has not been induced by human activities.

The surface of the large mound is characterized by distinctive rounded knolls (Figure 23 inset C). Similar seafloor

Continental Margin and Submarine Canyon Processes

Project lead: Charles Paull
Project manager: Roberto Gwiazda
Project team: Krystle Anderson, David Caress, Eve Lundsten, Hans Thomas
Collaborators: Clarke Alexander, Skidaway Institute of Oceanography, Savannah, Georgia; Phil Barnes, National Institute of Water and Atmospheric Research, Auckland, New Zealand; Jamie Conrad, Brian Edwards, and Mary McGann, U.S. Geological Survey, Menlo Park, California; Scott Dallimore and Michael Riedel, Natural Resources Canada, Sidney; Saulwood Lin and Char-Shine Liu, National Taiwan University; Thomas Stevens, Royal Holloway, Surrey, United Kingdom; Peter Talling, National Oceanographic Centre, Southampton, United Kingdom

textures have been observed in other AUV and ROV surveys of Hydrate Ridge (off Oregon), Bullseye Vent (off Canada), and the Santa Monica Mound (off Southern California)—methane-derived, carbonate-bearing sites that overlie seafloor gas hydrate deposits. Paull hypothesized that at least the surface of this Eel Canyon mound has been produced by both carbonate precipitation and methane venting. The processes that give rise to this distinctive topography, as well as the mechanisms by which hydrocarbons are able to flow through the seafloor within the gas hydrate stability zone, are the subjects of ongoing study. The information derived from AUV surveys and ROV observations proved to be essential components of this investigation and neither of the cruise objectives could have been addressed effectively without the combined use of these state-of-the-art exploration tools.

Natural laboratory offers insights on ocean chemistry dynamics

Gas hydrate outcrops in Barkley Canyon off the coast of Vancouver Island, Canada, and nearby gas vents provided a natural laboratory for chemist Peter Brewer and his team to study the dynamics of gas and oil rising from the seafloor. The hydrates—created when cold and pressure in the deep sea force the formation of a cage-like ice structure around methane and other gases—could have a significant impact on global climate if they are disturbed and the trapped gases are released and escape to the atmosphere. Brewer has been perfecting techniques to measure and observe these hydrates as well as other gases and oil emanating from the seafloor in their natural environment.

Although the team had visited the Barkley Canyon site before, this trip saw the first expeditionary use of the Raman pore-water insertion probe with a tripod stand, a new tool to improve measurement accuracy. The probe is part of the spectroscopy system that shoots a laser beam at a tiny sample of water; the signal that bounces back provides information about the chemicals found in the water. On previous expeditions, the ROV pilots had inserted the pore-water probe manually using the ROV manipulator arm. This required very delicate placement of the probe tip and a very slow and tedious insertion of the probe taking care to keep the insertion absolutely straight. Any wavering of the ROV arm during this step would create an oval hole allowing ambient seawater to channel down along the length of the probe into the sediments and alter the pore-water chemistry. While the pilots were often successful at this,

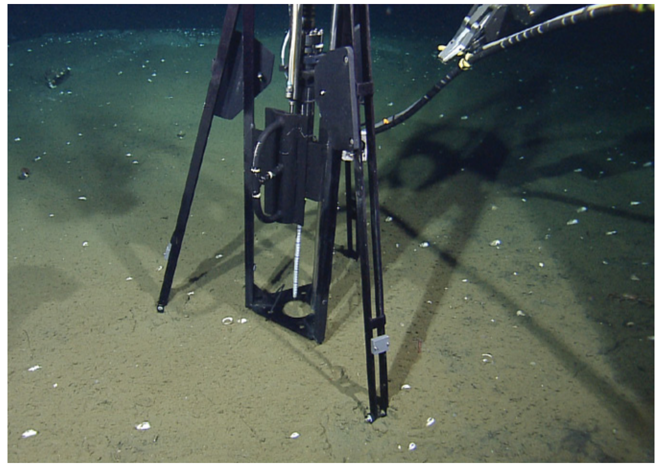


Figure 26: The pore-water-probe insertion tripod is placed on the seafloor for the first time at Barkley Canyon. The pore-water probe is inserted slowly into the sediment by actuation of a linear ram on the tripod. This simple hydraulic function allows for a perfectly straight insertion into the sediment without making herculean demands upon the ROV pilots to do so using the robotic arm. Sampling of the pore waters can then be done every five centimeters into the sediment.

there were moments when the ROV was either tugged by the tether or moved by bottom currents ruining the insertion and causing great frustration for the pilots and the science team.

This time a new tripod, built by MBARI's Machine Shop staff, was used to control the insertion of the laser Raman spectrometer pore-water probe (Figure 26). Separating the insertion tripod from the ROV eliminated the earlier issues, and a near-perfect rate of successful insertions was achieved. Additionally, the insertion depths were more precisely controlled with the tripod's hydraulic actuator driving the Raman pore-water tip into the seafloor. The probe was inserted into the upper 35 centimeters of sediment, pushing it deeper step-wise at five-centimeter intervals to obtain a profile of the pore-water concentrations of methane, sulfate, and dissolved hydrogen sulfide. Bacteria in the sediment pore-water quickly consume what little oxygen there is and then resort to reducing the pore-water sulfate to hydrogen sulfide in order to use the abundant organic matter as an energy source. With the laser Raman spectrometer, the disappearance of sulfate can be clearly seen in the profiles, as well as the simultaneous increase of the hydrogen sulfide and methane bands (Figure 27).

Of equal interest is the question of the stability of hydrate mounds and what happens to them over time. It has been widely speculated that if the methane gas locked inside

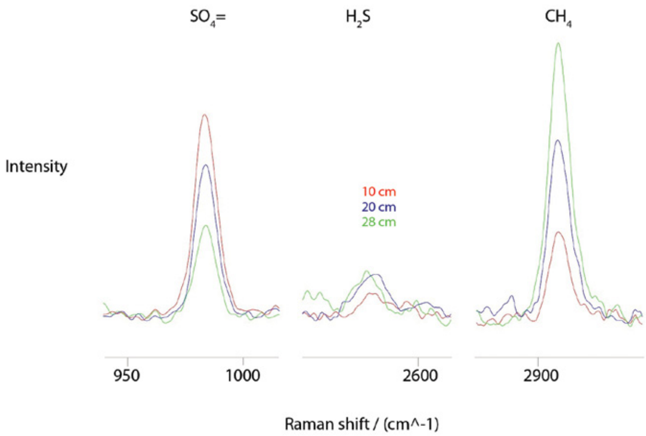


Figure 27: Pore-water profiles of sulfate ($SO_4=$), hydrogen sulfide (H_2S) and methane (CH_4) as measured in situ by the laser Raman spectrometer pore-water probe in a small pit with bacterial mat.

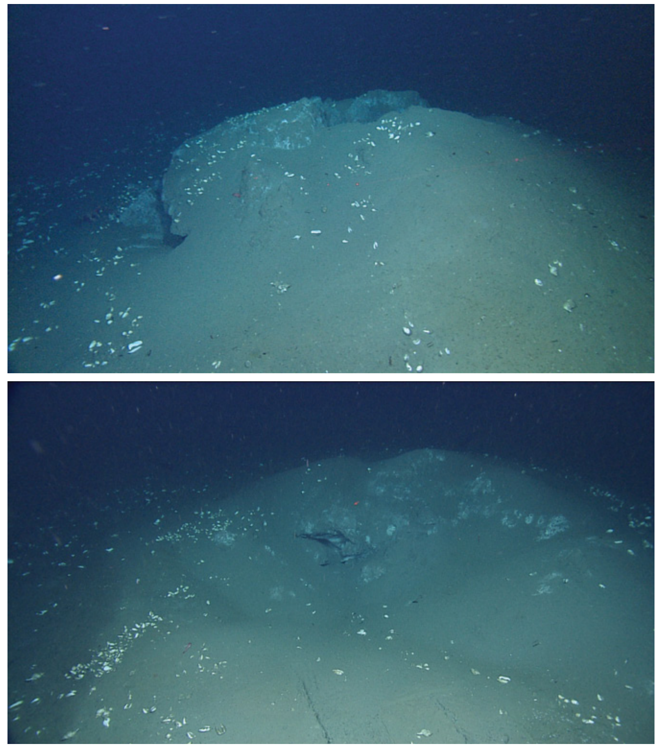


Figure 28: This mound created by the formation of solid hydrates under a layer of sediment changed dramatically in just a few years. In 2009 (top) it was dome-shaped with an obvious overhang on the left. When revisited in 2011 (bottom) the dome and the overhang had disappeared.

the hydrate phase were released from its frozen ice cage, and it could migrate through the sediment and seawater to reach the atmosphere, it would, as a greenhouse gas, contribute to global warming. Explosive release of methane could have an immediate and potentially dangerous local effect. One of the advantages of returning to the same site several years later is the ability to detect slow changes. Comparing images from 2006 and 2009 with what the team saw in 2011 confirmed that changes in the hydrate mounds had occurred (Figure 28). However, the pore-water profiles obtained showed that most of the methane remained within the sediments where it was oxidized by bacteria.

Whereas the Barkley Canyon site provided massive gas hydrate deposits to sample and explore, the Bullseye and Amnesiac Gas Vents visited during the expedition provided a much different geologic setting. At both locations, some sites were actively venting gas from the seafloor and others that were formerly active had gone dormant. Collection of pore-water profiles from both types of sites provided insight into the impact of active gas venting on sediment pore-water chemistry and what happens to the pore-water chemistry once the venting stops. The pore-water insertion probe tripod allowed for well-controlled and evenly spaced samples in the profiles, and its ease of use allowed for the collection of many more profiles than could have been obtained if the insertions had to be done exclusively with the ROV manipulator.

In addition to the MBARI science projects, two pore-water OsmoSamplers were deployed (Figure 29) for collaborator Laura Lapham, a former MBARI summer intern who is now an assistant professor at the University of Maryland's Center for Environmental Science. Lapham will use the samples collected by these instruments to make long-term observations of the pore-water concentrations of methane and sulfate at several discrete depths to provide insight into potential migration of the gases and how the chemistry changes over time.

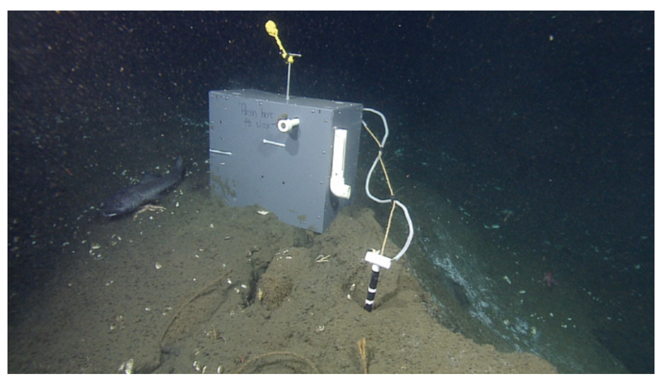


Figure 29: An OsmoSampler was placed on this mound to make long-term observations of the pore-water concentrations of methane and sulfate at several discrete depths.

At the active gas venting sites, gas and oil samples were collected for collaborator Michael Riedel who participated in the cruise as an official observer for the Canadian government while the ship was working in Canadian waters. Laboratory analysis of these samples will provide evidence on the sources of the gases and their formation processes. Brewer's group also ran experiments on some of the oil samples, finding surprising little out-gassing from the oil, suggesting that a process occurring in the sediments separates the oil from the gas. These results were markedly different from an experiment conducted earlier in the year in Monterey Bay with synthetic oil and gas mixtures using the naturally occurring light oil emanating from the sediments surrounding the gas hydrate outcrops.

While the Brewer group was at sea, they were also able to help a friend in need. Canadian colleagues contacted Riedel when an instrument on their NEPTUNE seafloor network of cabled observatories suffered a pressure-case leak. The flooded instrument was drawing down the power to all the other instruments on the node requiring that it be shut down. Since the MBARI ROV was "in the neighborhood" the Canadian team requested assistance. MBARI's ROV pilots were eager to help. So, while "flying-by" one day, they disconnected the flooded instrument (Figure 30). NEPTUNE Canada was happy to report that once that instrument was removed from the node, power was restored and all other instruments were then working normally.

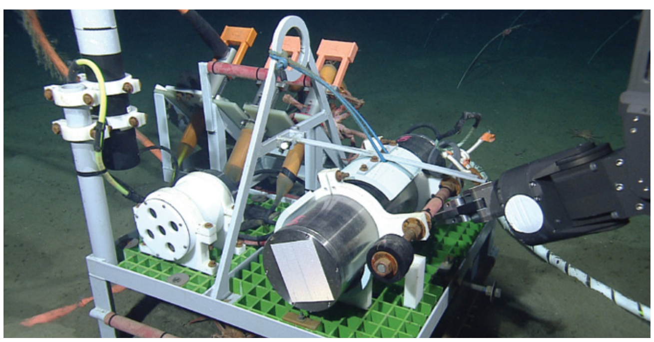


Figure 30: The instrument platform for the NEPTUNE Canada seafloor observatory seismometer. In the foreground is the robotic arm from the remotely operated vehicle *Doc Ricketts*, which disconnected an instrument at the request of the Canadians. Look closely and you may notice a hockey puck or two used on the platform.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter G. Brewer, William Kirkwood
Project manager: Edward Peltzer
Project team: Andreas Hofmann, Peter Walz
Collaborators: Laura Lapham, University of Maryland, Solomons; Ira Leifer, University of California, Santa Barbara; and Michael Riedel, Natural Resources Canada, Sidney

Probing the depths for signs of microbial life

Hydrothermal vents teeming with microbial life in the deep waters off the Pacific Northwest were a perfect testing ground for the Deep Environmental Sample Processor (D-ESP). This instrument, built by MBARI under the direction of Chris Scholin and Jim Birch, uses DNA probe technology and chemical sensors to detect microorganisms and the substances on which they thrive. In essence it is a self-contained, robotic laboratory that can acquire "raw seawater" samples and autonomously process the samples. Further refinement of this instrument was sponsored primarily by NASA's Astrobiology Program in concert with collaborators at Harvard University and the California Institute of Technology as part of efforts to develop tools and techniques that may someday aid in the search for life on other planets. Sites like these hydrothermal vents might be found on other worlds—places that may harbor extraterrestrial microbes similar to those on Earth. For that reason, deployment of the D-ESP at the site known as Ashes has long been a major goal of this project (Figure 33).

At depths greater than 1,600 meters below the sea surface, life around the Ashes vent field is dominated by tube worms and microbes that thrive on chemicals found in the hot, nutrient-rich water emanating from cracks and vents in the seafloor. The microbial communities in these environments are very diverse; some species are concentrated in the warm waters exiting the seafloor and other species are found primarily in cold waters more typical of the deep ocean. The researchers' primary objective was to determine if the D-ESP could detect these different microbes in concert with chemical and physical measurements that give a sense of the origin of the fluids.

The weather in this area, about 300 miles off the coast of Oregon, has historically been rough enough to impede work at sea. Thus, much of the preparation for this mission focused on engineering modifications to enhance the autonomous capabilities of the D-ESP since it was likely that the instrument would have to run for extended periods absent any human intervention. The instrument package needed

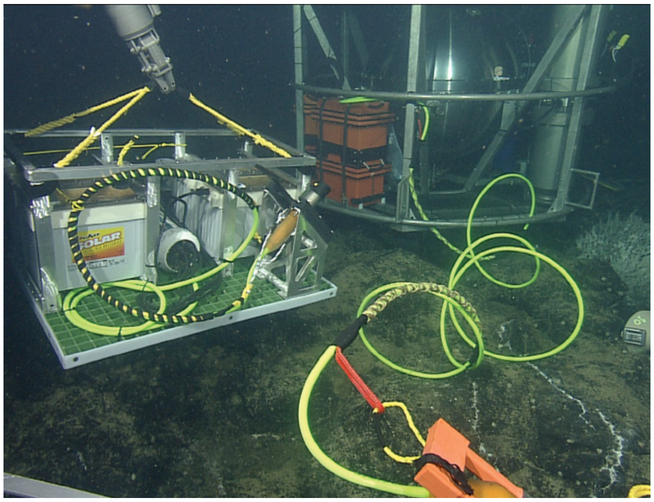


Figure 31: The Deep Environmental Sample Processor (the silver sphere) sits on an elevator that can lift it back to the sea surface. The battery pack at left was changed out every two days to assure continued power.

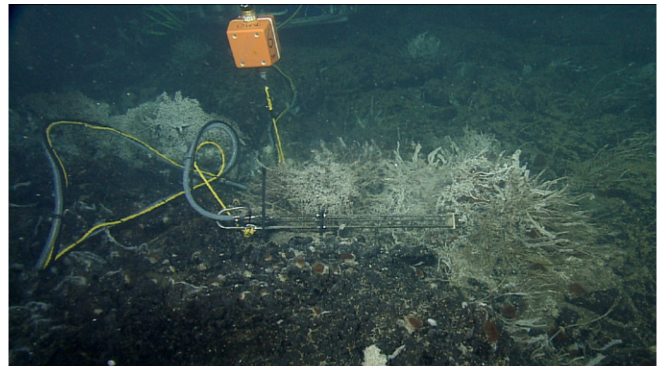


Figure 32: The sample wand with its tip positioned in a crack where warm water was coming out of the seafloor.

sufficient power to operate for at least two days at a time, to be retrievable from the seafloor without the ROV, to sample different sources of fluids without moving the device, and to ensure that power loss during the mission would not require recovery onto the ship before resuming operations.

Powering the D-ESP for extended periods in deep waters is always a challenge, particularly with the addition of an in situ mass spectrometer (ISMS) designed by collaborators at Harvard. The ISMS detects inorganic chemicals that fuel microbial growth and serve as tracers for vent fluids. It is key to providing an environmental context through which analysis of the microbial communities must be viewed, but it is also a power-hungry device. The D-ESP can only operate safely for 24 hours when it is running the ISMS, yet the experimental plan required multiple days of continuous operations. The D-ESP's batteries can be charged with an ROV, but that would require daily dives—a risky assumption in that environment. For this reason, the team's electrical engineer designed an external battery pack that could provide an extra 24 hours of power (Figure 31). After the D-ESP was deployed, the ROV *Doc Ricketts* carried the additional battery pack down and plugged it into the instrument. Each day thereafter, the external battery pack was swapped with a freshly charged one so that the D-ESP always had sufficient power for at least two days of uninterrupted operations. Should the need to recover the instrument arise without an ROV present, an acoustic modem would allow commands from the ship to release a weight so the instrument package could float to the surface. However, the external battery pack would hamper this ascent, so the team's mechanical engineer designed a harness system that would allow the rising D-ESP to pull free from the battery sled, leaving it for later retrieval from the seafloor. Luckily, this feature was never needed.

