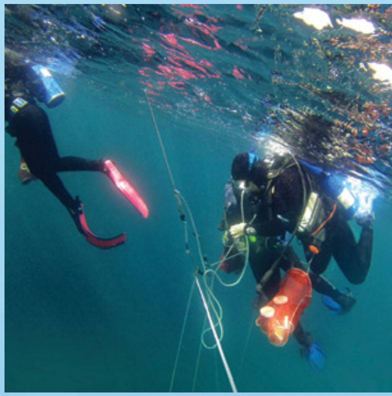
25TH ANNIVERSARY

MBARI

Monterey Bay Aquarium Research Institute

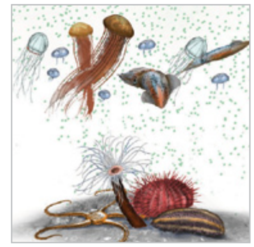
2012 ANNUAL REPORT



The first 25 years

This mosaic of MBARI Founder David Packard was printed as a large banner in celebration of the institute's 25th anniversary in 2012. The individual tiles represent MBARI's first 25 years of discovery, development, research, and growth. The mosaic was generated with AndreaMosaic software. An interactive version, in which close-ups of each individual tile can be seen, is available at http://www.mbari.org/about/history/Packard/Packard_MBARI_25years.htm

Table of Contents



View From the Masthead

This past year marked a number of significant milestones for MBARI. First, plans made in 2010 to retire MBARI's coastal class ships, the *Point Lobos* and *Zephyr*, and replace them with a single vessel finally came to fruition. That decision was based on the evolving needs of the institute and economic forces, both of which dictated flexible and cost-effective operations for working locally as well as far from home.

For many of us at MBARI, the retirement of the *Point Lobos* and *Zephyr* marked a watershed moment for the institute. The *Point Lobos* was MBARI's first ship and, in many ways, our mascot. It served to kick-start what became long-running programs grounded in remotely operated vehicle (ROV) technology, development of new sensor systems, and chemical and biological investigations that range from the sea surface to the seafloor. During its 24 years of service, mostly in Monterey Bay, the *Point Lobos* ushered in a host of discoveries and technology developments that raised MBARI's visibility and credibility. Likewise, the *Zephyr* played host to a number of MBARI's flagship projects—notably, our autonomous underwater vehicle (AUV) development effort. The *Zephyr's* ability to travel up and down the coast, venturing from Mexico to Canada and far offshore, was a huge boost in propelling many unforeseen applications of the AUV.

Those storied ships have now been replaced by the *Rachel Carson*. That vessel will allow us to continue and enhance our ROV and AUV operations, as well as other science and engineering programs, and to travel beyond the confines of Monterey Bay when necessary. The combination of flexibility and range is the cornerstone on which we aim to build our future seagoing capabilities.

Celebrating our 25th anniversary marked another major milestone in 2012. David Packard formalized MBARI's founding in the spring of 1987 with a vision that we would enhance our knowledge of the ocean and pursue exploration of the deep sea in innovative ways. Packard sought to foster true partnerships among scientists and engineers who would design, build, and use novel instruments and systems. Marine operators who sail our ships, pilot our vehicles, and manage other at-sea equipment were also integral to this equation, to help spur discovery and innovation in ways that would set MBARI apart from traditional oceanographic institutions. To commemorate the anniversary of his vision, an image of Packard was converted into a mosaic of photos that document snapshots of MBARI's 25-year history (see inside cover). The poster was released midyear in conjunction with our annual open house. The event drew one of the largest crowds ever as the general public came to learn more about what we do and to witness Julie Packard, chair of our board and daughter of David and Lucile Packard, formally christen the *Rachel Carson*. It was a fabulous moment. One of the guests in attendance aptly and enthusiastically noted, "This is history in the making!"

The christening of the R/V *Rachel Carson* near the 50th anniversary of the release of Rachel Carson's book, *Silent Spring*, was a coincidence. Nevertheless, Carson's vivid portrayal of the inextricable link between human

Twenty-five years ago, MBARI's headquarters were located at 160 Central Avenue, Pacific Grove, California.

activities and the living world around us was not lost. The present-day debate surrounding climate change and ocean acidification are potent reminders of that fact. Carson's personal scientific achievements, as a pioneer among women scientists, and her call for environmental awareness, were ultimately the factors that inspired us to name our new coastal vessel after her.

The confluence of anniversaries and milestones was also a powerful reminder that time is passing quickly and the world is fast evolving. A number of our staff and members of our board of directors have been with MBARI since its beginning. A great deal has changed since our humble start at 160 Central Avenue in Pacific Grove, when a handful of employees made the best of modest and makeshift lab space that was simply defined by "wet" and "dry" areas. At the time, efforts to refine the operation of the *Point Lobos* and ROV *Ventana* were all-consuming. A database project was initiated so that ROV observations recorded on videotape could be quantified and cross-referenced with other environmental parameters. Other sensor system developments were also just beginning, and an organized effort to establish and standardize sustained chemical and biological measurements in Monterey Bay began in earnest. The *Western Flyer*, our present-day regional class research vessel, was just an artist's rendering on the wall, and *Tiburon*, the new-generation ROV around which that ship would be built, was still on the drawing board. The notion of developing and operating sophisticated AUVs as we know them today came not long after MBARI's founding, but at the time it seemed a distant pipe dream far from realization.

Looking back, it is clear that the early decisions to focus on technology development and foster science/engineering partnerships ultimately set in motion a flurry of innovations and discoveries that would have been impossible to achieve in the absence of Packard's long-term vision. The project updates in this year's annual report exemplify how that "go long" philosophy has paid off in innumerable ways. So much of what we highlight today, and at times take for granted, is a result of an unwavering commitment to tackle complex problems that can take years to solve, accepting the challenges, risks, and failures that are associated with that path, insisting on excellence, and daring to be different. We owe that spirit to David Packard.

For me, marking our 25th anniversary is as much a lightpost that points a way to the future as it is a time to take stock of past accomplishments. MBARI has matured a great deal since our founding. We have entered a new phase of institution building, refreshing our long-term vision and setting the stage for the coming decades, just as we did many years ago. This vision, which we are setting forth in our Technology Roadmap, is based on the science themes outlined in our 2011 Strategic Plan. It rests on the recognition that the ocean is undergoing profound changes due to both natural forces and human activities. In the short time since our founding, the work we have done in Monterey Bay and elsewhere reveals an ocean environment that is on the move. Our findings are also a testament to the fact that there are many mysteries to solve and discoveries yet to be made. Development of new technologies for observing the ocean and conducting innovative experiments were the catalysts that made those advances possible. I look forward to completing our Technology Roadmap next year and am inspired to consider the prospects for what we can achieve in the coming decades. In the meantime, 2013 promises to be another year full of excitement, challenges, and adventure!

Chair of the Board Julie Packard christened MBARI's newest research vessel, R/V *Rachel Carson*, with Master Aaron Gregg and MBARI President Chris Scholin.

Chris Scholin
President and Chief Executive Officer

Monterey Bay as a Window to the World

For 25 years, MBARI scientists have focused on biogeochemical cycles and ecosystem processes using Monterey Bay as a primary study site. The technologies developed at MBARI are helping elucidate how water masses and processes within Monterey Bay interact with ecosystems in adjacent waters. Several research groups are using new technology to better understand the biological ramifications of a more acidic/lower oxygen ocean—studies that could improve interpretation and prediction of large-scale changes across the Pacific and around the globe.

MBARI also co-hosted an important conference on ocean acidification, to help further the discussion among experts from around the world as to what this phenomenon will mean for ocean ecosystems and people.

The biological pump

How will increasing carbon dioxide levels, lower oxygen, and climate change impact the ocean? To predict future ocean conditions, oceanographers need a better understanding of how marine food webs, nutrient cycles, and the biological pump (Figure 1) respond to changes in the ocean environment.

The biological pump is a complex series of interdependent processes that transport carbon and other biologically active elements from the ocean's surface to its interior, and transfer energy from the smallest of living things to top predators. During photosynthesis, microscopic algae use energy from the sun to convert carbon dioxide into living tissue. When the algae die, or get consumed and excreted, some of the organic carbon from their tissues sinks down as tiny particles into the midwater twilight zone and the deep seafloor, feeding animals in those habitats. As the detritus descends, bacteria and the animals degrade it, consuming oxygen and producing carbon dioxide and inorganic nutrients, such as nitrate. Some portion of those deep-sea nutrients return to the sea surface via mixing or upwelling, completing the nutrient cycle.

In rich coastal ecosystems the nutrients upwelled to the surface result in blooms of microscopic algae that are grazed directly by krill and small pelagic fishes. These "forage" species provide food for larger animals, including commercially important fishes. These coastal systems are considered leaky in that a large fraction of the organic carbon from photosynthesis sinks to the deeper ocean.

In contrast, the oligotrophic gyres hundreds of kilometers offshore represent a very different ecosystem where nutrients are limited and extremely tiny photosynthetic plankton dominate. Their grazers are also tiny and together create a tight microbial loop where the ammonium excreted by the grazers refuels the phytoplankton. The compact food web curtails the development of a more complex food chain because there is not enough organic material to support large populations of forage species or their predators.

MBARI's Controlled, Agile, and Novel Observing Network (CANON) Initiative aims to improve understanding of the processes that drive the biological pump and shape ocean ecosystems. The initiative—a joint effort of eight MBARI research teams, with Francisco Chavez as project manager—focuses on plankton blooms, oxygen minimum zones, open-ocean eddies, and primary production. During CANON field programs, researchers employ a variety of tools and methods at sea to observe in a detailed way how organisms respond to environmental perturbations—a view that has not been possible previously.