Even with these efforts to assure two days of uninterrupted power, there was always the chance that the ROV could not be launched for several days. If the D-ESP was in the process of analyzing a sample and ran low on power, the machine might stop in an unsafe state, and be unable to restart without recovery and disassembly. To prevent this, the group's software engineer wrote code that monitored battery voltage so that if it fell below a predefined threshold, the D-ESP would begin shut-down procedures that would allow an orderly start once a fresh battery pack was delivered. Again, luckily, this feature was never needed on this expedition.

Another requirement was the need to collect water samples from specific locations, particularly fluids within the hydrothermal vent itself and "background" seawater away from the vent. To accomplish this without having to physically move the D-ESP, the engineering team developed a sample wand with multiple intake ports (Figure 32). The wand could be extended up to 10 meters away from the D-ESP and be placed in the venting fluids; the tubing between the vent and the instrument acted like a heat exchanger to cool fluids prior to their entry into the instrument's water analysis system. The wand also had alternative sample inlets that allowed for collection of fluids from "background" waters other than those coming directly out of the vent. The wand tip was equipped with a temperature sensor to discern when it was placed directly in a vent stream. If the temperature of the source fluids were too hot, the pumping

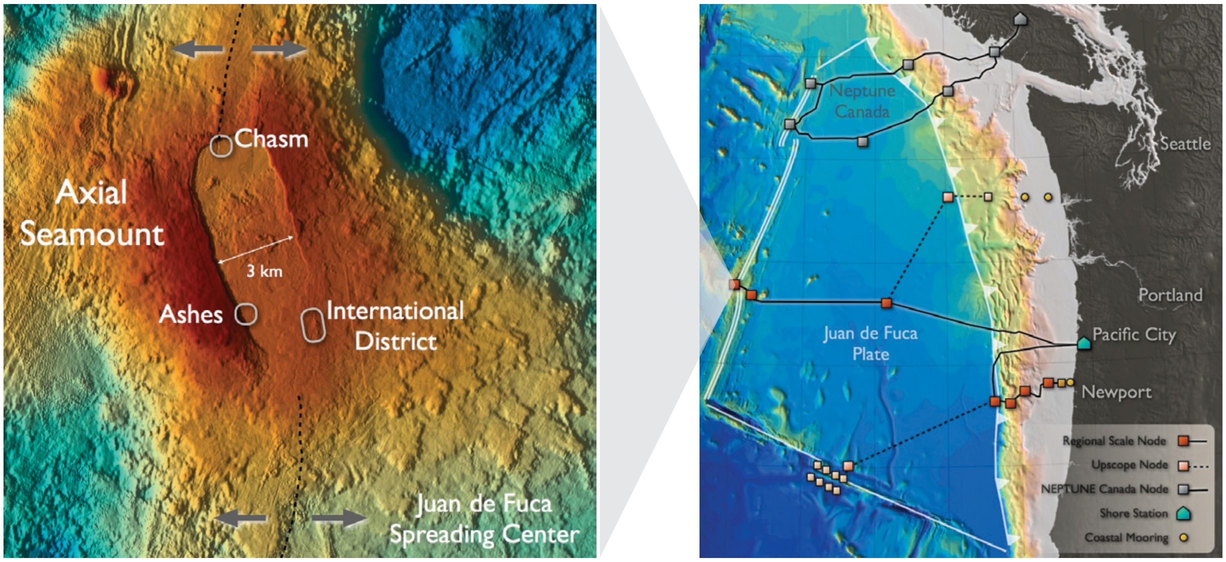


Figure 33: Site map showing location of the Ashes vent field—where the D-ESP was deployed—within the context of NSF's planned Ocean Observatories Initiative regional scale node cabled observatory (courtesy of J. Delaney).

system would be disabled to prevent inadvertent intake of fluids that could damage the instrument. Once more, the fail-safe system was not required on this expedition.

With all these features in place, the D-ESP was readied for its most challenging mission to date. The ISMS and other chemical and physical sensors showed extreme sensitivity to frequent alterations in fluid chemistry, and clearly revealed large shifts when fluids were collected from the D-ESP itself, the vent, and then about one meter above the vent. The instrument's DNA probe analyses also reflected shifts in microbial community structure consistent with the changes in source waters. For the first time ever, real-time remote application of DNA probe technology at active hydrothermal vents in the deep sea was proven feasible. The success of this mission paves the way for much longer duration deployments of the D-ESP at Axial Seamount and other locations, particularly with the advent of the NSF's Ocean Observatories Initiative and the installation of the cabled observatory at Axial (Figure 33). In preparation for operations on that cable network expected to begin in 2015, the D-ESP will be deployed on the MARS cable node in Monterey Bay for a six-month trial in 2013.

SURF Center (Sensors: Underwater Research of the Future)

Project leads: James Birch, Chris Scholin

Project manager: James Birch

Project team: Kevin Gomes, Julio Harvey, Scott Jensen, Roman Marin III, Gene Massion, Doug Pargett, Mike Parker, Christina Preston, Brent Roman, John Ryan, Brian Schlining, Rich Schramm, William Ussler

Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Alexandra Boehm and Kevan Yamahara, Center for Ocean Solutions, Stanford University, California; Laurie Connell, University of Maine, Orono; Edward DeLong and Elizabeth Ottesen, Massachusetts Institute of Technology, Cambridge: Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Clement Furlong and Scott Soelberg, University of Washington, Seattle; Peter Girguis, Harvard University, Cambridge; Kelly Goodwin, Southwest Fisheries Science Center, La Jolla, California; Raphael Kudela, Julie Robidart, and Jonathan Zehr, University of California, Santa Cruz; Deirdre Meldrum and Cody Youngbull, Arizona State University, Phoenix; Mary Ann Moran and Vanessa Varaljay, University of George, Athens; Victoria Orphan, California Institute of Technology, Pasadena; Mark Strom, Northwest Fisheries Science Center, Seattle, Washington; Stephen Weisberg, Southern California Coastal Water Research Project, Costa Mesa, California; Robert Vrijenhoek and the CANON team, MBARI

A new view of microbial life near the sea surface

A collaborative expedition to the waters near Hawaii offered another opportunity to test the Environmental Sample Processor (ESP) technology, this time with the version of the instrument that operates near the sea surface. In the sun-illuminated upper portion of the ocean, microscopic plankton integrate nutrients, water, and light into living matter through photosynthesis. This process is essential to the support of life on earth, and to global biogeochemical cycling—through which continuous transformations of chemical compounds cause the elemental building blocks of life to flow.

The functioning of photosynthesis and all that stems from it varies greatly according to the nature of the oceanic environment, especially with regard to the availability of nutrients. Vast areas of the sunlit subtropical ocean contain very low concentrations of nutrients. Evolving within these impoverished environments, microscopic life has adapted, including the ability to transform nitrogen gas from the atmosphere at the sea surface into forms of nitrogen that can be used in photosynthesis. This process, called nitrogen fixation, supports most of the photosynthetic primary production in the surface waters of the open ocean. While nitrogen fixation is known to be of great importance, its complex workings within diverse microbial communities remain a mysterious realm of research, one in which technological innovations are essential for the advancement of scientific understanding.

As part of the Center for Microbial Oceanography: Research and Education (C-MORE)—an NSF-sponsored Science and Technology Center—the University of Hawaii coordinated research activities for a 2011 Hawaiian cruise including several participants: MBARI; Massachusetts Institute of Technology; Woods Hole Oceanographic Institution; University of California, Santa Cruz; Stony Brook University; and Oregon State University. MBARI contributed scientific expertise and the unique technology of the ESP to monitor the abundance and activities of microscopic life-forms, thereby providing a window into the world of biogeochemical cycling. As part of the expedition on the R/V *Kilo Moana* to the subtropical ocean north of Hawaii, an ESP was set out in the ocean to drift freely with the wind and currents for a study of the microbial processes driving the transformation and utilization of nitrogen (Figure 34).

Viewed from space, ocean surface topography revealed that the path followed by the drifting ESP was greatly influenced by eddies (vortices of water circulation). These are evident as circular regions of elevated sea level (numbered 1 and 2 in Figure 35a). During the first six days it was deployed, the ESP was transported northeastward along the western side of a clockwise-spinning eddy (Figure 35a). In the few days before recovery, the ESP changed direction toward the southeastern side of another clockwise-spinning eddy, which was north of the first eddy and interacting with it (Figure 35b).

ESP environmental and molecular data revealed how the two eddies differed physically and biologically. At the depth of the drifting ESP (approximately 25 meters below the sea surface) the more northern eddy was warmer, saltier, and lower in chlorophyll (a proxy for photosynthetic organisms) (Figure 36). While nitrogen fixation within the first eddy was dominated by the cyanobacterium *Crocosphaera*, which was more active at night, nitrogen fixation within the second eddy was dominated by a different cyanobacte-

Figure 34: MBARI's Gene Massion, left, and Roman Marin III, and collaborator Julie Robidart, work on the Environmental Sample Processor on the deck of the R/V *Kilo Moana*.

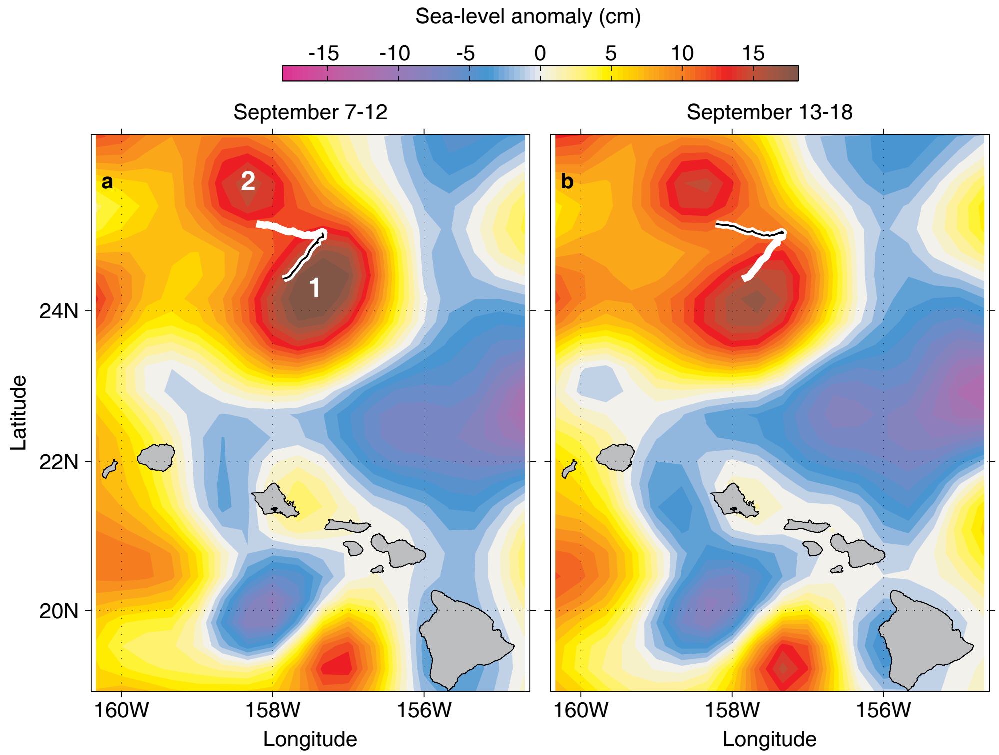


Figure 35: Ocean surface topography maps derived from satellite radar altimetry during the drifting ESP experiment. The sea-level anomaly is computed relative to the spatially-dependent long-term mean. Eddies that influenced the transport path of the ESP are numbered 1 and 2. The drift track from the entire experiment is shown in white in both maps; the portion of the drift track corresponding with each period of altimetry measurements is highlighted in black.

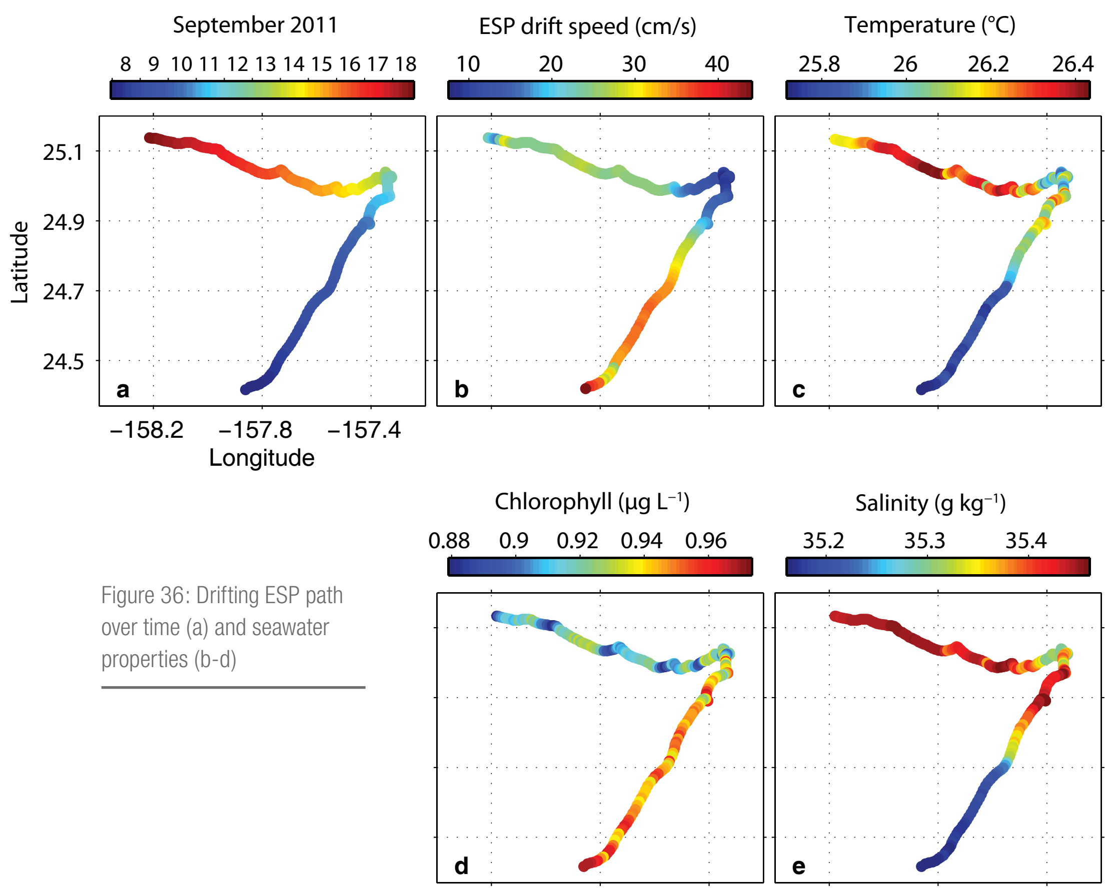


Figure 36: Drifting ESP path over time (a) and seawater properties (b-d)

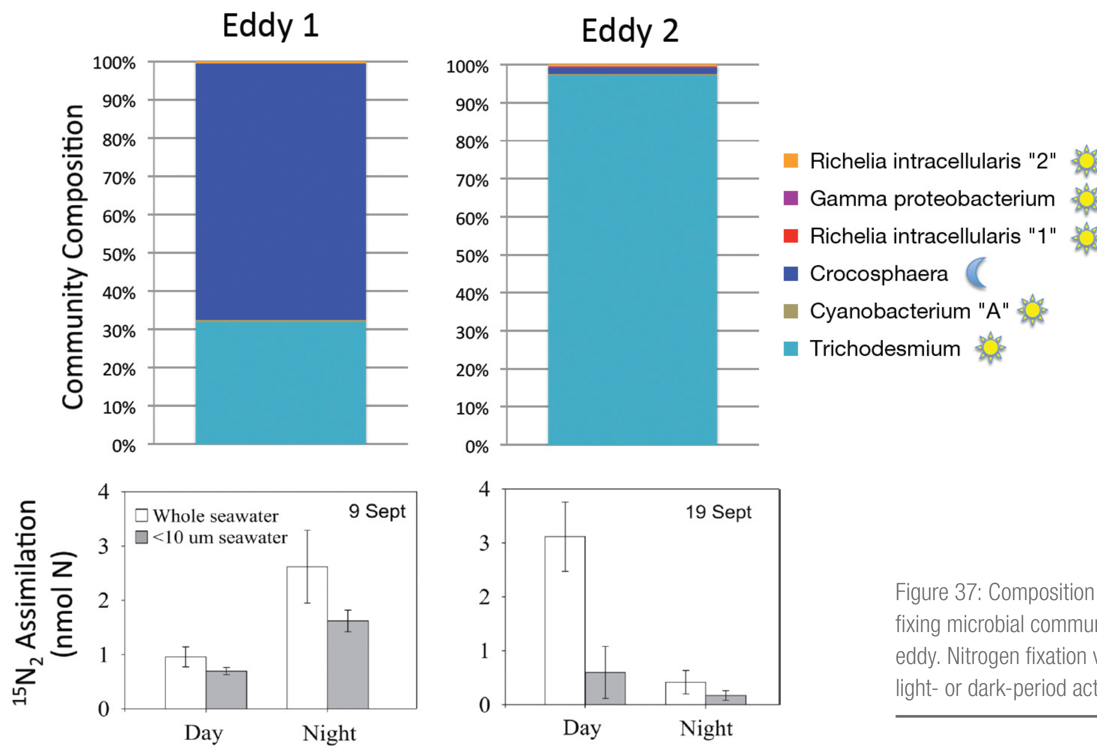


Figure 37: Composition and activity of the nitrogen-fixing microbial community at locations within each eddy. Nitrogen fixation values represent totals for full light- or dark-period activity.

rium, *Trichodesmium*, which was more active during the day (Figure 37). Beyond these striking differences between the neighboring eddies, variations in the microbial community were observed within the eddies over scales of hours and kilometers. Such small-scale variations in the composition and activity of the nitrogen-fixation microbial community had never been observed before.