CANON field experiments

One of CANON's goals is to demonstrate technologies that can characterize dynamic biological processes on microscopic scales over periods of weeks. With a wide

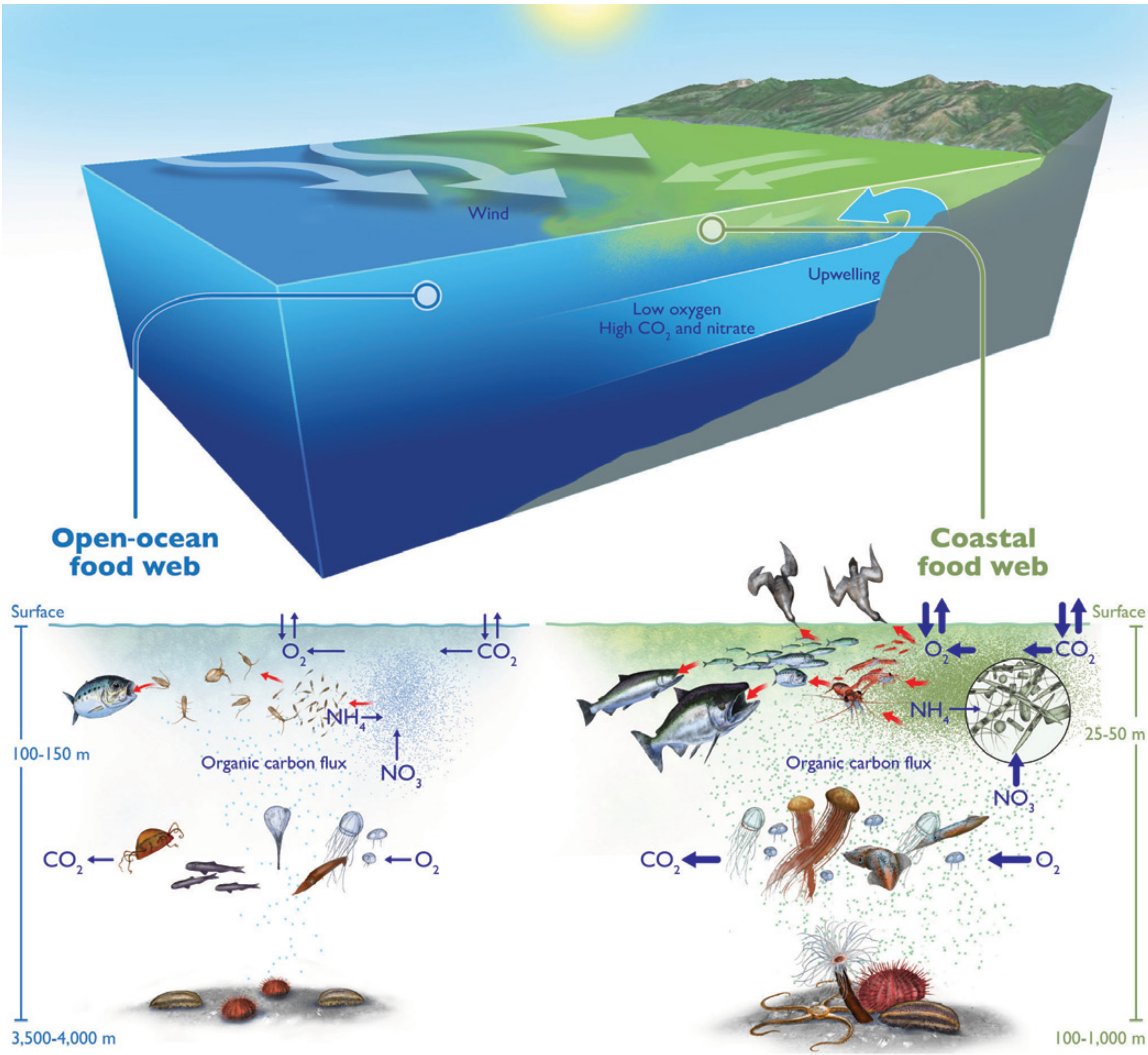


Figure 1: The biological pump plays a critical role in the global carbon cycle, with processes involving phytoplankton, the animals that consume them, and the bacteria that assimilate their wastes. Off Central California, coastal upwelling brings cold, nutrient-rich waters from 50-100 meter depths up to the sea surface through the combined effects of wind, the earth's rotation and the coastline (top panel). Sunlight and the natural fertilizers stimulate the phytoplankton blooms dominated by diatoms that feed forage species such as krill and small fishes (lower right panel). The forage species nourish top predators such as birds and larger fishes, producing a complex food web. A large fraction of the organic material produced at the sea surface sinks into the deep sea providing food for midwater and benthic organisms. In contrast, far offshore, the nutrient-poor subtropical open ocean (lower left panel) is dominated by tiny photosynthetic plankton (one to three microns in diameter) whose grazers are of similar or slightly larger size. Recycled nutrients such as ammonium drive the tight food web with fewer top predators and less export of material to the deep ocean.

range of sophisticated instruments deployed at sea during field experiments, scientists need to assimilate information from many sources—for example, a robotic DNA lab called the Environmental Sample Processor (ESP), autonomous underwater vehicles (AUVs), underwater and sea-surface drifters, moorings, radar, and remote-sensing satellites—to understand the movement of water masses and how organisms respond to changing conditions.