Oceanic microbial community structure and function are generally referenced against environmental conditions that are assessed at the time samples are collected. However, the biological community collected at any one time is derived from past as well as present conditions. Consequently, it is difficult to establish detailed cause and effect relationships since the history of the community or population in question is generally not known. The intention of the drifting ESP experiment was to observe microscopic life in its natural frame of reference, which is moving with the ocean currents, thereby permitting resolution of time-dependent evolution of a microbial population. However, truly moving with the ocean currents is easier said than done. Surface ocean currents, which push the drifting ESP's float, may differ significantly from currents at the depth of the instrument itself. Further, winds can push on the float, causing its path to diverge from the direction of the ocean currents.

Measuring the ocean currents between the ESP and the surface during this experiment, the team evaluated how effectively the ESP moved with the ocean currents. If the ESP had moved perfectly within a laminar flow, measured ocean currents above it would be zero. However, the measurements showed that waters flowed past the ESP at speeds up to about 15 centimeters per second, and they were stronger within the second eddy by a factor of two. This experiment thus provided motivation for further technological innovation—to truly go with the flow. A long-term goal is to translate this experimental system into one that is capable of actively identifying, tracking, and sampling coherent microbial populations so that changes in their commu-

Environmental Sample Processor and the Center for Microbial Oceanography: Research and Education (C-MORE) Hawaii Expedition

Project lead: Gene Massion
Project manager: Jim Birch
Project team: Kim Fulton-Bennett, Roman Marin III, John Ryan
Collaborators: Eizabeth Ottesen, Massachusetts Institute of Technology, Cambridge; Julie Robidart, University of California, Santa Cruz

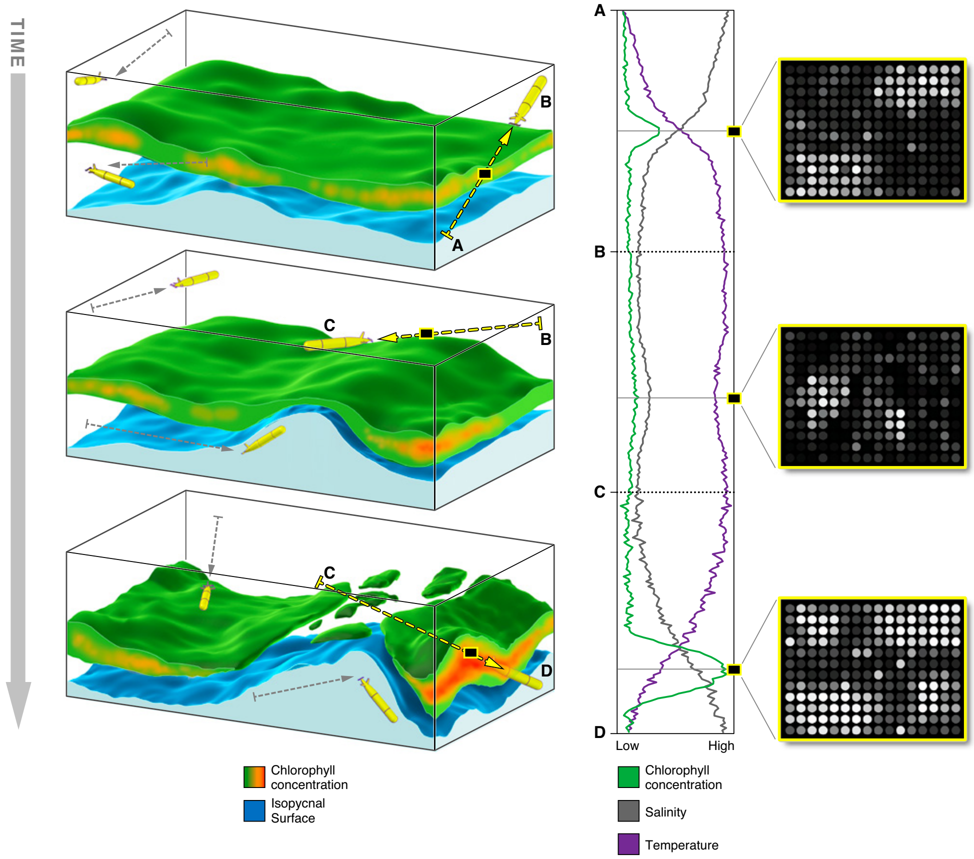


Figure 38: Illustration showing a hypothetical fleet of three autonomous underwater vehicles (AUVs) characterizing properties of the seawater column over both space and time. An internal wave redistributes a layer of phytoplankton. A subset of AUV data in the center column shows the AUV's record of basic ocean properties (chlorophyll, salinity, and temperature). A sample collected during each transit is processed to reveal microorganisms' gene content and expression (right). With the coordinated operation of the AUVs and other equipment, chemical and physical perturbations and the biological response are recorded with respect to space and time.

nity structure and gene expression can be assessed with respect to both space and time domains (Figure 38). Real-time analysis algorithms developed for autonomous underwater vehicles (AUVs) will provide the onboard intelligence required to take molecular detection when and where it is most needed by scientific research.

Exploring climate impacts in the Sargasso Sea

The Sargasso Sea is one of the most nutrient-poor areas of the world ocean, delineated by the Gulf Stream on the west, the North Atlantic Current to the north, the Canary Current to the east, and the North Atlantic Equatorial Current on the south (Figure 39). One of the most distinctive features of the Sargasso Sea is the brown alga, *Sargassum*, which forms floating patches on the sea surface and harbors a diverse assemblage of flora and fauna. MBARI

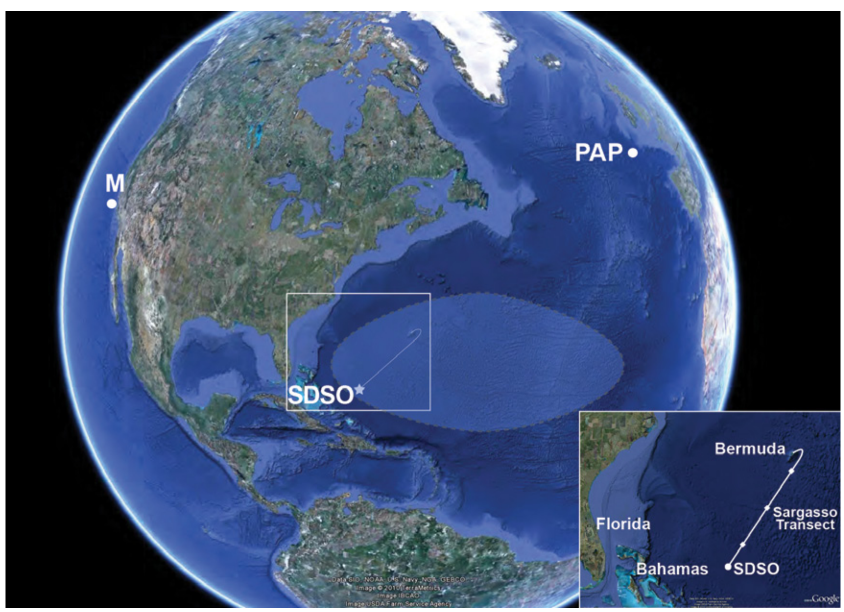


Figure 39: Google map showing Sargasso Sea (light blue ellipse) and three existing deep-sea observatories (white dots on globe). Inset shows Bermuda-Bahamas transect with four stations.

ecologist Ken Smith sampled this unique sea-surface community—as part of a collaborative project between MBARI and Schmidt Ocean Institute—in February and again in August 2011, more than 30 years after he and others conducted extensive studies of the sea life there. The effects of climate change on oceanic ecosystems and carbon cycling should be most evident in these nutrient-poor surface waters that are densely populated by the distinctive *Sargassum* community. A critical question was whether this community has changed over time. Another goal was to develop a time-series monitoring observatory in collaboration with the Marine Science and Technology Foundation to measure the impact of changes in climate on organic carbon export (food supply) including *Sargassum*, to the deep-sea community as part of this very food-poor oceanic ecosystem.

Co-investigators Smith and Alana Sherman, and their team, established research stations along a 965-kilometer-long transect across the western portion of the Sargasso Sea between Bermuda and the Bahamas (Figure 39, inset) where Smith had conducted *Sargassum* community studies decades earlier. These stations were in open ocean areas where water depths ranged from 5,000 to 5,400 meters. At the final station on the southwest end of the transect, their Sargasso Deep-Sea Observatory was deployed on the seafloor at a depth of 5,400 meters. This station was situated generally south of the subtropical convergence zone in an area of very low primary productivity and presumed low food supply to the seafloor.

The floating *Sargassum* community is dominated by two brown algal species, *Sargassum natans* and *Sargassum fluitans*. The floating algal patches, ranging in size from a small plate to large rafts meters in diameter, serve as productive oases in otherwise food-poor surface waters, providing nutrients, attachment sites, and aggregation sites for a wide variety of species (Figure 40). More than 30 common species of animals ranging from flatworms to fishes and representing six different phyla live well-camouflaged amid the *Sargassum*. The total abundance of animals associated with *Sargassum* in 2011 showed little difference from the densities reported in the 1970s. However, the preliminary analyses show significant changes in abundance of individual species, with increasing numbers of crabs and other decapod crustaceans and decreasing numbers of fishes, such as the *Sargassum* fish, *Histrio histrio*. The next step is to compare these biological changes with surface water temperature and acidity increases over the past 40 years. Sherman and Smith also used satellite imagery to provide a regional scale mapping of *Sargassum* and to show how the changes observed are related to the distribution and movement of *Sargassum* across the Sargasso Sea.

Data from the Sargasso Deep-Sea Observatory indicate that changes in climate influence the entire ocean to great depths. The deep-sea observatory deployed in the southern Sargasso Sea in February 2011 consisted of sediment traps moored at 600 and 50 meters above the seafloor to collect sinking food particles and a time-lapse camera to take hourly images of seafloor-associated animals and events (Figure 41). This observatory is part of an effort to monitor carbon export and accumulation in the deep ocean and its impact on seafloor communities as changing climate impacts surface ocean productivity and ultimately the source of food for the entire ocean. Two similar observatories—one in the North Pacific and another in the eastern North Atlantic—provide data for comparative studies.

Figure 40: *Sargassum* patch floating on sea surface with close-ups of several of the most unique species. Clockwise from top left, a nudibranch (about one centimeter long), a shrimp (about five millimeters long), a crab (about one centimeter long) and a fish (about two centimeters long).

Figure 41: Sargasso Deep-Sea Observatory diagram with pictures of a sediment trap, camera tripod, and a benthic image of a cirrate octopod at 5,400 meters depth.

Based on data from the first six months, Smith and Sherman saw a significant, unexpected, seasonal pulse of particulate food to the seafloor, including fragments of *Sargassum*. In the time-lapse images of the seafloor during that first six-month deployment a strong "benthic storm" in February was surprising considering the great depth and the distance from any topographic features such as the continental margin, islands, or bathymetric irregularities. Smith's team is attempting to relate this phenomenon to current-meter records available in the region. Smith and Sherman hope to keep this observatory on the seafloor for a long time by developing camera and sensing systems that can function over longer periods and require only annual maintenance. Such systems are planned for the deep-sea observatories in the Sargasso Sea and the North Pacific to continue monitoring the significant climate-related changes already observed, with the ultimate goal of gaining a broader global perspective and improved predictive capability.

Sargasso Sea Expedition

Project leads/managers: Alana Sherman, Ken Smith
Project team: Larry Bird, Jake Ellena, John Ferreira, Dale Graves, John Ryan, Susan von Thun
Collaborators: Marine Science and Technology Foundation; Schmidt Ocean Institute; Dan Barshis and Judit Pungor, Hopkins Marine Station of Stanford University, Pacific Grove, California; Jeffrey Drazen, University of Hawaii, Manoa; Jim Gower and Stephanie King, Fisheries and Oceans Canada, Institute of Ocean Sciences, Vancouver; Mark Miller, California State University, Monterey Bay; Debbie Nail Meyer, Carlsbad, California; Kathleen Sealey, University of Miami, Florida

Weird and Wonderful

Although MBARI ROVs have been plying the waters of the deep ocean for close to 25 years, the scientists directing those vehicles still regularly come upon animals they have never seen before, and sometimes they discover unfamiliar behaviors that some of these bizarre creatures display. This year's installment of Weird and Wonderful is designed to showcase just a handful of these amazing, and oftentimes enigmatic, creatures of the deep.

Figure 42: Only this mass of empty egg cases remained behind after the octopus babies hatched following four years of close watch by their mother. More than 250 egg cases were counted in this mass. Inset, the octopus mother shortly before the eggs hatched.

Against the odds, deep-sea life goes on

As a rule, cephalopods are secretive animals. Among the most covert aspects of their behavior are the details of their reproduction. Through persistence and good luck, the Midwater Ecology team has recently teased out the secrets of three deep-sea species.

The long-term observation of a mother octopus brooding her eggs at a depth of 1,400 meters finally came to an end in 2011. On a dive in October with the remotely operated vehicle (ROV) *Ventana,* researchers discovered the tattered remains of more than 250 egg cases that had contained developing embryos just a month before (Figure 42). Two of the recently hatched youngsters were spotted on the rock that day but the mother, like all octopus mothers, was gone—most likely having died after her offspring had hatched. Careful measurements over more than four years confirmed that a single clutch of eggs was involved, and characteristic scars on the mother's arms made it certain that she was the same brooding individual seen on each dive. This series of observations documents the longest egg-brooding period of any animal species ever recorded.

Another mystery revealed was the second discovery of a deep-sea squid brooding its eggs deep in the water column (Figure 43). Until recently squid were not known to exhibit any parental care; they either deposited their eggs on the seafloor or released drifting egg masses into the water. In 2005 the Midwater Ecology team discovered a squid species that may hold its eggs in its arms for as long as nine months. In 2011 the team documented a second deep-living squid species that holds and protects its eggs while they develop into hatchlings. The advantage of this reproductive strategy, like that of the brooding octopus, is that parental care allows the embryos to develop into full-fledged miniature adults, that have a far

Figure 43: *Bathyteuthis* squid carries her eggs, for perhaps as long as nine months, as she swims through the midwater. The squid mantle is 72 millimeters (2.8 inches) long. The mother's large eyes allow her to spot danger and carry her eggs to safety.

greater chance of success than they would as free-living larvae.

A different reproductive strategy revealed in 2011 is the "shot in the dark" approach to mating that is taken by yet another deep-living squid. *Octopoteuthis* is a solitary and uncommon species that lives in deep, dark waters where opportunities to find a mate must be few and far between (Figure 44). The team discovered that both males and females showed abundant evidence of having been implanted externally with sperm packets from males of the same species. It appears that this strategy calls for male *Octopoteuthis* to deliver sperm packets to any member of their species that they encounter, regardless of gender. In this strategy: sperm are cheap and no opportunity to mate is lost.

Figure 44: This female *Octopoteuthis* has photophores visible on the tips of its arms. The *Octopoteuthis* is about 150 millimeters (almost six inches) long. The pale specks on her mantle are sperm packets called spermatangia.

Adaptations to life in the deep sea are many and varied. They sometimes seem bizarre and outlandish, but they have evolved to suit the conditions in the habitat where these species live, and given that these three cephalopods have been found widely scattered around the eastern North Pacific and elsewhere, they must work.

Feeling for a feeding

How does a blind lobster find its food? The distinct feeding strategy of blind deep-sea lobster larvae was observed at MBARI for the first time. When the larvae detect movement, they sweep their long pincers over their carapace to seize the food item (Figure 45). The larvae are covered with thousands of fine sensory hairs for detecting such encounters in the dark depths, and are capable of capturing and feeding on live shrimp as well as natural detritus. One fed on the discarded filter of the giant larvacean *Bathochordaeus*.

Very little is known about the transformation that occurs when these lobsters molt from their large, planktonic forms into seafloor-dwelling adults. MBARI researchers have observed 16 of these larvae over the last two decades, and found that they reside deep in the midwater, in areas of very low oxygen where food and predators are scarce. They belong to the family Polychelidae, a group of blind lobsters that inhabit the bathyal and abyssal plains of the world ocean. The adults bury themselves into the muddy seafloor and survive by scavenging organic material.

Traditional net sampling severely damages the fragile larvae, particularly the long, thin pincers that are found on their first pair of legs. The MBARI Midwater Ecology team successfully collected three of the larvae with an ROV and kept them in the cold seawater laboratory for observation. One larva survived for 10 months by consuming a variety of food items.

With larvae now feeding in captivity, the Midwater Ecology team plans to observe the stage at which they molt into their adult form. Dozens of different larval forms have been discovered, but few have ever been assigned to known adult species names. The team will try to unravel some of those enigmas on larvae found in Monterey Bay. This research brings a ray of light to some of the dark mysteries of the deep, where blind larvae lead to unknown blind adults.

Figure 45: Blind lobster larva feeding on a mysid in the seawater lab; at right, a closeup of the mysid in the larva's claw. The outer shell is about five centimeters (two inches) tall. Lab studies are attempting to discover how long the larvae reside in the water column.

Bombs away!

The polychaete worm *Swima bombiviridis*, nicknamed the "green bomber" by Steve Haddock and colleagues, is a segmented worm that lives very deep in the sea (Figure 46). Except for its gut, *Swima* is mostly transparent and swims with undulating style by paddling its fringe of long spikey projections. The worm carries a variety of elaborate appendages near its head. The worm can shed some of the tiny capsules which suddenly burst into brilliant green light on release. It is the flashiest representative of an entire branch of polychaete worms that had gone undescribed until recently. Molecular studies by collaborator Karen Osborn have confirmed that it is a close relative to the bizarre "squid worm" found deep in the South Pacific, yet another example of the many weird and wonderful creatures that inhabit the ocean depths.

Figure 46: *Swima bombiviridis* earned its nickname "the green bomber" from the tiny capsules that are located just below its head and glow bright green when the worms release them from their bodies. These worms sometimes reach 30 millimeters (1.1 inch) in length.

Locating the perfect fishing site

Siphonophores—relatives of jellyfish—grow by elongating and differentiating along a central tube. Even compared to its unusual relatives, this newly described species of siphonophore, *Resomia ornicephala*, has some notably unique traits. It was originally nicknamed the "R200" because in Monterey Bay it is almost always found close to 200 meters deep. Steve Haddock and collaborator Phil Pugh hypothesize that its narrow depth range is related to its second unique trait: it dangles stinging tentacles augmented by fluorescent lures (Figure 47). These lures, shaped a bit like a bird's head, give this species its name ("orni" meaning bird and "cephala" head). To be properly visible, the tentacles must be illuminated by dim blue light, like the light at 200 meters below the surface. Its main prey is small shrimp-like krill, which apparently find the colorful lures irresistible. A single siphonophore can be 30 centimeters long and have several dozen "stomachs", and invariably when the ROV cameras encounter *Resomia ornicephala*, a few of these stomachs will be full of recently caught prey. These same lures serve to attract scientists, who continue to find new animals in the mysterious deep sea and tease out their means of survival in this strange, dark environment.

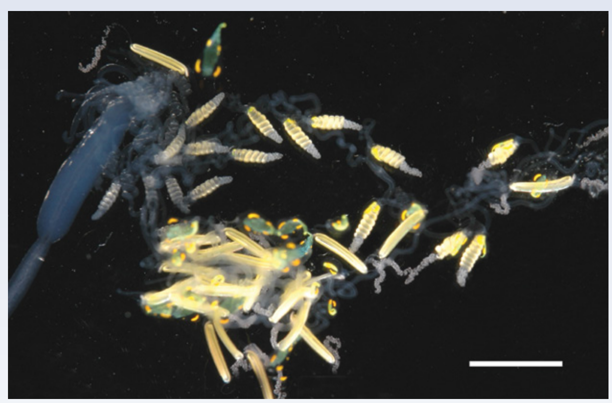


Figure 47: Fluorescent lures dangle from the end of stinging tentacles on the siphonophore *Resomia ornicephala*. Krill attracted to the lights are stung then drawn into one of the siphonophore's stomachs. Scale bar equals three millimeters.

On the Horizon

An extended two-ship research expedition to Mexico and the launch of a new research vessel will be two highlights of 2012, a year in which MBARI also marks its 25th anniversary. The expedition will provide unique opportunities to extend MBARI's work in high-priority research areas, while the new ship will significantly enhance the institute's ability to work efficiently at sea.

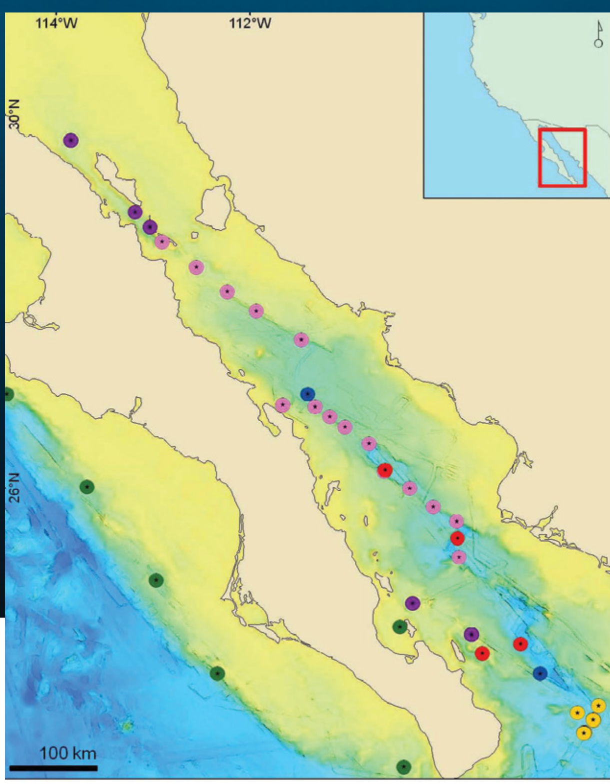


Figure 48: Map of research sites to be visited during the 2012 Gulf of California expedition. The different colors each represent a different research group's study locations.

Gulf of California expedition

In February MBARI's research vessel *Western Flyer* departed for the Gulf of California. The research vessel *Zephyr* followed shortly after with the mapping autonomous underwater vehicle (AUV), the *D. Allan B.* MBARI researchers and their Mexican collaborators coordinated schedules and research goals to maximize this opportunity, carving the three-month expedition into segments to focus on different ocean issues (Figure 48). The expedition takes researchers to a little-explored region known to contain hydrothermal vents, undersea volcanoes, seafloor gas deposits, and large areas of ocean marked by oxygen depletion. Scientific studies provide new insight when comparisons in time and space can be made and this expedition offers both. Many of the scientists sailing on this cruise participated in MBARI's 2003 expedition to the Gulf of California, so they may observe changes over the years. And the phenomena studied here can be compared and contrasted with what has been learned in Monterey Bay as well as other locales.

The expedition began with a series of stations along the California and Baja coasts to collect water samples and other data from the poorly understood California Undercurrent that flows northward along the continental shelf of North America.

On following segments of the expedition, various MBARI science groups used the remotely operated vehicle (ROV) *Doc Ricketts* to explore the biology, chemistry, and geology of the region. The R/V *Zephyr* ran a number of missions to acquire detailed mapping data from the AUV *D. Allan B.* to aid the geologists and chemists in locating optimal research sites.

The expedition took years of planning and many months of working out regulatory matters, but the discoveries and knowledge gained will make it well worth the effort.

New ship provides greater range and flexibility

In 2010, MBARI created an Ocean Access Plan to address the institute's long-term seagoing needs. Central to that plan was a two-ship fleet that should consist of one regional vessel capable of missions up and down the west coast of North America and one coastal vessel to handle missions closer to home. The R/V *Western Flyer*, and a planned replacement years down the line, meet the regional need. For the coastal vessel, it was decided to retire the R/V *Point Lobos* and the R/V *Zephyr* in favor of a single ship that would in effect be a hybrid of those two vessels.

Figure 49: The *Odyssea Team* operated out of Louisiana carrying supplies out to oil rigs in the Gulf of Mexico.

Director of Marine Operations Steve Etchemendy and Chief Financial Officer Mike Pinto set about looking for the perfect replacement, visiting seven prospective vessels in Louisiana and Texas. They soon found a likely candidate, the *Odyssea Team* (Figure 49). With assistance from naval architects Glosten Associates, a plan was developed to convert the offshore supply vessel into a research vessel.

The ship was sent to a shipyard in Louisiana for painting, shafts, rudders, props, and bow thruster work and arrangements were made for the remaining work to be completed in Alameda, California (Figure 50). The ship, soon to be christened the R/V *Rachel Carson* in honor of the writer, scientist, and ecologist, transited to California via the Panama Canal. The *Rachel Carson's* background is much like that of MBARI's first vessel, the *Point Lobos*, which proved to be a reliable research workhorse for 23 years. The *Point Lobos* also had been an oil-field supply boat in Louisiana before being purchased by MBARI, sailed through the Panama Canal, and converted to a worthy research vessel.

Figure 50: The ship with a fresh coat of paint and new name.

Once the R/V *Rachel Carson* arrives in Moss Landing, MBARI's Marine Operations and engineering teams will install the cranes, the remotely operated vehicle system, control room, and other equipment that have been removed from the R/V *Point Lobos*. After the R/V *Zephyr* returns from the Gulf of California and conducts its last science mission, the entire launch and recovery system for the autonomous underwater vehicles will be moved over to the *Carson* as well. The new ship is currently scheduled for sea trials in July and August.

A silver anniversary

When MBARI's founder, David Packard, established the institute in 1987, he emphasized the development of new tools and technologies to explore the deep sea. As we celebrate the institute's 25th year, we are keeping Packard's vision foremost in our minds and continuing to focus on how MBARI will move forward and carry innovation through the next 10 to 25 years. MBARI is small and limited in resources compared to other oceanographic institutions so we plan carefully to make the most of our resources. The development of a technology roadmap, as mentioned on page 3, is an important step in perpetuating Packard's vision. This roadmap will outline technology projects to complement our strategic plan.

Recognition of our 25th anniversary will underlie many of our events and activities in the coming year, but will not itself be a focus. MBARI sets its sights on the future, rather than the past, with strategies for expanding our reach, enhancing collaborations, and inspiring the next generation. MBARI's work with our sister institution, the Monterey Bay Aquarium, will reach millions of aquarium visitors with creative exhibits and educational programs. That collaboration will continue to support teacher workshops this summer to carry ocean issues and environmental messages into classrooms across the country.

To help share many of our discoveries and developments with our community and the public, we are looking at making MBARI's 2012 Open House on July 21st a special one. Last year, many of our engineers and scientists created some great new activities and displays for the annual event (Figure 51). We plan to keep the momentum going to make sure this continues to be an event to showcase our best work and our cutting-edge research and technology.

Remarkable images from the MBARI archives will expand our reach via the web, news stories, the MBARI YouTube channel (Figure 52), and social media to highlight our socially relevant work. Daily reports from our expeditions will give us an opportunity to explain deep-sea science and its importance to the public at large.

So be on the lookout for news from MBARI; join us on Facebook, Twitter, YouTube or, if you are nearby, at our Open House!

Figure 51: Visitors to the 2011 Open House learn about the inner workings of the autonomous underwater vehicle.

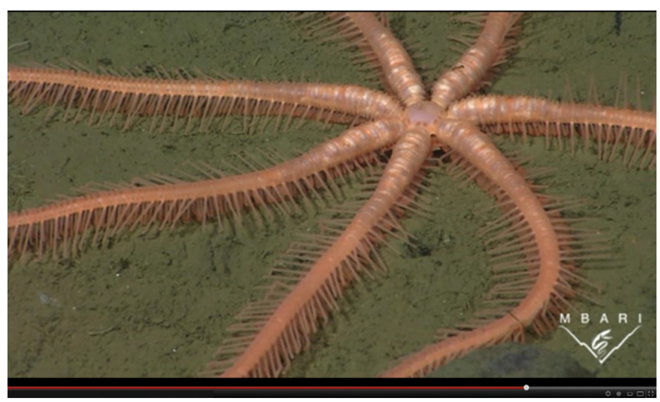


Figure 52. MBARI is using various social media to reach a wider audience with our news, images, and video. This screen shot is from one of many video productions posted at www.YouTube.com/MBARIvideo.

Behind the Scenes:
Sharing MBARI Technology for the Greater Good

The transfer of technology and know-how developed at MBARI to other researchers, educators, policy makers, resource managers, industry, and the general public is an important institute goal. Serving such a broad audience requires that we take a flexible approach to meeting this goal.

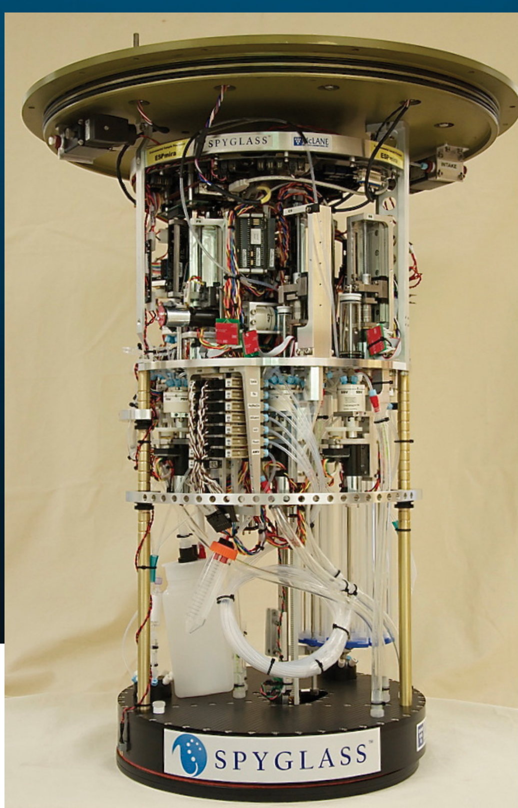


Figure 53: Spyglass Biosecurity, Inc., is manufacturing and distributing the MBARI-developed Environmental Sample Processor under a license from MBARI.

Early efforts to share MBARI's developments centered around the remotely operated vehicle (ROV) *Tiburon*, one of the institute's first major projects. After designing and building the advanced ROV in-house, MBARI engineers worked directly with their counterparts from Woods Hole Oceanographic Institution and the French Research Institute for Exploration of the Sea to transfer lessons learned and *Tiburon* technology for use on their ROVs.

More recently MBARI engineers provided ocean observatory software technology to the European Seas Observatory Network and for buoys in the Great Lakes and in New Zealand. MBARI software engineer Tom O'Reilly led the move for MBARI's plug-and-work PUCK protocol to be adopted as an Open Geospatial Consortium (OGC) standard. That adoption means that as more oceanographic instruments apply the standard protocol, users will find it easier to install and keep track of instruments and data on moorings and ocean observatories.

Similarly, research collaborations have extended the use of MBARI genetic probes for identifying harmful algae and their toxins. Cooperative research and direct exchanges of the technology with other institutions such as NOAA's National Ocean Service Marine Biotoxins Laboratory and New Zealand's Cawthron Institute greatly enhance opportunities for extended field programs and further development and application of probe technology. As a result, these fast, accurate genetic methods have been adopted for routine monitoring of harmful algal blooms in New Zealand and elsewhere.

Traditionally, academic researchers have published their research findings and technical developments in journals and on the Internet and given presentations at conferences. These established academic methods have proven effective for transferring some of our developments. For example, MB-System, a free, open-source software package to process mapping data developed by MBARI's Dave Caress and Dale Chayes of Lamont-Doherty Earth Observatory, is now widely available and used by researchers around the world. To support transfer of our Video Annotation and Reference System (VARS) to other scientific institutions, MBARI held a two-day technical workshop with participants from Australia, Japan, and around the U.S. The technical content of that workshop and the VARS software are available on SourceForge, an open-source software development website.

Publication and small workshops, however, are not always enough to effect technology transfer. A different approach is needed to broadly distribute complex technologies that require technical support on a larger scale than MBARI can provide. In such cases, licensing technology for commercial manufacturing is the most practical way to extend the reach of MBARI developments. Commercial ventures can lower the unit cost of building and distributing instruments while providing adequate technical support and training to users. When a staff member thinks his or her invention fits this model, Director of Information and Technology Dissemination Judith Connor leads a review by the institute's intellectual property committee of the potential application and commercial partners for the invention. With help from Luis Mejia and others at Stanford University's Office of Technology Licensing, the committee develops a licensing strategy, taking the technical and market risks into consideration, and decides whether to apply for patent protection. There's financial risk to evaluate: What is the likelihood of licensing the technology versus the considerable expense of patenting?

One of MBARI's early patents was issued for an autonomous genomics laboratory for in situ use in the ocean—an instrument now known as the Environmental Sample Processor (ESP). Subsequently inventor Chris Scholin (who is MBARI's president and a senior scientist) successfully secured additional funding—from the National Science Foundation, NASA, the Gordon and Betty Moore Foundation, and others—to further the development of the ESP and genetic probes. The MBARI team continued to improve the system and demonstrated its successful use in the ocean. From that body of work a start-up company, Spyglass Biosecurity, Inc., licensed the technology and has recently begun to manufacture the ESP, marketing it to research groups around the U.S. and abroad (Figure 53).

Not all inventions and know-how need be patented to generate commercial interest. MBARI has licensed to Satlantic the non-patented In Situ Ultraviolet Spectrophotometer (ISUS) for analyzing nutrients in seawater and the Land/Ocean Biogeochemical Observatory (LOBO) mooring developed by Ken Johnson's group (Figure 54). The group's newest development, an adaptation of Honeywell International's Durafet pH sensor for use in seawater has also recently been licensed to Satlantic. These examples show how the creative adaptation of off-the-shelf components, publication of successful research use, and the sharing of expertise with commercial partners can extend MBARI's reach and get new instruments into the hands of other scientists.

MBARI technology moves out into the broader research community through less formal pathways as well. Many postdoctoral fellows and summer interns have gone on to careers elsewhere applying the knowledge and technology they learned while at MBARI. And special partnerships with the Monterey Bay Aquarium and the Center for Ocean Solutions help transfer technology like the Free Ocean Carbon Dioxide Enrichment (FOCE) equipment—and subsequent results and impacts discovered through its use—to policy makers, educators, and the general public. Similarly another Ocean Solutions' collaboration is investigating use of MBARI's ESP to improve methods for testing water quality as mandated by state and federal law.

Together, these various pathways enable sharing of cutting-edge technology and discoveries with the world outside MBARI, helping meet a key aspect of MBARI's mission—to not only develop better instruments, systems, and methods for scientific research in the deep waters of the ocean, but to make those discoveries and inventions available for the greater good.

Figure 54: A mooring in the Land/Ocean Biogeochemical Observatory (LOBO) provides real-time measurements of chemical fluxes into, within, and out of Elkhorn Slough. The LOBO design and software have been licensed to a commercial partner for manufacture and distribution.

Project Summaries

Application of Chemical Sensors

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Patrick Gibson, Hans Jannasch, Josh Plant, Carole Sakamoto
Collaborators: Todd Martz, Scripps Institution of Oceanography, La Jolla, California; Joe Needoba, Oregon Health and Science University, Portland; Steve Riser and Dana Swift, University of Washington, Seattle

By the end of 2011, 20 profiling floats equipped with the ISUS nitrate sensor had been deployed in the subtropical Pacific and Atlantic Ocean basins, in high latitudes in the Pacific, Southern Ocean, and Arctic Ocean, and in the Arabian Sea. The float in the Arctic has clearly shown the timing and magnitude of the fall plankton bloom. The float in the Arabian Sea showed the intensity of the oxygen minimum zone and the loss of nitrate due to nitrate reduction processes. The team also continued to support the operation of a chemical sensor network in Elkhorn Slough and the nearshore waters of Monterey Bay. Measurements in 2011 have been used to analyze the impacts of ecological restoration projects in the slough.