Principal Researcher for Autonomy Kanna Rajan recognized that CANON's complicated interdisciplinary experiments

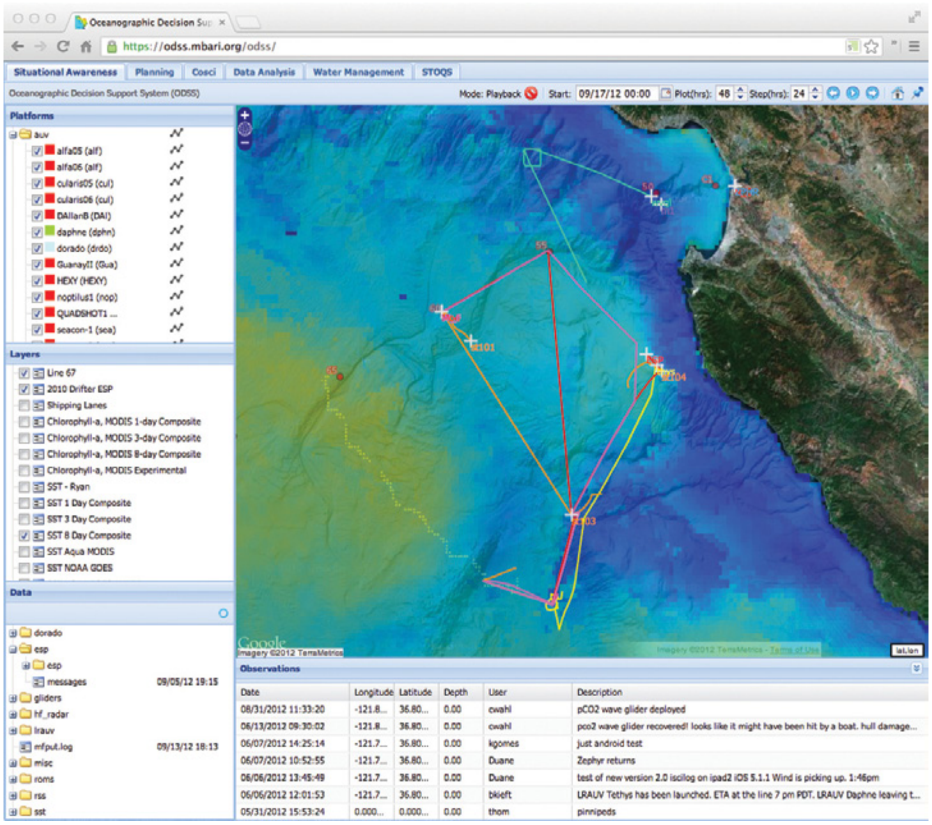


Figure 2: MBARI's Oceanographic Decision Support System (ODSS) displays the positions of ships, autonomous vehicles, and drifting instruments used in the CANON September 2012 field experiment, with links to the data on the left.

required decision-support tools to help the many collaborating researchers plan and coordinate large field programs. The engineering team, led by Thom Maughan, came up with a solution called the Oceanographic Decision Support System (ODSS), a web-based portal that also incorporated collaborative tools and techniques developed under Chief Technologist Jim Bellingham. The system provides a graphical user interface so that the collaborating researchers can readily see the location of each research tool at sea, its trajectory, and information needed to test hypotheses and track the changing biological events under investigation (Figure 2). Before a field experiment, the research team makes plans based on historical data and simulations. Using information from previous missions, machine learning, and real-time data coming in from experiments, computers on shore can plan new sampling patterns to adapt the robots to track the evolving biological phenomena. The team can develop an algorithm to find a particular signal, such as high chlorophyll, then use it in concert with the live data being collected and direct water sampling accordingly. The diverse types of data provided through the ODSS also guide the decision on which samples to submit for further analysis.

The ODSS solution is unique because it distributes control of activities, allowing revision of plans by the robots or humans. With ODSS web-based communications and data-management systems, researchers can make high-level decisions during the day and rely on automated robotic control at night. The system allows the team to respond to events, for example tasking an AUV to collect a water sample. After a field program, the ODSS is available to replay a sequence of events, analyze results, and archive and disseminate information for use in future planning.

Putting CANON technology to work

Repeated surveys of local waters found a substantial plume of ammonium extending from Monterey Bay to over 100 kilometers offshore—a finding that challenged the view that the Central California system was fueled mostly by upwelled nitrate. The unpredicted prevalence of ammonium is a reminder of the complexities of the coastal ecosystem and how much of its dynamics and functioning remains unexplained.

The observation raised questions on how nitrogen cycling associated with the biological pump changes between coastal and offshore ecosystems. What physical conditions lead to

Figure 3: Scientist Francisco Chavez used the ODSS aboard the R/V *Western Flyer* to follow evolving conditions and plan the CANON experiment in real time.

the formation of a subsurface plume of ammonium? How fast was ammonium produced and consumed and how did this affect the nitrogen cycle? What role does this play in organizing the food web? Could the producers and consumers be identified autonomously and genetically? With these questions in mind, the 2012 CANON team planned seasonal experiments—the first in Monterey Bay and the second offshore—both centered on elucidating the distribution, production, and consumption of ammonium.