Aquarium-MBARI Partnership

Project leads: Chris Harrold, George I. Matsumoto
Project manager: George I. Matsumoto
Project team: Nancy Barr, James Barry, Lori Chaney, Judith Connor, T. Craig Dawe, Kim Fulton-Bennett, Steven Haddock, Hendrik Jan Ties Hoving, Linda Kuhnz, Lonny Lundsten, Julie Martin, Thom Maughan, Craig Okuda, Tom O'Reilly, Josh Plant, Michael Risi, Bruce Robison, Kyra Schlining, Nancy Jacobsen Stout, Josi Taylor, Susan von Thun
Collaborators: Rita Bell, James Covel, Humberto Kam, Traci Reid, Kim Swan, and Jaci Tomulonis, Monterey Bay Aquarium, California

The Monterey Bay Aquarium (MBA) and MBARI collaboration included updating of the *Mysteries of the Deep* auditorium program and renovation of the aquarium's Open Sea Exhibit. MBARI staff participated in the World Ocean Day celebration at the aquarium and provided lectures and tours of MBARI for MBA volunteers. MBARI scientist Steve Haddock worked closely with the designers of a new jellies exhibit. The project team began planning a symposium on the Ocean in a High-CO_2 World to be held in Monterey in 2012, co-sponsored by MBA and MBARI. MBA staff expertise with large meetings is proving to be invaluable. Several MBARI researchers mentored students in the aquarium's Watsonville Area Teens Conserving Habitats program and provided a venue for the end-of-the-year symposium for friends and family. A camera placed on the MARS observatory provided MBA with a new source for live seafloor video.

Autonomous Underwater Vehicle (AUV) Infrastructure Support

Project leads: David Caress, John Ryan
Project manager: John Ryan
Project team: Mike McCann

This infrastructure project includes AUV mission planning, software development, science data processing, data archiving, dissemination, and preparation of results for publication. During 2011, the team made improvements and upgrades to the mapping vehicle data systems, supported science users of the data and MB-System software, and supported shore-side data management and processing capabilities for benthic imaging and upper-water-column AUVs. The group also prepared for an expedition to study hypoxia in the Santa Monica basin using the *Dorado* AUV, tested a novel particle-imaging sensor on *Dorado*, and completed analysis and publication of *Dorado* AUV results from the 2010 mission to map deep oil plumes in the Gulf of Mexico.

Benthic Biology and Ecology

Project lead/manager: James Barry
Project team: Kurt Buck, Taewon Kim, Chris Lovera, Eric Pane, Josi Taylor, Patrick Whaling
Collaborators: Scott Doney, Woods Hole Oceanographic Institution, Massachusetts; Craig McClain, University of North Carolina, Durham; Stephen Widdicombe, Plymouth Marine Laboratory, United Kingdom

This research team has examined the physiological responses of deep-sea animals (brachiopods, urchins, crabs) to reduced ocean pH (ocean acidity) and warming—environmental changes associated directly with fossil fuel emissions to the atmosphere and human-induced climate change. Although most deep-sea animals have some capacity for tolerating expected changes in deep-sea conditions, their nutritional status (fed or unfed) and available oxygen appear to play an important role. When given extra food or more oxygen (for animals living in the normally hypoxic oxygen minimum zone), test animals were considerably more tolerant to ocean acidification. Field studies using the benthic respiration system have shown that activities of deep fragile urchins (*Strongylocentrotus fragilis*) which live at depths of 200 to 1,200 meters, effectively straddling the oxygen minimum zone (OMZ), are limited greatly by the low oxygen levels in the core of the OMZ. Provided with more oxygen, the urchins double or triple their respiration rates, indicating that processes such as mobility, feeding, digestion, and growth are likely to be limited for urchins living in the OMZ, and that lower oxygen levels in the future would likely be even more stressful. Jim Barry also leads an important component of this project—the advancement of international research in ocean acidification and outreach to policy makers and the public—with his testimony, interviews, talks, and participation as an advisor to several organizations.

Benthic Event Detector

Project leads: Charles Paull, William Ussler
Project manager: Brian Kieft
Project team: Larry Bird, Dale Graves, Bob Herlien, Denis Klimov

AUV multibeam mapping surveys, ROV vibracoring, and simple experiments have shown that Monterey Canyon is an active conduit for the movement of enormous quantities of sediment from the nearshore environment to the Monterey deep-sea fan. Brief sediment transport events are capable of moving boulder-sized objects hundreds of meters down the canyon. Sediment may be carried predominantly in suspension above the seafloor in high-energy turbidity currents that flow down a canyon, or it may flow down canyon as a slurry that resembles fresh concrete sliding down a chute or as large coherent slabs. The Benthic Event Detector (BED) is being developed to determine the magnitude, timing, and dynamics of sediment debris flow events in upper Monterey Canyon. Results from a series of acoustic transducer burial tests indicate that it will be possible to transfer data from a BED buried in up to three meters of sediment without recovery of the instrument. Evaluation of potential motion sensors has progressed using a combination of kinematic modeling and laboratory experiments. Initial mechanical and electrical designs have been completed in preparation for an engineering design review.

Benthic Exchange Events and Near-Boundary Mixing on the Continental Shelf

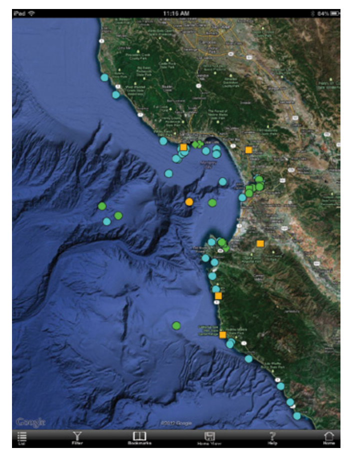
Project lead: James G. Bellingham
Project team: Michael Godin, Brett Hobson, Thomas Hoover, Brian Kieft
Collaborators: Erika McPhee-Shaw, Moss Landing Marine Laboratories, California; William Shaw and Tim Stanton, Naval Postgraduate School, Monterey, California

This collaborative effort focused on understanding mixing processes on the continental shelf. The MBARI contribution revolves around using the *Tethys* long-range autonomous underwater vehicle (LRAUV) to characterize turbulent processes in the vicinity of several seafloor instruments. *Tethys* is uniquely suited to make these observations as it is large enough to carry the relevant instruments and has the endurance to make repeated measurements for periods of a week or more. In late October *Tethys* was used to collect physical and optical data along an east-west nearshore ocean section to the south of Moss Landing. The capabilities developed for this effort are directly applicable to MBARI's CANON Initiative because turbulence is likely highly relevant to biological processes.

Central and Northern California Ocean Observing System (CeNCOOS)

Project leads: Francisco Chavez, Steve Ramp, Leslie Rosenfeld
Project managers: Heather Kerkering, Leslie Rosenfeld
Project team: Fred Bahr, Tom Wadsworth
Collaborators: 14 principal investigators from 12 institutions

CeNCOOS supports a network of data-gathering technologies, which together with numerical models and data management systems, enhance knowledge of changing ocean conditions and contribute to coastal management decisions. These technologies include high-frequency radar for measuring surface currents, profiling gliders to characterize the vertical and horizontal structure of the ocean, and moorings and shore stations to collect meteorological, chemical, biological, and physical data. CeNCOOS, together with neighboring regional observing systems, is working with state agencies, the West Coast Governors Alliance, and other organizations to apply the information and knowledge gained to address questions relating to ocean acidification, harmful algal blooms, marine protected areas, and other issues. In mid-2011, CeNCOOS started serving near-real-time data via an iPhone application in addition to the data portal on the CeNCOOS website (www.cencoos.org).



CeNCOOS data display on an iPhone.

Chemical Sensor Program

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Patrick Gibson, Hans Jannasch, Gene Massion, Josh Plant, Carole Sakamoto
Collaborators: Greg Brown, Robert Carlson, and Alex Gu, Honeywell International, Inc.; Todd Martz, Scripps Institution of Oceanography, La Jolla, California; Steve Riser and Dana Swift, University of Washington, Seattle

In a joint effort with Honeywell International, Inc., Ken Johnson's team developed improved, pressure-tolerant packages for the Honeywell Ion Sensitive Field Effect

Transistor pH sensor. High-pressure operation of these systems was then demonstrated in a pressure- and temperature-regulated test system developed in MBARI's Chemical Sensor Lab. These systems will ultimately provide a completely solid state pH sensor that can be used in global scale sensor networks, such as the Argo array, to allow processes such as ocean metabolism and ocean acidification to be observed autonomously. The project team also began field deployments of an improved version of the Digital Submersible Chemical Analyzer designed to allow common, laboratory-based analyses to be reliably performed in situ. The team's immediate goals are to deploy autonomous systems for phosphate and ammonium analyses in coastal and open-ocean arrays.

Compact Ocean Models Enable Onboard AUV Autonomy and Decentralized Adaptive Sampling

Project lead/manager: James G. Bellingham
Project team: Sergey Frolov, Michael Godin, Yanwu Zhang
Collaborators: Michael Cook and Jeffrey Paduan, Naval Postgraduate School, Monterey, California

Autonomous underwater vehicles have the agility and endurance to adapt their sampling strategy to better characterize changing ocean processes. When the ocean changes rapidly, onboard decision making becomes essential. However the vehicle is greatly hampered by the lack of access to shore-based data and models. To provide AUVs with the situational information to respond more efficiently, this project has focused on developing predictive ocean current models capable of being run on an AUV's modest computer, and updated over a slow satellite link. The team used two years of high-frequency radar observations off Monterey Bay to create statistical models that approximate the dynamics of the ocean. The new model was more accurate than existing statistical and circulation models for the same area. The effort then shifted to implementing the code on the AUV. Supporting infrastructure already in place includes AUV software capable of adaptive sampling of ocean features (fronts and phytoplankton patches). Remote control from shore via satellite link has been extensively tested, including passing new missions and scripted behaviors.

Cooperative Oceanography and Virtual Experiments

Project lead/manager: James G. Bellingham
Project team: Michael Godin, Dorota Kolber

This effort seeks to develop an online tool to support cooperative operation of complex environmental field programs by teams in different locations. Development is focusing on two interdependent categories: data-system tools and human-collaboration tools. Data-system tools include data collection mechanisms, data conversion, exploration, and visualization. Human-collaboration tools include discussion forums and data annotation, both of which are provided via a web-accessible portal. The project created and operated a data-management system and portal for a large Office of Naval Research field program in the western Pacific focused on ocean responses to typhoons. Efforts in this project are closely coupled to MBARI's CANON Initiative, and the data system and portal developed under this effort were also used for CANON field programs in 2011.

Core Conductivity-Temperature-Depth (CTD) Data

Project lead: John Ryan
Project manager: Erich Rienecker
Project team: Gernot Friederich, Mike McCann, Reiko Michisaki, Kim Reisenbichler, Bruce Robison, Rich Schramm

Support continued on the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. The validation of ROV oxygen-sensor data continued; both ROVs are now outfitted with dual sensors for improved data quality. Preparation for integration with the R/V *Rachel Carson* has begun.

Core Mooring Data

Project lead: David Caress
Project manager: Mike McCann
Project team: Fred Bahr, Francisco Chavez

This project provides for the institutional support of core data from MBARI moorings. A subset of mooring data (surface CTD, T-string, meteorological, GPS, ADCP and pCO_2 data) have been designated as core data streams, which means that support for the collection, processing, and archiving of the data is provided on an institutional basis rather than through individual projects or divisional budgets.

Core Navigation Data

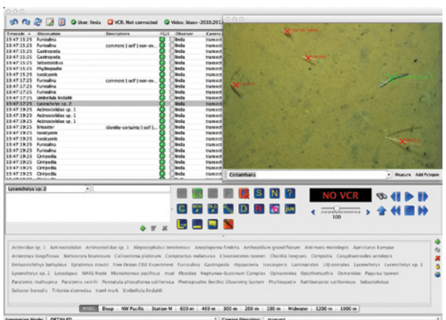
Project lead/manager: David Caress
Project team: Knute Brekke, Mike Burczynski, T. Craig Dawe, Dale Graves, Linda Kuhnz, Dana Lacono, Eric Martin, Mike McCann, D.J. Osborne, Randy Prickett, Bryan Schaefer, Rich Schramm, Mark Talkovic

The collection, processing, and archiving of core data is provided on an institutional basis with oversight by the MBARI Data Users Committee. In 2011 the project included operation and maintenance of the ROV and ship navigation hardware, maintenance and development of software for automated processing and archiving of navigation data, editing of ROV navigation, and monitoring of the data quality. The primary challenge continued to be hardware and calibration issues with the ROV *Doc Ricketts* navigation.

Core Outline Video Annotation

Project lead: John Ryan
Project manager: Lonny Lundsten
Project team: Lori Chaney, Linda Kuhnz, Karen Salamy, Brian Schlining, Kyra Schlining, Nancy Jacobsen Stout, Susan von Thun

The MBARI Video Annotation and Reference System (VARS) has been used for all video annotations conducted in the lab and at sea. The resulting database and the accompanying video archive contain more than 3.7 million observations and 4,261 unique concepts from over 18,000 hours of deep-sea video. In 2011, video lab staff annotated over 1,100 hours of ROV video. In collaboration with several projects across the institute, the annotation team continued to prepare for expanding capabilities from archiving and annotating ROV recorded video tape to include still images and hard-disk-drive-based video files and images collected from various imaging platforms. The project team worked closely with engineer Mike McCann to transform the outdated database ROV log into a web-accessible version that is available to all MBARI staff through the expedition database. Tape logging, advanced querying, metadata export, and tape-label printing are all available through this web interface.



Graphical user interface for video annotation.

Education and Research: Testing Hypotheses (EARTH)

Project lead/manager: George I. Matsumoto
Collaborators: Nora Deans, North Pacific Research Board, Anchorage, Alaska; Darcy Dugan, Alaska Ocean Observing System, Anchorage; Kris Holdereid, Kasitsna Bay Marine Laboratory, Seldovia, Alaska; Marilyn Sigman, Centers for Ocean Science Education Excellence, Anchorage, Alaska

During the 2011 EARTH workshop, teachers compared data from the Monterey Accelerated Research System and the Alaska Ocean Observing System looking for similarities and differences, and generating stories and lesson plans on coastal margins and microbial communities. The team discussed many suggestions for disseminationing the EARTH workshop style and content. Three EARTH participants have held successful one-day professional development workshops in their school districts and several of the participants have presented at regional and national meetings and/or published in peer-reviewed literature. One of the criteria for being included in the 2011 workshop was for the teachers to share lessons they learned.


Russ Hopcroft describes the Gulf of Alaska at EARTH workshop.

Feasibility of Digital 35-Millimeter Video Camera for ROV Use

Project leads: Mark Chaffey, Steve Haddock
Project manager: Todd Walsh
Project team: Dave French, Lonny Lundsten

This feasibility study investigated using new digital 35-millimeter video technology on MBARI's ROVs. Current advances in these high-definition imaging systems are marked not only by greatly increased resolution of the image captured (at least four times that of high-definition video), but also by increased dynamic range, greater latitude for post-production adjustment, and higher frame rates. These advances can be used to better describe, identify, or discover new organisms. Camera systems which most closely matched the form-factor and capabilities required for use by the institute were identified. Optical limitations were examined to verify the ability of these cameras to produce visual range specifications comparable to existing systems.

Genetically Encoded Luminescence for In Vivo Imaging

Project lead/manager: Steven Haddock
Project team: Warren Francis, Gerard Lambert, Amy McDermott, Meghan Powers, Nathan Shaner
Collaborators: Andy Baxevanis and Christine Schnitzler, National Institutes of Health, Bethesda, Maryland; Mikhail Matz, University of Texas, Austin

The goals of this project are to discover the chemical and genetic underpinnings of bioluminescence. Researchers have been working on the luciferin biosynthesis pathway for the copepod *Gaussia* and conducted extensive transcriptome sequencing. Luminescent proteins were expressed in bacteria and yeast with a variety of vectors and screened for interaction. Several siphonophores, a polychaete and a chaetognath worm, and a few comb jellies were also sequenced. This research has yielded interesting and novel photoproteins and fluorescent proteins and is being written up in several publications on luminescence chemistry and genes.

Handheld Tissue Sampler

Project leads: Larry Bird, Erika Raymond, Robert Vrijenhoek
Project manager: Erika Raymond

When a diver is recording the diversity and behavior of fishes, specimen-collection protocols include the collection of animals and preservation of tissue samples from those specimens. However the collection of multiple specimens is often impractical or impossible, particularly for larger species. An alternative method using a diver-held tissue-sampling and tagging device coupled with a high-definition video camera was developed. A T-shaped spear-tip adaptor manufactured at MBARI allows for simultaneous tagging and tissue sampling for mid-sized to larger fishes. The tips can be mounted to a pole spear or a banded speargun with a quick-release for ease of use underwater.

Lagrangian Sediment Trap/Vertical Profiler

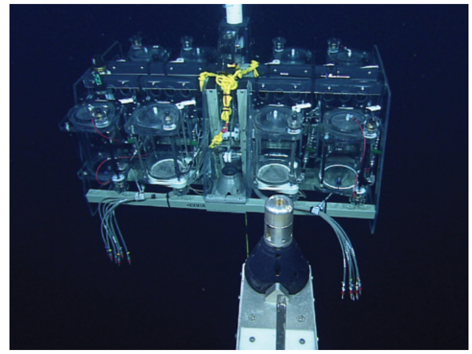
Project leads: Alana Sherman, Ken Smith
Project manager: Alana Sherman
Project team: Larry Bird, Brett Hobson

The core of the Lagrangian Sediment Trap (LST) is a Sounding Oceanographic Lagrangian Observer (SOLO) float that contains a variable buoyancy engine. This enables the LST to sink to a set depth, drift at that depth, and then resurface, on preset time intervals. Four sediment-trap funnels with sequencing collection cups were mounted on top of each float to collect sinking particulate matter. The LST chassis wiring was redesigned to improve the ease of preparing for deployment. Two new SOLO floats were acquired from Scripps Institution of Oceanography, as was an acoustic profiler for future field experiments.