Researchers had access to an ODSS interactive map displaying ships and sensor systems, as well as the data they generated, so that the participants were kept aware of ever-changing conditions (Figure 3). The spring experiment occurred during a period of exceptionally strong upwelling. The windy conditions prevented much work from the available small boats, but the autonomous vehicles performed splendidly. Sensors revealed the highest levels of carbon dioxide and most acidic water ever seen in Monterey Bay. An MBARI AUV repeatedly tracked, and took targeted water samples of, the upwelling front—the edge of the plume of nutrient-rich waters forced to the surface—to detect the rise and decline of upwelling in exquisite detail.

In autumn, the R/V *Western Flyer* transited offshore followed by the same autonomous vehicles, all in search of the ammonium plume. Once it was located, an ESP equipped for a variety of analyses and sample collections was set adrift to follow currents and microbial populations, and track their activities. Scientists aboard the *Western Flyer* carried out additional sample analyses designed to follow the biogeochemical and ecological dynamics in the waters around the ESP.

The 2012 experiments provided information on the biological pump processes active in local waters, and help us better understand how the ocean works and how it could

Forage species

In the California Current and other coastal upwelling regions, nutrients, ocean circulation, and meteorological conditions determine the overall ecosystem productivity. However, the structure of the food web determines the spatial distribution, rates, and pathways by which this productivity is cycled through the ecosystem to the deep sea. Central to that cycling pathway in coastal ecosystems are forage species. In upwelling systems these organisms include krill and small pelagic fishes near the base of the food web that can efficiently funnel the organic matter created by photosynthesis to higher trophic levels, since in many cases forage species feed directly on diatoms and other algae. This linkage serves as a linchpin in transferring climate-driven variability to the larger marine animals including commercially important fishes.

To improve predictive capability, further refinement and expansion of models that include the forage species are needed. In parallel, researchers need to develop the means for measuring key components—the diatoms, zooplankton, small pelagic fishes—and integrating those measurements into the models with traditional fisheries information.

Sardines are forage fishes near the base of the food web.

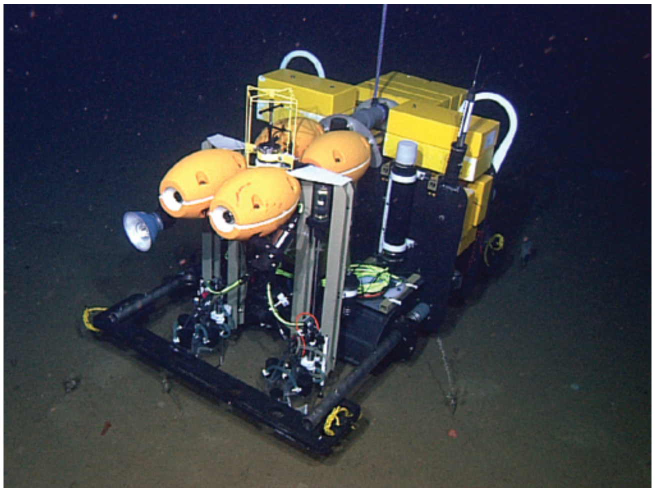


Figure 4: The Benthic Rover on the seafloor.

change over the next few decades, or even centuries. A basic CANON goal is to use ODSS developments to accelerate the processing of information collected from this type of complicated experiment.

Taking the laboratory into the deep

The deep ocean, the world's largest ecosystem, plays a crucial role in the global carbon cycle. However, the processes occurring in the deep ocean remain poorly understood due to the technical and logistical challenges of sampling this vast environment. Changes in these processes can occur on seasonal, annual, or episodic time scales. To understand the impact of climate change or rising carbon dioxide levels in the deep sea, sustained observation of this remote ecosystem is required.

Roving the seafloor

Towards that end, Marine Ecologist Ken Smith and Engineer Alana Sherman led a team that built a seafloor-roving vehicle. The Benthic Rover was developed for taking long-duration measurements of particulate organic material (food) reaching the seafloor and the subsequent response of organisms living in and on the sediments. The vehicle is not designed to travel long distances; it moves only 10 meters every few days to an undisturbed site to make new measurements. The Rover carries batteries and instructions for a six-month or longer unattended mission (Figure 4).

The vehicle is equipped with a suite of scientific instruments including two respirometers. Each has a clear plastic cylinder, sealed on the top and open on the bottom, which is inserted into the seafloor to create a closed volume of seawater and sediment. The respirometer measures the changes in the oxygen in the enclosed chamber as organisms living in the sediment respire. These measurements are a proxy for estimating the food consumption of these organisms. The Benthic Rover is also equipped with a high-resolution camera that captures images of the seafloor as the vehicle moves between sites. From these photo transects researchers can identify organisms on the seafloor and maintain a record of food that has fallen from above, such as carcasses of dead animals. A separate camera system displays chlorophyll fluorescence on the seafloor, providing another measure of the amount and quality of food reaching the benthic community.

Figure 5: Engineer Paul McGill checks the Benthic Rover's battery pack after its retrieval.