Midwater Ecology

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Hendrik Jan Ties Hoving, Rob Sherlock
Collaborators: Stephanie Bush and Brad Seibel, University of Rhode Island, Kingston; Jeffrey Drazen, University of Hawaii, Manoa; William Gilly, Hopkins Marine Station of Stanford University, Pacific Grove, California; Steven Haddock, George Matsumoto, and Ken Smith, MBARI; Christine Huffard, Conservation International, Indonesia; Karen Osborn, Smithsonian Institution, Washington, D.C.; Louis Zeidberg, California Fish and Game, Monterey

Using the Midwater Respirometry System (MRS) the team measured the critical oxygen consumption thresholds of key midwater species. MBARI's MRS is a unique instrument that allows scientists to measure the oxygen consumption of midwater animals in situ, without subjecting them to the physiological stresses of decompression and thermal trauma. These data, coupled with oxygen profiles generated during ROV dives, and with vertical distribution data from the Midwater Time Series were combined for analysis. The results clearly showed that as Monterey Bay's oxygen minimum zone (OMZ) expanded, several important and abundant midwater species have relocated their centers of vertical distribution significantly closer to the surface. The strong correlation between their threshold oxygen requirements (as measured by the MRS) and the upward shift of specific oxygen concentrations, is persuasive evidence that these species are being driven out of their historical habitat by the growing OMZ. The ecological consequences of this upward shift may be dire, because many midwater species feed near the surface at night, then migrate to darker depths during daylight to avoid visually cued predators. Being forced toward the surface increases the risk of predation for these species, which could potentially lead to trophic cascade and a collapse of former community structure.


MBARI's Midwater Respirometry System.

Midwater Time Series

Project lead: Bruce Robison
Project manager: Rob Sherlock
Project team: Kim Reisenbichler, Kristine Walz
Collaborators: Stephanie Bush, University of Rhode Island, Kingston; Steven Haddock, Kyra Schlining, and Susan von Thun, MBARI; Karen Osborn, Smithsonian Institution, Washington, D.C.; Julia Stewart, Hopkins Marine Station of Stanford University, Pacific Grove, California

Quantitative video transects of the midwater were made primarily using the ROV *Ventana*, recorded at sea, then annotated in the video laboratory. The time series enables the quantification of long-term ecological patterns relative to a suite of hydrographic measurements, such as oxygen, temperature, and salinity. Extending back almost two decades, these time-series data are uniquely valuable. In 2011, the team completed a database that allows researchers to mine and manipulate an ever-increasing amount of data and variables. Leveraging off the Midwater Ecology project, the team began to explore different camera setups and systems (other than ROV) for collecting imagery and data. Such comparisons will help make the transition from an ROV-based time series to one that is more autonomous.

Mini ROV

Project leads: Dale Graves, Charles Paull, Alana Sherman
Project manager: Dale Graves
Project team: John Ferreira, Frank Flores, Chad Kecy, Tom Marion, Mike Parker
Collaborator: Scott Dallimore, Geological Survey of Canada

This team is developing a portable, low-cost, ROV system that can be sent for launch from ships of opportunity around the world and operated with a small crew. The vehicle is capable of dives to 1,000-meter depths, video transects, instrument deployments and recoveries, and limited sampling. It will have interchangeable tool packages for mission-specific payload and sampling requirements. With partial funding from the Geological Survey of Canada, the vehicle is being built, in part, for expeditions to the Arctic Sea to explore the gas venting and associated seafloor morphologies that develop along the Arctic margin. Essential elements of the ROV were completed in 2011 concluding with successful test-tank trials of the vehicle. Development and testing are to be completed in 2012, prior to a scheduled June expedition to the Arctic.

Modification of In Situ Respirometers for Ocean Acidification Studies

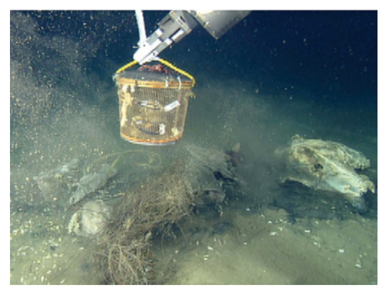
Project leads: James Barry, Kurt Buck, Kim Reisenbichler
Project manager: Bob Herlien
Project team: Craig Okuda, Michael Risi

Two in situ respiration systems were developed to measure the metabolic performance of animals under conditions mimicking those expected under future climate change. One system was designed for studying midwater animals, the other for studying benthic animals. During deployments, respiration rates are measured in each chamber, both with ambient seawater and with water saturated with carbon dioxide or oxygen. Results from respiration-system deployments during 2011 indicate that even though some animals (sea urchins) can live in the core of the oxygen minimum zone, their metabolic rates are limited by the very low oxygen levels found there. Engineering efforts during 2011 in support of the in situ respirometers addressed several technical issues that emerged during the initial deployments of the system. A new "elevator" for transporting the benthic respirometer to the seafloor was designed and built to provide more flexibility in where the instrument can be launched and what gear can be included. The electric pumps were improved and a new method was identified for measuring pH in the chambers. Programming scripts were tested and system documentation was completed.

Molecular Ecology and Evolution

Project lead: Robert Vrijenhoek
Project manager: Shannon Johnson
Project team: Julio Harvey, Roman Marin III, John Ryan, Chris Scholin, Haibin Zhang
Collaborators: Katharine Coykendall, U.S. Geological Survey, Kearneysville, West Virginia; Shana Goffredi, Occidental College, Los Angeles, California; Joe Jones, University of South Carolina, Columbia; Crispin Little, Leeds University, United Kingdom; Mary McGann, U.S. Geological Survey, Menlo Park, California; Victoria Orphan, California Institute of Technology, Pasadena; Karen Osborn, Smithsonian Institution, Washington, D.C.; Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Tom Schultz, Andrew Thaler, and Cindy van Dover, Duke Marine Laboratory, Beaufort, North Carolina; Anders Warén, Swedish National Museum, Stockholm; Yong-Jin Won, Ewha Womans University, Seoul, South Korea

With the completion of 10 years of fieldwork studying whale falls, the research team recovered all deployed experimental equipment in 2011, restoring the sites to natural conditions, as required by the Monterey Bay National Marine Sanctuary. These studies produced many discoveries including a new genus (*Osedax*) of bone-eating worms containing at least 20 species, the worm's growth of complex "roots" that penetrate and digest bones, the colonization of other types of bones by these worms, and a new genus (*Rubyspira*) of bone-eating snails. While previous studies concluded that whale carcasses provide habitats that might persist a half-century or more, this project team found carcasses degrade much faster in the oxygenated waters of Monterey Bay. For example, the carcass of a 20-meter-long blue whale deployed at 1,018 meters depth disappeared in less than eight years. Visiting the site in 2011 revealed very little visual evidence that a dead whale had resided at that location. The deep sea is not necessarily a burial ground for carbon from the upper layers of the ocean. The Monterey whale-fall studies revealed rapid recycling of organic nutrients into the benthic ecosystem. The Molecular Ecology team continued its collaborative studies on assessments of zooplankton diversity and abundance in Monterey Bay, and disparities among different sampling methods such as plankton net tows versus AUV *Dorado* water samples.



An experimental basket of bones hangs from the ROV manipulator arm.

Molecular Probe Chemistries for Investigating Microbial Ecology

Project lead: Chris Scholin
Project manager: James Birch
Project team: Elif Demir-Hilton, Roman Marin III, Christina Preston, William Ussler
Collaborators: Donald Anderson, Woods Hole Oceanographic Institution, Massachusetts; Alexandra Boehm and Kevan Yamahara, Center for Ocean Solutions, Stanford University, California; Laurie Connell, University of Maine, Orono; Edward DeLong and Elizabeth Ottesen, Massachusetts Institute of Technology, Cambridge; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Peter Girguis, Harvard University, Cambridge; Kelly Goodwin, Southwest Fisheries Science Center, La Jolla, California; Raphael Kudela, Julie Robidart, and Jonathan Zehr, University of California, Santa Cruz; Deirdre Meldrum and Cody Youngbull, Arizona State University, Tempe; Mary Ann Moran and Vanessa Varaljay, University of Georgia, Athens; Victoria Orphan, California Institute of Technology, Pasadena; Mark Strom, Northwest Fisheries Science Center, Seattle, Washington; Stephen Weisberg, Southern California Coastal Water Research Project, Costa Mesa, California; Robert Vrijenhoek and the CANON team, MBARI

This project is aimed at developing DNA probe- and antibody-based assays for detecting microorganisms, specific genes, and gene products emphasizing studies of microbial ecology, biogeochemical cycling, and harmful algal blooms. The overall goal is to craft these assays in a way that allows for their application in conventional laboratory settings as well as on autonomous systems such as the Environmental Sample Processor (ESP), but not necessarily restricted to the ESP. This work complements engineering developments and field operations encompassed by the Sensors: Underwater Research of the Future (SURF) Center.

Monterey Bay Time Series

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Gernot Friederich, Jules Friederich, Monique Messié, Reiko Michisaki, Chris Wahl
Collaborator: Marguerite Blum, University of California, Santa Cruz

The 2009-2010 El Niño flipped to La Niña during winter of 2010-11. La Niña faded last spring and summer, but resurged in the winter of 2011-12. Thus the storm track was displaced northwards, Central California was in near drought, and the ocean was cold. Against this background, spring and summer Monterey Bay phytoplankton were abundant and productive, supported by increased upwelling of nutrients. This production will support increased abundance of zooplankton, fishery species, and marine mammals. This project continues to monitor health and change in Monterey Bay and the California Current with cruises, moorings, and gliders. The team supported the Monterey Bay CANON experiments during April, June, and September with drifter deployments and CTD sampling. During these experiments the lab obtained a novel platform, a Wave Glider from Liquid Robotics. In October the lab participated in the CANON 2011 cruise aboard the R/V *Western Flyer*, and conducted drift experiments in both oligotrophic and mesotrophic waters, supported by a several-week deployment of the long-range AUV *Tethys*. And finally, the lab has been building and deploying pCO_2 moorings to monitor ocean pH along the west coast of North America.

Mooring Maintenance

Project leads: Francisco, Chavez, Kevin Gomes, Mike Kelley
Project manager: Mike Kelley
Project team: Paul Coenen, Dave French, Craig Okuda, Erich Rienecker, Rich Schramm
Collaborators: Curtis Collins, Naval Postgraduate School, Monterey, California; Mary Silver, University of California, Santa Cruz

MBARI moorings, which provide time-series observations, are considered model systems for the network of coastal observatories planned for U.S. coastal waters. A number of MBARI scientists as well as outside institutions use data from the moorings. The moorings also serve as platforms for specific scientific investigations and instrument development. In 2011, a new hybrid M2 mooring was deployed in collaboration with the National Data Buoy Center. The M0 and M2 moorings were recovered in 2011, with no plans for further deployments.

Mooring Technology Collaboration

Project leads: Mark Chaffey, Andy Hamilton
Project manager: Mark Chaffey
Collaborator: Yannick Aoustin, French Research Institute for Exploration of the Sea, Brest

The purpose of this project is to support a proposal by the French Research Institute for Exploration of the Sea (IFREMER) for full European funding of an MBARI Ocean Observing System (MOOS)-type mooring system in the Atlantic Ocean. MBARI has collaborated with IFREMER to transfer knowledge and techniques of designing, modeling, and testing mooring riser cables. The second aspect of this project is an internal MBARI effort to qualify a new cable design based on high-modulus fibers that are more resistant to low-tension bending. The goal is to increase mooring-cable fatigue life from 18 to 36 months using new materials and methods, and to qualify additional cable vendors, while simultaneously conducting technology transfer. The cable testing is nearing completion. The design study was completed and the results were presented to IFREMER.

Monterey Ocean Observing System (MOOS) Upper Canyon Experiment

Project leads: James Barry, Charles Paull
Project manager: Mark Chaffey
Project team: John Ferreira, Kent Headley, Mike Kelley

All of the mooring system hardware was recovered from the upper Monterey Canyon site by the end of the year. This was a major setback to the project which had previously delivered high-quality data and had just missed a major Monterey Canyon turbidity event. The move to the shallower canyon experiment site had produced more stress on the anchor system and a previously unknown failure mode was discovered. Based on analyzing the environmental data and extensive numerical simulation, the team concluded that the shorter cable length at the new site, coupled with more surface wave energy, accelerated the friction-wear of the release link. The experiment did demonstrate that all of the major mooring electronic, communications, and data systems are fully mature, and that heavy maintenance and repair operations could be undertaken while at sea. The team also gained important experience for future work in modeling, designing, installing, and maintaining ocean observatories.

Observatory Middleware Framework (OMF)

Project leads: Kevin Gomes, Carlos Rueda
Project manager: Duane Edgington
Collaborators: Randal Butler, Terry Fleury, and Von Welch, National Center for Supercomputing Applications, University of Illinois, Urbana-Champaign

The prototype implementation of a generalized OMF was completed to integrate in situ sensors and demonstrate inter-observatory coordination and management for science applications. With funding from the National Science Foundation, the team designed and implemented a comprehensive performance evaluation and tuning of the OMF prototype. The evaluation enabled assessment of the impact of the various components and processing steps of the framework in a number of scenarios, including basic and secure message routing, and also identified critical bottlenecks, which were addressed successfully, resulting in dramatic overall performance improvement.

The O-Buoy Network of Chemical Sensors in the Arctic Ocean

Project lead/manager: Francisco Chavez
Project team: Gernot Friederich, Jules Friederich, Chris Wahl
Collaborators: Patricia Matrai, Bigelow Laboratory for Ocean Sciences, Boothbay Harbor, Maine; Don Perovich, U.S. Army Cold Regions Research and Engineering Laboratory, Hanover, New Hampshire; Paul Shepson, Purdue University, West Lafayette, Indiana; William Simpson, University of Alaska, Fairbanks

A total of six O-buoys have been moored in the ice of the Arctic Ocean to measure a wide variety of atmospheric gases and conditions. The information is provided in near real time to a variety of users. As part of the project MBARI has developed a low-cost, high-precision system for measuring the partial pressure of carbon dioxide in the atmosphere and deployed it on the existing O-buoys. The team began developing the capability to add sensors to detect CO_2, pH, oxygen, fluorescence, temperature, and salinity.

Ocean Margin Ecosystems Group for Acidification Studies (OMEGAS)

Project lead/manager: Francisco Chavez
Project team: Gernot Friederich, Jules Friederich, Chris Wahl
Collaborators: Jack Barth, Francis Chan, and Bruce Menge, Oregon State University, Corvallis; Steve Palumbi, Hopkins Marine Station of Stanford University, Pacific Grove, California; Brian Gaylord, Tessa Hill, Ann Russell, and Eric Sanford, University of California, Davis; Pete Raimondi, University of California, Santa Cruz; Margaret McManus, University of Hawaii, Manoa; Carol Blanchette, Gretchen Hofmann, and Libe Washburn, University of California, Santa Barbara

Working along the U.S. West Coast, the OMEGAS consortium is in the second year of a two-year field and laboratory, multi-site investigation of the ecological, physiological, and evolutionary responses of sea urchins and mussels to spatial and temporal variation in ocean acidification. Research to date has documented a dynamic oceanographic feature in the inner shelf of the California Current System that spans more than 1,200 kilometers and varies at tidal, diurnal, event, and seasonal temporal scales at local to ocean-basin spatial scales. MBARI provided the pH sensors used at intertidal sites from Oregon to Santa Barbara.

Ocean Observatories Initiative (OOI) Cyberinfrastructure (CI)

Project lead/manager: Duane Edgington
Project team: Kevin Gomes, Bob Herlien, Tom O'Reilly, Carlos Rueda, Brian Schlining

MBARI is participating in the design and implementation of the cyberinfrastructure system that integrates and presents the various aspects of the Ocean Observatory Initiative, a National Science Foundation-funded environmental observatory effort that covers a diversity of oceanic environments, ranging from coastal to the deep ocean. The MBARI team participated in design and construction of the sensing and acquisition, data management, and common operating infrastructure subsystems of the OOI-CI. The MBARI team participated in several design review sessions, evaluated the concepts put forward by the OOI-CI team against its experience with ocean observatories, and provided documentation, reports, source code, and design artifacts for technologies that were developed at MBARI. The team developed a prototype to enable communication between instruments and the CI, thus allowing the OOI-CI project to leverage the extensive and widely tested instrument driver set provided by MBARI's Software Infrastructure and Applications for MOOS. The team also contributed to the development of core CI modules.

Pelagic-Benthic Coupling and the Carbon Cycle

Project leads: Alana Sherman, Ken Smith
Project manager: Alana Sherman
Project team: Larry Bird, David Caress, Jake Ellena, Rich Henthorn, Brett Hobson, Linda Kuhnz, Paul McGill, Brian Schlining
Collaborators: Jeffrey Drazen, University of Hawaii, Manoa; Amanda Kahn, University of Alberta, Canada; Henry Ruhl, University of Southampton, United Kingdom; Tim Shaw, University of South Carolina, Columbia; Stephanie Wilson, Bangor University, United Kingdom

In 2011 the Benthic Rover was deployed for long time-series measurements of sediment community oxygen consumption for high-resolution temporal comparisons with food supply measured with sediment traps in the overlying water. Over the past year, the team has recorded the largest seasonal flux of particulate matter sinking to the seafloor in the past 23 years. They continue to examine possible correlations with climate indices and surface-ocean production. They are also working on increasing the longevity of the monitoring instrumentation to reduce ship-time support.

Precision Control Technologies for ROVs and AUVs

Project leads: Rob McEwen, Michael Risi, Steve Rock
Project manager: Steve Rock
Project team: David Caress, Brett Hobson, Charles Paull, Hans Thomas

One of the key capabilities required to enable the monitoring of changes on the seafloor is the ability to return to a particular site with an ROV or an AUV for repeat imaging or sampling. This project aims to overcome navigational problems that make such repeat imaging difficult. Engineers have adapted and extended a navigation approach that employs terrain-relative adjustments to eliminate the navigation error, a process referred to as Terrain Relative Navigation (TRN). In this approach, rather than surfacing to obtain a global positioning (latitude/longitude) navigation correction, the vehicle instead determines its position by correlating measured terrain contours against a stored on-board bathymetry map. A significant milestone in 2011 was a successful demonstration of using only TRN to return to a site in Soquel Canyon repeatedly using both the mapping AUV and the imaging AUV.

Renewable At Sea Power/PowerBuoy

Project lead/manager: Andrew Hamilton
Project team: James G. Bellingham, Francois Cazenave, Jon Erickson, Brett Hobson, Scott Jensen, Brian Kieft, Rob McEwen, Paul McGill, Wayne Radochonski

The self-contained wave-energy harvesting device under development for this project will be used to provide more electricity to remote instrumentation than is possible with wind or solar energy. In 2011 the project team completed the design, build, and test of the power-converter element. The element was then incorporated into a prototype system that successfully generated electricity in several field tests. Additionally, a docking station for the long-range autonomous underwater vehicle is being developed to allow AUVs to be recharged with energy harvested from the waves.

Salmon Applied Forecasting, Assessment, and Research Initiative (SAFARI)

Project lead/manager: Francisco Chavez
Project team: Monique Messié, Reiko Michisaki
Collaborators: Steven Bograd and David Foley, Southwest Fisheries Science Center, Pacific Grove, California; Eric Danner, John Field, Steve Lindley, Bruce MacFarlane, and Brian Wells, Southwest Fisheries Science Center, Santa Cruz, California; William Peterson, Southwest Fisheries Science Center, Newport, Rhode Island; Jarrod Santora and William Sydeman, Farallon Institute for Advanced Ecosystem Research, Petaluma, California

Since the collapse of the salmon fisheries in 2007, salmon has become a primary focus of ecosystem-based management for the U.S. This project, now in its third year, brings together salmon specialists, modelers, and oceanographers to understand and predict salmon dynamics off California. Remote and in situ data were used to develop dynamic habitat models for salmon based on krill abundance, sea level, and wind data. The forecast model for Chinook salmon, previously based on statistical regressions of the number of fish returning to rivers the year before, has been considerably improved by the SAFARI team. In addition, new models were developed that use krill and sea-level data to provide an assessment of future salmon conditions up to three years in advance. Improving the predictions using a coupled physical/biological model capable of forecasting oceanic conditions nine months in advance is being explored.

Salmon Ecosystem Simulation and Management Evaluation (SESAME)

Project lead/manager: Francisco Chavez
Project team: Monique Messié, Reiko Michisaki
Collaborators: Fei Chai, University of Maine, Orono; Yi Chao, Remote Sensing Solutions, Barnstable, Maine; Eric Danner, Steve Lindley, and Brian Wells, Southwest Fisheries

Science Center, Santa Cruz, California; David Foley and Frank Schwing, Southwest Fisheries Science Center, Pacific Grove, California; Robert Nisbet, University of California, Santa Barbara

This follow-up of the SAFARI project began in late 2011. While the primary focus of SAFARI was on marine ecosystems, Chinook salmon also depend on river and estuarine ecosystems. The physical-biological oceanic model developed under SAFARI will be coupled to models of the San Francisco estuary and the upper Sacramento River. Corresponding physical (temperature) and biological (food supply) solutions will be used to compile a dynamic energy budget for Chinook salmon. The resulting coupled models will be used to explore what drives variation in salmon growth and maturation, and the potential impacts of current and future water management, climate variability and global change.

Sedimentation Event Sensor

Project leads: Paul McGill, Ken Smith
Project manager: Paul McGill
Project team: Larry Bird, John Ferreira, Rich Henthorn, Brett Hobson, Denis Klimov, Alana Sherman

The Sedimentation Event Sensor (SES) collects sinking particulate matter on a one-inch-diameter sample slide at the base of a large funnel, and then records images and fluorescence measurements of the sample material before cleaning the slide in preparation for the next sample. This is in contrast to a conventional sediment trap, which collects material in a limited number of sample bottles that must then be analyzed in a laboratory after the instrument is recovered from the ocean. The SES was originally built in Ken Smith's lab when he was at Scripps Institution of Oceanography. The MBARI project team upgraded all of the SES electronics, improving the sensors and lowering the power consumption to allow the instrument to be deployed autonomously on battery power. The SES was tested on the MARS cable in 2011. A problem with the slide-handling mechanism was identified, analyzed, and rectified. The final test deployment was successful and the instrument is scheduled for deployment at a depth of 4,000 meters in 2012.

Self-Contained Plankton Imager

Project lead: Steven Haddock
Project manager: Alana Sherman
Project team: Mark Chaffey, Dale Graves, Julio Harvey, Brett Hobson, Chad Kecy, Michael Risi, Ken Smith

To better quantify how zooplankton are changing over time, this project is developing a small, lightweight, autonomous plankton-imaging system. The system will be self-powered and require no external tether, so that it can be deployed on moorings, piers, autonomous vehicles, and ships. Programmed prior to deployment, images will be taken at fixed intervals and stored locally. Scientific requirements have been gathered from potential users, and from these, a list of functional requirements have been compiled. Several off-the-shelf cameras are undergoing evaluation and underwater testing is in progress. A controller board with a simple, but powerful, microprocessor will interface the camera, a lighting source, and digital storage. The software will be open source to allow for end-user modification. Documentation of the resulting product will be available via the web as an interactive document to allow for easy replication at other institutions.

Technology Transfer: Observatory Software

Project manager: Duane Edgington
Project team: Kevin Gomes, Kent Headley, Bob Herlien, Tom O'Reilly

Several collaborations continued to transfer MBARI observatory technologies—software infrastructure and applications middleware (SIAM), plug-and-work protocol (known as PUCK), Shore-Side Data System (SSDS), and OASIS mooring technology—to external observatory projects, industry groups, and standards organizations. MBARI's PUCK protocol was formally adopted by the Open Geospatial Consortium (OGC) as part of their Sensor Web Enablement standards. PUCK defines a standard protocol for retrieving the information needed to operate an instrument from the device itself, thus enabling automatic "plug-and-work" functionality. In 2011, MBARI and the University of Hawaii successfully installed both SIAM and SSDS on the ALOHA cabled observatory and are using both systems to manage deployed instruments and the data coming from those instruments. SIAM documentation was updated and revised and made publicly available at http://www.mbari.org/moos/siam/docs/. In New Zealand a long-term, real-time monitoring system was developed and deployed off the South Island. The "TASCAM" mooring system was a collaborative effort by Tasman District Council, Cawthron Institute (an oceanographic institution in New Zealand), and MBARI. Cawthron designed the new buoy based on technology used on MBARI's moorings in Monterey Bay. MBARI contributed mechanical drawings, software, and OASIS mooring-controller electronics. This electronics package collects the data from all the different instruments and then sends this data back to shore in a useable form.

Mooring system in Tasman Bay, New Zealand.

Time-Lapse Camera

Project lead/manager: Dale Graves
Project team: Dave French, Michael Risi

A state-of-the-art time-lapse controller board was packaged with a high-resolution camera to provide MBARI scientists with 12-megapixel digital still pictures and time-lapse high-definition video. The system can be transported and deployed with a remotely operated vehicle. To assure optimal images, once the system has been deployed, the ROV can plug in to the camera system to transmit real-time images back to the ship, so that the crew can adjust lighting, framing, and focus. The time-lapse camera system is rated to 4,000 meters.

Using Learned Models to Improve Decision Support in CANON

Project lead: Maria Fox, Kanna Rajan
Project manager: Thom Maughan
Project team: Mike Godin, Frederic Py, Yanwu Zhang
Collaborators: Derek Long and Daniele Magazzeni, King's College London, United Kingdom

This project investigated using machine learning and model composition techniques on an AUV coordinated with the shore-side Oceanographic Decision Support System (ODSS). This effort explored design options that could be targeted to the long-range AUV. For the field experiment, the choice was made to use the *Dorado* AUV using the distributed autonomy approach with onboard planning via T-REX software connected to the shore-side agent running in the ODSS. The experiment tested a learned plan-based policy for controlling the path of an AUV tracking the perimeter of an algal bloom. The *Dorado* AUV successfully tracked sections of the perimeter of the selected algal patch in a manner suitable for collecting science-rich samples using sampling algorithms driven by AUV science sensors to fire the water samplers. The results of the test will be analyzed to determine whether the policy-based approach merits further development.

Video Annotation and Analysis Presentation (VAAP)

Project leads: Steven Haddock, Charles Paull, Brian Schlining
Project manager: Nancy Jacobsen Stout
Project team: Erica Curles, Linda Kuhnz, Lonny Lundsten, Kyra Schlining, Susan von Thun

The primary goal of this system is to present MBARI scientists with a multifaceted tool for exploring the extensive annotations database, which currently comprises nearly four million deep-sea observations. An internal web application, the Deep-Sea Guide, now provides search and display capabilities for descriptive and visual information about the animals and underwater features. Dynamically created results deliver data to users in several modes—taxonomic tree browsing, image galleries organized by keyword or hierarchically, and comparison tables which can be used to differentiate one species from another. In addition, a series of data-analysis techniques have been systematically applied to the observational data in order to create meaningful data products. These snapshots allow researchers to efficiently monitor and investigate temporal, spatial, and environmental trends and conditions for individual species or any group of related animals. The VAAP system is now actively being used as a prototype onshore and at sea.

Video Monitoring of Adult Fish Ladder Modifications to Improve Pacific Lamprey Passage at the McNary Dam Oregon Shore Fishway

Project lead/manager: Danelle Cline
Project team: Duane Edgington
Collaborators: Frank Loge and Donald Thompson, University of California, Davis

Pacific lamprey are an important ceremonial food for Native American tribes in the Columbia River basin. The decline of Pacific lamprey populations is a growing concern for tribal, state, and federal agencies. Recovery of the dwindling populations of lamprey depends on improving their successful passage through hydropower projects as they migrate upstream to spawning grounds. The goal of this work is to generate rigorous quantitative estimates of adult Pacific lamprey, using video and MBARI's Automated Visual Event Detection and Classification software. This collaborative effort with the University of California, Davis, made significant improvements to data processing time and to implementation of classification algorithms based on fish shape and motion.

Zooplankton Biodiversity and Biooptics in the Deep Sea

Project lead/manager: Steven Haddock
Project team: Lynne Christianson

Biodiversity studies of ctenophores, siphonophores, radiolarians, and hydromedusae were advanced by both morphological and molecular studies. Morphological data included observations on a new family of ctenophores, unique in its behavior and method of capturing prey. Molecular data for examining diversity and interrelationships of species were generated for three new genes on 96 samples each of ctenophores and of siphonophores, along with several dozen specimens of hydromedusae and deep-sea radiolarians. The results of these studies will be important for establishing baselines for marine communities, and evaluating the true extent (and potential changes) of biodiversity of the open ocean, by far the earth's largest habitat. The lab is also involved in public education and citizen science through the Jellywatch.org web page. This site is dedicated to monitoring trends in ocean health and ecology, particularly through the timing and occurrence of jellyfish blooms. It has collected well over 1,000 sightings since its launch in 2010.

Awards

Steven Haddock, Susan von Thun

Honorable mention, National Science Foundation's 2011 International Science and Engineering Visualization Challenge

Andreas Hofmann, Ed Peltzer, Peter Walz, and Peter Brewer

"Hypoxia by Degrees" cited by Faculty of 1000 as a "must read" paper and as one of the top seven papers in ecology in 2011.

Ken Johnson

Elected Fellow, American Geophysical Union

Alexandra Z. Worden

Scholar, Canadian Institute for Advanced Research Integrated Microbial Biodiversity Program

Environmental Sample Processor Team

(James Birch, Judith Connor, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, Chris Scholin)

Federal Laboratory Consortium Award for Excellence in Technology Transfer awarded to Lawrence Livermore National Laboratory and MBARI.

David Packard Distinguished Lecturer Carl Wunsch

MBARI President and Chief Executive Officer Chris Scholin presents Professor Carl Wunsch a medal to commemorate his 2011 David Packard Distinguished Lecture on climate and sea-level change. MBARI's distinguished lecturer program was established to recognize outstanding performance in marine science and engineering. Wunsch is the Cecil and Ida Green Professor of Physical Oceanography at the Massachusetts Institute of Technology. In 2006, Wunsch received the William Bowie Award, the highest honor of the American Geophysical Union, which recognized Wunsch as "a visionary in the study of the ocean and its roles in climate change" and for developing new tools and strategies for observing the ocean.

Invited Lectures

James P. Barry

Stanford University, California

Morro Bay Museum of Natural History, California

American Association for the Advancement of Science, Washington, D.C.

Naval Postgraduate School, Monterey, California

Lockheed Martin Advanced Technology Center, Palo Alto, California

University of California, Santa Cruz

Second International Marine Conservation Congress, Victoria, Canada

Stazione Zoologica di Napoli, Italy

Monterey Bay Aquarium, Monterey, California

NOAA Ocean Acidification Education Workshop, Marin Headlands, California

Hopkins Marine Station of Stanford University, Pacific Grove, California

California State Legislature, Sacramento, California

American Fisheries Society, Seattle, Washington

Biological Impacts of Ocean Acidification, Bremen, Germany

Environmental Law Conference at Yosemite, Fish Camp, California

SpectorDance, Marina, California

Society for Conservation Biology Think Tank, Auckland, New Zealand

National Institute of Water and Atmospheric Research, Wellington, New Zealand

James G. Bellingham

Naval Postgraduate School, Monterey, California

San Jose State University, California

Massachusetts Institute of Technology, Cambridge

Monterey Bay National Marine Sanctuary Symposium, Seaside, California

Global Earth Observing System of Systems, Kona, Hawaii

University of Rhode Island, Kingston

Chinese Academy of Sciences, Beijing

Tongji University, Shanghai, China

Shanghai Jiao Tong University, China

Zhejiang University, Hangzhou, China

University of Bremen, Germany

Peter Braccio

Conference Chair, Special Interest Group on Computer Graphics and Interactive Techniques, Vancouver, Canada

Peter G. Brewer

International Panel on Climate Change Workshop, Okinawa, Japan

Monterey Institute of International Studies, California

Plenary Lecture, Canadian Meteorological and Oceanographic Society, Vancouver, Canada

David Caress

University of Bremen, Germany

American Geophysical Union, San Francisco, California

Mark Chaffey

French Research Institute for Exploration of the Sea, Brest

Francisco Chavez

American Society of Limnology and Oceanography, San Juan, Puerto Rico

Ocean Carbon and Biogeochemistry Workshop, Woods Hole, Massachusetts

Moss Landing Marine Laboratories, California

National Aeronautics and Space Administration, Washington, D.C.

Club FARO de Vigo, Spain

Universidad de Vigo, Spain

University of Porto, Portugal

Centro de Investigação Marinha e Ambiental, Porto, Portugal

Laboratoire d'Océanographie de Villefranche, France

Institut de Recherche pour le Développement, Sete, France

EUR-OCEANS Conference, Toulouse, France

Instituto de Ciencias Marinas, Barcelona, Spain

Pacific Grove Museum of Natural History, California

David Clague

University of California, Berkeley

American Geophysical Union, San Francisco, California

Judith Connor

Monterey Bay Aquarium, Monterey, California

University of California, Berkeley

Stanford University, California

Point Lobos State Reserve, Carmel, California

Fulbright Scholars, Monterey, California

Federal Laboratory Consortium Far West Region, Monterey, California

Sergey Frolov

Gordon Research Conference on Coastal Ocean Modeling, Mount Holyoke, Massachusetts

United States Geological Survey, Menlo Park, California

Naval Research Laboratory, Monterey, California

Kim Fulton-Bennett

Science Communications and Marine Public Information, Washington, D.C.

Steven Haddock

California College of the Arts, San Francisco

California State University, Monterey Bay

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

Coastal Marine Biolabs, Ventura, California

The Evergreen State College, Olympia, Washington

Hopkins Marine Station of Stanford University, Pacific Grove, California

California Mathematics Engineering Science Achievement, University of California, Santa Cruz

American Society of Limnology and Oceanography, San Juan, Puerto Rico

Hendrik Jan Ties Hoving

Oregon Institute for Marine Biology, Charleston

Ken Johnson

Stanford University, California

Argo Oxygen Workshop, Brest, France

University of Gothenburg, Sweden

Center for Microbial Oceanography: Research and Education, Honolulu, Hawaii

Hopkins Marine Station of Stanford University, Pacific Grove, California

U.S. Ocean Carbon and Biogeochemistry Summer Workshop, Woods Hole, Massachusetts

Surface Ocean Lower Atmosphere Study/Integrated Marine Biogeochemistry and Ecosystem Research, Paris, France

Observatoire Midi-Pyrénées, Toulouse, France

Microlaboratoire d'Analyses In Situ pour des Observatoires Environnementaux Workshop, Toulouse, France

Shannon Johnson

Aquarium of the Pacific, Long Beach, California

University of California, Santa Cruz

Keynote Address, Expanding Your Horizons Conference, Monterey, California

George I. Matsumoto

California State University, Monterey Bay

Monterey Bay Aquarium, Monterey, California

Seldovia Tribal Marine Science Workshop, Alaska

Lawrence Hall of Science, Berkeley, California

The Tech Museum, San Jose, California

Alaska Marine Science Symposium, Anchorage

Jennifer Paduan

American Geophysical Union, San Francisco, California

Charles Paull

Long Marine Laboratory, University of California, Santa Cruz

Canadian Geohazards Workshop, Sidney

Korean Institute of Geoscience and Mineral Resources, Daejon

Gordon Conference on Polar Science, Ventura, California

California State University, Fresno

Seventh International Conference on Gas Hydrates, Edinburgh, Scotland

Geological Society of America, Minneapolis, Minnesota

American Geophysical Union, San Francisco, California

U.S. Science Support Program Associated with the Integrated Ocean Drilling Program, San Francisco, California

Edward Peltzer

EUR-Oceans Conference on Ocean Deoxygenation and Implications for Marine Biogeochemical Cycles and Ecosystems, Toulouse, France

Kanna Rajan

Association for the Advancement of Artificial Intelligence Spring Symposium, Stanford, California

University of California, Berkeley

Honda Research Institute, Mountain View, California

National University of Singapore Tropical Marine Science Institute

Shenyang Institute of Automation, Chinese Academy of Sciences

Centre for Artificial Intelligence and Robotics, Defence Research and Development Organization, Bangalore, India

Robotics Sciences and Systems Conference, Los Angeles

International Conference on Intelligent Robots and Systems, San Francisco, California

IEEE Workshop on Advanced Robotics and its Social Impacts, Half Moon Bay, California

Council of European Aerospace Societies, Venice, Italy

Polytechnic University of Cartagena, Spain

IBM Research, Delhi, India

National Institute of Ocean Technology, Chennai, India

Indian Institute of Technology, Madras

Bruce Robison

Steinbeck Institute Lecture, Salinas, California

California State University, Monterey Bay

Scripps Institution of Oceanography, La Jolla, California

Steve Rock

University of California, Berkeley

John Ryan

Workshop on Transatlantic Research and Development Collaboration Connected to Oil Spills in Arctic Waters, Houston, Texas

Alliance for Coastal Technologies Workshop on Aquatic Sampling Technologies, Monterey, California

LatMix Synthesis Workshop, Stanford, California

Christopher Scholin

U.S. Department of Energy Joint Genome Institute, Walnut Creek, California

University of Southern California, Los Angeles

Ocean Carbon and Biogeochemistry Workshop, Woods Hole, Massachusetts

Hopkins Marine Station of Stanford University, Pacific Grove, California

Tongji University, Shanghai, China

Zhejiang University, Hangzhou, China

Chinese Academy of Sciences, Bureau of High-Technology Research and Development, Beijing

Shanghai Jiao Tong University, China

Alana Sherman

Keynote Address, Expanding Your Horizons Conference, Monterey, California

Josi Taylor

Dissertations Initiative for the Advancement of Climate Change Research VI Scholars Symposium, Colorado Springs, Colorado

NOAA Office of Ocean Exploration and Research Teacher Workshop, La Jolla, California

Girls in Ocean Science Conference, The Ocean Institute, Dana Point, California

Expanding Your Horizons Conference, Monterey, California

William Ussler

Deep Sea and Sub-Seafloor Frontier Meeting, Grenoble, France

Rifle Integrated Field-Scale Subsurface Research Challenge planning meeting, Carmel, California

Robert C. Vrijenhoek

Korea Ocean Research and Development Institute, Ansan

Plenary Lecture, Dasan Conference, GyeongJu, South Korea

University of Vienna, Austria

National Museum of Natural History, Washington, D.C.