Complementary data sets are generated by other long-term monitoring instruments deployed along with the Benthic Rover. Funnels on sediment traps collect samples of food sinking toward the seafloor. Those samples and information from the Benthic Rover help address questions about how the relationship between food supply and benthic com-

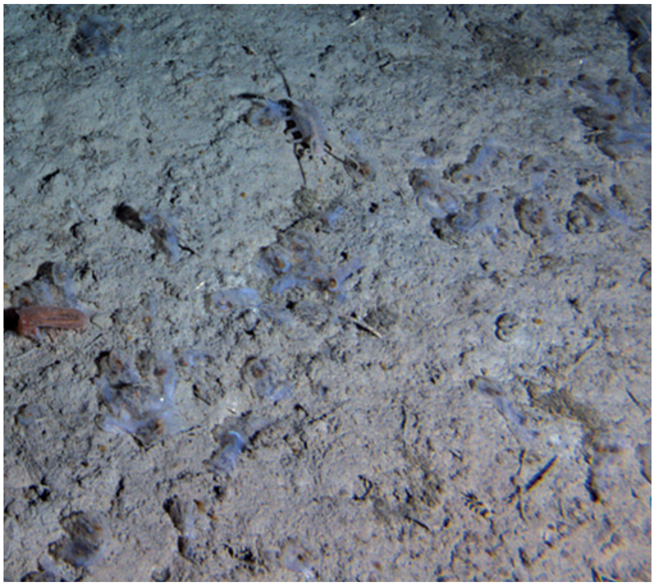


Figure 6: The soft-sediment seafloor at Station M is covered with an abundance of salp carcasses (the light-colored gelatinous objects) in this photo taken in June with the camera on the Benthic Rover.

munity response changes over time scales ranging from days to decades.

After many test deployments in Monterey Bay, the Benthic Rover was sent to the seafloor at Station M (a deep-sea site about 220 kilometers off the California Coast), where it completed its first autonomous deployment from November 2011 to June 2012. After redeployment in June, the vehicle was again recovered in excellent condition in November 2012 with another six-month data set, for a complete year-long record (Figure 5).

The Rover revealed an unprecedented "spring bloom" of salp carcasses and material that sank to the seafloor. Salps are gelatinous filter feeders that live in the upper ocean. These animals are of particular interest because they are very efficient at filtering a wide size range of planktonic organisms from large volumes of seawater. Their waste and carcasses sink rapidly to the seafloor (Figure 6) and serve as a high-organic-carbon food source for the benthic community. Thus the presence of large numbers of salps on the seafloor from late March through June represents a massive influx of food. Without instruments that monitor continuously, critical episodic events such as this pulse of salps are likely to be missed completely and the details of the functioning of the biological pump would remain a mystery.

During the salp bloom of spring 2012, satellite sensor measurements of sea-surface chlorophyll showed a strong correlation to the sediment-trap samples and Benthic Rover respirometer data measured at a depth of 4,000 meters. These independent measurements provide a vivid illustration of how events at the surface are intimately connected with those at great depth.

Measuring animal respiration in situ

One key consequence of rising temperatures is that oxygen concentrations will decline. To understand how marine life will fare as oxygen is depleted, scientists assess organisms' respiration and other functions under different conditions. Measuring the effects of changing oxygen levels on deep-sea animals is technically challenging. Capturing deep-sea animals and studying them at the surface subjects them to decompression, warming, different water chemistry, and other stresses, so those measurements may not be accurate. Rates measured in situ are expected to more closely represent the normal metabolism of deep-sea animals. For many deep-sea species that would not survive capture and transport to the surface, in situ instruments are the only way to directly measure their metabolic rates.

Addressing this issue requires taking the laboratory into the ocean by developing automated respirometers to measure the oxygen consumption of animals in environments where they actually live. It also makes it possible to manipulate conditions within the respirometer chambers to study the effects of potential changes in ocean conditions in a controlled fashion, and thereby test specific ideas as to how animals respond to changing conditions. MBARI's working relationships between scientists and engineers, coupled with ready access to deep water with ships and remotely operated vehicles (ROVs), has led to major advances in this line of research.

The respirometer team, led by Bob Herlien, Kurt Buck, and Kim Reisenbichler, developed modular multi-chamber respiration systems tailored for animals from deep-sea habitats. The Benthic Respiration System (BRS) and the Midwater Respirometry System (MRS) were built using control and data-storage technology previously developed for MBARI moorings. The two respirometry systems use the same sensors, pumps, and software, but differ significantly in their modes of deployment and the types of animals they study.

Each system has eight respiration chambers, allowing for replicate experiments that simultaneously measure metabolism in up to seven animals and a control. Replication of experiments is a key feature, considering the cost of ship and ROV time. Each chamber has an oxygen sensor and a number of pumps used to flush the chamber, stir, inject, or withdraw fluids. To simulate environmental changes like ocean acidification, specific quantities of carbon dioxide-saturated seawater can be injected at programmed intervals to raise the acidity in the respiration chamber. Alternatively, oxygen-saturated or reduced-oxygen seawater can be injected to raise or lower the oxygen content. Samples of chamber water can be withdrawn at any time for analysis. Flushing pumps can refill the chambers to prevent asphyxiating the test animals, thus allowing repeated measurements under ambient or experimental conditions. Both systems are expandable, so investigators can increase the number of chambers, sensors, and functions, as space allows.