Pennsylvania State University, State College

Alexandra Z. Worden

Microbial Diversity Institute, Yale University, New Haven, Connecticut

Plant Genomes and Biotechnology: From Genes to Networks Meeting, Cold Spring Harbor Laboratory, New York

European Molecular Biology Conference on Comparative Genomics of Eukaryotic Microorganisms, Sant Feliu de Guixols, Spain

University of California, Santa Cruz

Phycological Society of America, Seattle, Washington

University of Hawaii, Honolulu

111th General Meeting American Society of Microbiology, New Orleans, Louisiana

Yanwu Zhang

AUV-Based Technologies in Offshore Oil and Gas Monitoring Workshop, Stavanger, Norway

Marine Technology Society TechSurge Workshop, Sarasota, Florida

Second International Workshop on Seafloor Observation, Shanghai, China

Tongji University, Shanghai, China

Shanghai Jiao Tong University, China

Zhejiang University, Hangzhou, China

Mentorships

James P. Barry

Taewon Kim, postdoctoral fellow (effects of ocean acidification and hypoxia on marine animals)

Tom Knowles, M.S. student, Moss Landing Marine Laboratories (effects of ocean acidification on jellyfish)

Kristy Kroeker, Ph.D. student, Hopkins Marine Station of Stanford University (effects of ocean acidification on marine communities)

Cheryl Logan, Ph.D. student, Hopkins Marine Station of Stanford University (metabolic effects of ocean acidification and hypoxia on marine fishes)

Josi Taylor, postdoctoral fellow (physiological effects of ocean acidification and related environmental changes on marine animals)

James P. Barry, Josi Taylor

Gayani Thilakarathna, graduate summer intern, University of Peradeniya, Sri Lanka (skeletal growth zones as indicators of age in the deep-sea urchin *Strongylocentrotus fragilis*)

James G. Bellingham

Sergey Frolov, postdoctoral fellow (design of optimal observatories for algal bloom monitoring and prediction)

James Birch

Elif Demir-Hilton, postdoctoral fellow (in situ detection and enumeration of microorganisms using the Environmental Sample Processor)

Peter G. Brewer

Andreas F. Hofmann, postdoctoral fellow (chemical and physical limits to aerobic marine life)

Peter G. Brewer, Edward Peltzer

Elizabeth Coward, undergraduate summer intern, Haverford College (rates of CH_4 displacement by a N_2-CO_2 mixture in CH_4 hydrates)

Francisco Chavez

Monique Messié, postdoctoral fellow (study of the Peru upwelling ecosystem, with comparisons to California and other upwelling systems)

Brendan Tougher, graduate summer intern, University of San Francisco (Wave Glider autonomous surface vehicle ocean acidification sensor integration for marine management applications)

Francisco Chavez, Heather Kerkering

Shandy Buckley, graduate summer intern, Moss Landing Marine Laboratories (correlations between satellite and in situ data to see if a proxy for ocean pH could be developed from remotely sensed measurements)

David Clague

Nichelle Baxter, Ph.D. student, University of Florida, Gainesville (origin of near-ridge seamount chains)

Jason Coumans, M.S. student, McGill University (petrologic work on samples collected at Taney Seamounts)

Christoph Helo, Ph.D. awarded, McGill University (explosive submarine volcanism on Axial Seamount N.E. Pacific Ocean, Juan de Fuca Ridge)

Charlotte Humphrey, Ph.D. student, Manchester Metropolitan University (bioerosion of reefal limestones)

Bruce Pauly, Ph.D. awarded, University of California, Davis (in situ micro-analytical investigations of palagonitization)

Ryan Portner, postdoctoral fellow (categorizing volcaniclastic deposits on seamounts)

Isobel Yeo, Ph.D. student, Durham University (formation of pillow ridges along mid-ocean ridges)

Danelle Cline, Duane Edgington

Gregor Bwye, undergraduate summer intern, University of Aberdeen (developing autonomous classification with Eye-in-the-Sea and the Automated Visual Event Detection and Classification system)

Judith Connor

Kevin Miklasz, Ph.D. student, Hopkins Marine Station of Stanford University (biomechanical analysis of algal physiology, ecology and evolution)

Kim Fulton-Bennett

Jane Lee, graduate student intern, University of California, Santa Cruz (science communications)

Amy West, graduate student intern, University of California, Santa Cruz (science communications)

Steven Haddock

Warren Francis, M.S. student, University of California, Santa Cruz (chemistry of marine luminescence)

Kristian McConville, undergraduate summer intern, Highlands Science Specialist School (towards a comprehensive taxonomic key for the phylum Ctenophora)

Amy McDermott, undergraduate student, University of California, Santa Cruz (novel luciferases)

Meghan Powers, M.S. student, University of California, Santa Cruz (novel luciferases)

Nathan Shaner, Helen Hay Whitney postdoctoral fellow (biosynthesis of coelenterazine)

Ken Johnson

Patrick Gibson, postdoctoral fellow (nitrate and ammonia cycling in Elkhorn Slough)

Tanya Novak, M.S. degree awarded, Moss Landing Marine Laboratories (nitrate transport to Monterey Bay: investigating source inputs from Elkhorn Slough)

Linda Kuhnz

Cesar Chavez, high school student, Pajaro Valley High School (effectiveness of wetland animal crossing structures)

David Gonzalez, high school student, Pajaro Valley High School (effectiveness of wetland animal crossing structures)

Dyani Jacobo, high school student, Pajaro Valley High School (native dune habitats)

Vanessa Mata, high school student, Pajaro Valley High School (effectiveness of wetland animal crossing structures)

Jose Ramierez, high school student, Pajaro Valley High School (native dune habitats)

Eddy Reyes, high school student, Pajaro Valley High School (native dune habitats)

Lalli Singh, high school student, Pajaro Valley High School (effectiveness of wetland animal crossing structures)

Esmeralda Toledo, high school student, Pajaro Valley High School (effectiveness of wetland animal crossing structures)

Linda Kuhnz, Alana Sherman, Ken Smith

Erynn Thompson, undergraduate summer intern, West Valley College (investigation of holothurian abundances at Station M)

Lonny Lundsten, Charles Paull

Grant Duffy, graduate summer intern, University of Southampton (megafaunal benthic ecology of the submarine canyons of Southern California)

Julie Martin

Bella Jimenez, high school student, Pajaro Valley High School (biodiversity of benthic invertebrates in South Marsh and Whistle Stop Lagoon)

Rita Medina, high school student, Pajaro Valley High School (biodiversity of benthic invertebrates in South Marsh and Whistle Stop Lagoon)

Jonathan Rincon, high school student, Pajaro Valley High School (biodiversity of benthic invertebrates in South Marsh and Whistle Stop Lagoon)

Joaquin Torres, high school student, Pajaro Valley High School (biodiversity of benthic invertebrates in South Marsh and Whistle Stop Lagoon)

George I. Matsumoto

Aixely Ferreira, high school student, Pajaro Valley High School (aquatic invertebrates: sessile invertebrate diversity in two locations)

Paul Garcia, high school student, Pajaro Valley High School (aquatic invertebrates: sessile invertebrate diversity in two locations)

Xianjia Huang, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville Slough)

Josh Jimenez, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville Slough)

Jorge Juarez, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville Slough)

Aldo Rincon, high school student, Pajaro Valley High School (aquatic invertebrates: sessile invertebrate diversity in two locations)

Karina Zepeda, high school student, Pajaro Valley High School (aquatic invertebrates: sessile invertebrate diversity in two locations)

Thom Maughan, Kanna Rajan

Jeremy Gottlieb, graduate summer intern, University of California, Santa Cruz (ocean front detection)

Charles Paull

Katie Maier, Ph.D. student, Stanford University (AUV surveys of Lucia Chica deep-water channels)

Wayne Radochonski

Meng Cai, graduate summer intern, University of Hawaii at Manoa (characterizing underwater acoustics using the Monterey Canyon sediment tracking acoustic receiver)

Kanna Rajan

Philip Cooksey, undergraduate student, California State University, Monterey Bay (artificial intelligence for ocean engineering and science)

Jnaneshwar Das, Ph.D. student, University of Southern California (probabilistic approaches to patch advection)

Rishi Graham, postdoctoral fellow (distributed autonomy)

Sandeep Kumar, Indian Institute of Technology, Madras (using algorithms for ocean feature detection)

Laximarayan Narasimhan, Ph.D. student, Indian Institute of Technology, Madras (automated planning and execution using Teleo-Reactive Executive)

Jose Pinto, Ph.D. student, University of Porto, Portugal (onboard decision making and control)

William Teck Tan, Ph.D. student, National University of Singapore (sampling and control using AUVs)

Bruce Robison

Hendrik Jan Ties Hoving, postdoctoral fellow (investigating the means to determine the age of deep-living squids and other invertebrates)

Alexis Walker, graduate summer intern, University of California, Santa Cruz (the form and function of the hypertrophied tentacle of deep-sea jelly *Atolla*)

Steve Rock

Sean Augenstein, Ph.D. awarded, Stanford University (feature-based navigation)

Shandor Dektor, Ph.D. student, Stanford University (terrain-based navigation for AUVs)

Sarah Houts, Ph.D. student, Stanford University (terrain-based navigation for AUVs)

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

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

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

Jose Padial, Ph.D. student, Stanford University (feature-based navigation)

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

John Ryan

Ricardo Vicente, M.S. student, Naval Postgraduate School (synthetic aperture radar remote sensing)

Brian Schlining, Nancy Jacobsen Stout

Erica Curles, undergraduate summer intern, University of California, Santa Cruz (advancing MBARI's Deep-Sea Guide)

Christopher Scholin

Kevan Yamahara, Center for Ocean Solutions early career fellow (development of water quality assays for use on the second- and third-generation Environmental Sample Processor)

Alana Sherman, Ken Smith

Mark Miller, undergraduate student, California State University, Monterey Bay (*Sargassum* community time-series structure)

Josi Taylor

Anthony Barrios, high school student, Pajaro Valley High School (effects of ocean acidification on the behavior and physiology of subtidal crabs)

Esteban Guerrero, high school student, Pajaro Valley High School (effect of low pH levels in the ocean on the behavior of Elkhorn Slough snails)

Anyssa Luna, high school student, Pajaro Valley High School (effects of ocean acidification on the behavior and physiology of subtidal crabs)

Mariela Ramirez, high school student, Pajaro Valley High School (effect of low pH levels in the ocean on the behavior of Elkhorn Slough snails)

Margarita Solano, high school student, Pajaro Valley High School (effects of ocean acidification on the behavior and physiology of subtidal crabs)

Ventura Vega, high school student, Pajaro Valley High School (effects of ocean acidification on the behavior and physiology of subtidal crabs)

Anna Zavala, high school student, Pajaro Valley High School (effect of low pH levels in the ocean on the behavior of Elkhorn Slough snails)

Robert Vrijenhoek

Vanessa Rae Flores, graduate summer intern, Humboldt State University (gene flow in a hydrothermal vent tubeworm)

Jenna Judge, Ph.D. student, University of California, Berkeley (evolution of gastropods on chemosynthetic and biogenic substrates)

Erika Raymond, Schmidt Ocean Institute postdoctoral fellow, (development of autonomous fish sampler)

Gillian Rhett, M.S. student, Moss Landing Marine Laboratories (meiofuana at Monterey whale-falls)

Norah Saarman, Ph.D. student, University of California, Santa Cruz (genetics of mussel hybrid zones)

Haibin Zhang, postdoctoral fellow (molecular ecology of marine zooplankton)

Alexandra Z. Worden

Yun-Chi Lin, graduate student, Taiwan (molecular phylogenetics of natural eukaryotic microbial communities)

Darcy McRose, graduate student, Stanford University (the role of vitamins in regulating growth of environmentally relevant *Micromonas* clades)

Melinda P. Simmons, Ph.D. student, University of California, Santa Cruz (conserved introner elements and representation in natural phytoplankton populations)

Shuangchun Yan, postdoctoral fellow (*Micromonas* physiology under different growth conditions and nutrients availability)

Peer-Reviewed Publications

Adams, L.G. and **G.I. Matsumoto** (2011). The benefits and challenges of using real-time data in the classroom: Perspectives from the students, educators, and researchers. *Marine Technology Society Journal*, **45**: 55-58.

Barry, J.P., S. Widdicombe, and J.M. Hall-Spencer (2011). Effects of ocean acidification on marine biodiversity and ecosystem function. In: *Ocean Acidification*, edited by J.-P. Gattuso and L. Hansson. Oxford University Press, pp. 192-209.

Bertrand, A., A. Chaigneau, S. Peraltilla, J. Ledesma, M. Graco, F. Monetti, and **F.P. Chavez** (2011). Oxygen: A fundamental property regulating pelagic ecosystem structure in the Coastal Southeastern Tropical Pacific. *PLoS ONE*, **6**: E29558, doi:10.1371/journal.pone.0029558.

Bolstad, K.S.R. and **H.J.T. Hoving** (2011). Spermatangium structure and implantation sites in onychoteuthid squid (Cephalopoda: Oegopsida). *Marine Biodiversity Records*, **4**: doi: 10.1017/S175526721000120X.

Castro, C.G., C.A. Collins, **J.T. Pennington**, D. Zuniga, and **F.P. Chavez** (2011). Spatial distribution and offshore export of total organic carbon along the eastern boundary of the Subtropical North Pacific. *Advances in Oceanography and Limnology*, **2**: 93-106, doi: 10.1080/19475721.2011.626941.

Cazenave, F., **Y. Zhang**, E. McPhee-Shaw, **J.G. Bellingham**, and T.P. Stanton (2011). High-resolution surveys of internal tidal waves in Monterey Bay, California, using an autonomous underwater vehicle. *Limnology and Oceanography: Methods*, **9**: 571-581, doi: 10.4319/lom.2011.9.571.

Cazenave, F., R. Zook, D. Carroll, S. Kim, and M. Flagg (2011). Development of the ROV SCINI and deployment in McMurdo Sound, Antarctica. *Journal of Ocean Technology*, **6** (3): 39-58.

Ceballos, A., S. Bensalem, A. Cesta, L. de Silva, S. Fratini, F. Ingrand, J. Ocón, A. Orlandini, **F. Py**, **K. Rajan**, R. Rasconi, and M. van Winnendael (2011). A goal-oriented autonomous controller for space exploration. In: *Proceedings of the 11th Symposium on Advanced Space Technologies in Robotics and Automation*, the European Space Agency/European Space Research and Technology Centre, Noordwijk, the Netherlands.

Chavez, F.P., **M. Messié**, and **J.T. Pennington** (2011). Marine primary production in relation to climate variability and change. *Annual Review of Marine Science*, **3**: 227-260, doi: 10.1146/annurev.marine.010908.163917.

Clague, D.A., **J.B. Paduan**, **D.W. Caress**, **H. Thomas**, W.W. Chadwick Jr., and S.G. Merle (2011). Volcanic morphology of West Mata Volcano, NE Lau Basin, based on high-resolution bathymetry and depth changes. *Geochemistry, Geophysics, Geosystems*, **12**: QOAF03, doi: 10.1029/2011GC003791.

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Project manager: Nancy Barr
Project team: Judith Connor, Patricia Duran, Mariah Salisbury, Chris Scholin
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On the cover: To learn how a more acidic ocean will affect deep-sea life, sea urchins (*Strongylocentrotus fragilis*) are placed in controlled chambers to which additional carbon dioxide is added. These tests are conducted at sea with the Free Ocean Carbon Dioxide Enrichment (FOCE) apparatus and the Benthic Respirometry System, and in the laboratory, where these animals were photographed by Todd Walsh. See stories on pages 12, 40, and 45.

Back cover: The container in which the urchins' movements will be closely observed is loaded into the FOCE apparatus, which is attached to the MARS cabled observatory in Monterey Bay. See story page 12.

Inside front cover: Divers Erich Rienecker (foreground) and Kim Reisenbichler jump from the stern of the research vessel *Zephyr* to set up the power buoy, which is designed to harvest energy from waves. Aboard the ship are, from left, Jim Boedecker, Perry Shoemake, and Mike Kelley. See story page 48. *Photo by Paul McGill.*

Inside back cover: After serving as MBARI's workhorse research vessel for almost 24 years, the *Point Lobos* conducted its last science mission on December 1, 2011. See pages 2 and 35. *Photo by Kim Fulton-Bennett.*

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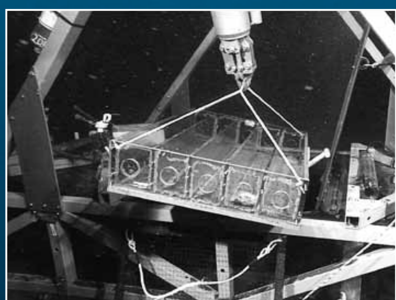

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Monterey Bay Aquarium Research Institute

7700 Sandholdt Road
Moss Landing, CA 95039-9644
831.775.1700
www.mbari.org