The basic experimental procedure is the same for both systems. After an animal has been gently loaded into a chamber, the system flushes ambient seawater into the chamber, stirring to eliminate stratification, while oxygen is monitored for a prescribed period of perhaps six to 12 hours. When that cycle ends, the flushing pump renews the chamber water, and resets conditions for the next cycle. This process is repeated several times to characterize the typical respiration rate of the animal under normal deep-sea conditions and control measurements recorded from one unoccupied chamber. Metabolism is calculated from the mass of the animal and the rate of decrease in oxygen in the chamber.

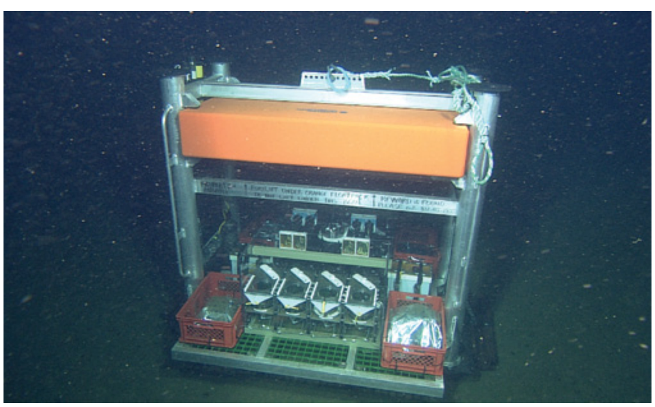


Figure 7: The Benthic Respirometer System on the Gulf of California seafloor at 1,575 meters depth.

Benthic respirometry

The Benthic Respirometer System (BRS) is deployed over the side of the ship on an elevator—a weighted platform to transport items to the seafloor and back. An ROV follows the BRS and uses a suction sampler to gently capture seafloor animals and place them in the respirometry chambers (Figure 7). Deployments of the BRS can be extended for several weeks, based on the experimental design and battery power available. The system can also be transported for use in remote locations such as the Gulf of California during the 2012 expedition.

Midwater respirometry

The Midwater Respirometry System (MRS) (Figure 8) was developed with different constraints than the BRS and is the only system of its type in the world. Because many midwater animals are delicate and soft-bodied, they cannot be collected with a robotic manipulator. Therefore the MRS is carried on the front of an ROV and animals are collected by maneuvering the vehicle (and the respirometer) so that an individual animal is entrained within one of the eight chambers. Once it is loaded with animals and control chambers, the ROV moves the MRS onto one of two sub-surface moorings that lie deep below the surface of Monterey Bay. Each deployment lasts from 24 to 48 hours at depths between 200 and 3,000 meters, comparable to the depth where the animals were collected. The length of deployment is determined by the type and delicacy of the animal, the experimental goals, and the system's battery capacity. Battery power is weight-limited because the system must be carried by an ROV and deployed on a slender mooring line.

Figure 8: The Midwater Respirometry System mounted on the front of ROV *Ventana* as seen in the ROV's video.

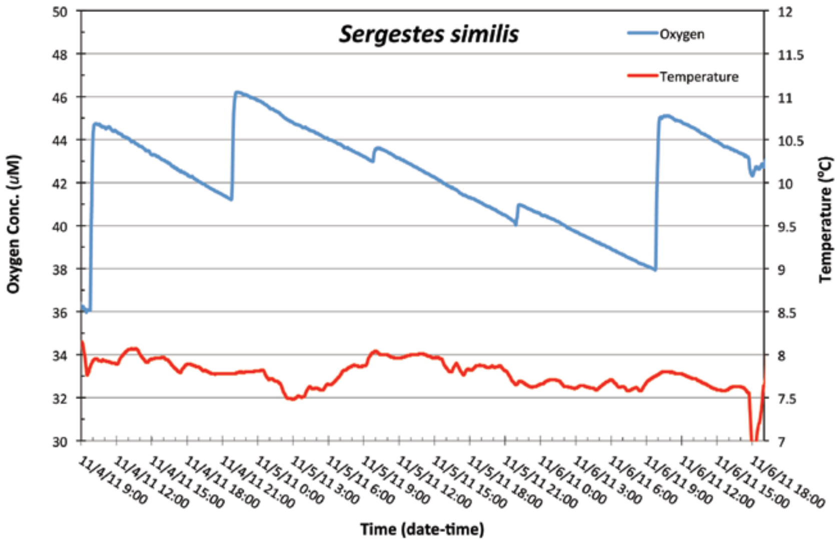


Figure 9: Changes in oxygen concentration and temperature over time in one MRS chamber during five "flush" cycles. The shift in oxygen concentration at the start of each incubation period was due to differing oxygen levels in the surrounding seawater during each flush cycle. Above, *Sergestes similis*, which is about 7.5 centimeters (three inches) long.

Initial experiments with pH alterations focused on the midwater shrimp, *Sergestes similis* (Figure 9). The midwater ecology group has measured the respiration rates of over 21 species, ranging from delicate comb jellies to robust squids, completing 42 successful scientific deployments of the system. The midwater and benthic research groups have just begun to exploit the capabilities of this device and are eager to expand the range and scope of species studied.

Linking past to present

MBARI researchers have proven Monterey Bay to be an effective site for testing of new technologies and research methods. One of the critical goals for the institute is to expand the use of instruments and know-how developed here to research efforts outside the region. Two very different lines of investigation in Monterey Bay have aligned to similar conclusions in deep-sea research conducted well outside the bay. Both teams converged on the same fundamental finding—that the deep sea is far more variable and subject to climatic changes than might otherwise be suspected.

Changes in oceanic oxygen

Bob Vrijenhoek and his molecular ecology group examine the evolutionary history and geographical connectivity among populations of marine animals. Most of their efforts over the past 20 years have focused on invertebrate animals that inhabit deep-sea hydrothermal vents and hydrocarbon seeps. These deep-ocean habitats are commonly portrayed as stable safe havens for ancient animals, including a number of "living fossils". Such habitats were hypothesized to shelter ancient species from catastrophic events such as meteor collisions or large-scale volcanism that precipitated the global mass species extinctions in shallow-water and terrestrial habitats at the end of the Permian and Cretaceous periods.

Studies conducted by this research group provide a different view. The dominant animals occurring around deep-sea chemosynthetic vents and seeps arose relatively recently, following the Paleocene-Eocene Thermal Maximum (PETM) event about 60 million years ago. Although chemosynthetic animals derive most (or all) of their energy from geochemical sources, they still require oxygen to exploit their narrow ecological niches. Oceanic oxygen concentrations have varied considerably on geological time scales, decreasing during periods with elevated temperatures. Low oxygen levels in the deep-ocean during the PETM event resulted in large-scale extinctions of animals, creating opportunities for later invasions by the molluscs, annelid worms, and crustaceans found in chemosynthetic environments after the oxygen levels again increased (Figure 10). Thus, deep-sea environments do not differ from the terrestrial and near-shore marine realms in their susceptibility to climate changes that alter water temperatures and deep-ocean circulation. Consequently, global warming and contingent disturbance of oxygen supply are highly relevant to the health of Earth's ocean, from the sunlit surface waters to the great depths where essential minerals and nutrients are recycled.

Ocean dead zones

MBARI's unique access to the deep sea allows researchers to make direct observations and compare the cascade of effects on ecosystems that occur as ocean oxygen levels decline. Marine animals have evolved special capabilities

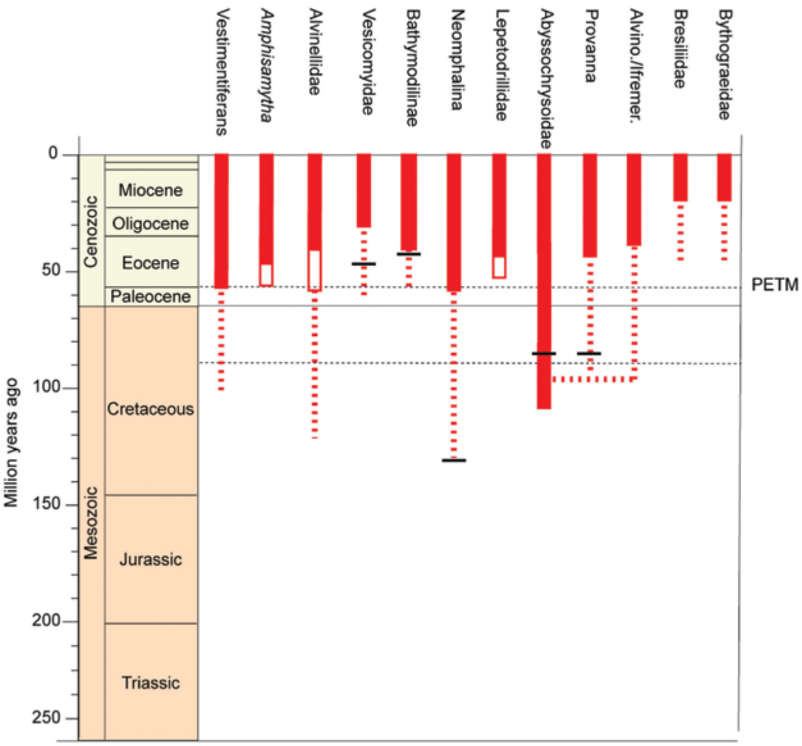


Figure 10: History shows us that changes in ocean chemistry impact animals in the deep sea. Estimates of the ages of various invertebrate groups living in chemosynthetic environments based on DNA evidence. PETM marks the Paleocene-Eocene Thermal Maximum. Black hash mark indicates verified dated fossils used to calibrate the molecular estimates. Dashed lines indicate possible ages of lineages that gave rise to modern species. White areas denote alternative estimates based on assumptions of different evolutionary rates. Modified from Vrijenhoek (2013) *Deep-Sea Research II*.

to deal with the zones of low-oxygen waters that occur at mid-depths along our coast, but at some point limits are reached and sharp transitions occur where whole categories of life-forms cannot survive. That means that true "dead zones", where oxygen-breathing marine animals are completely gone, do occur and, disturbingly, their range is increasing.

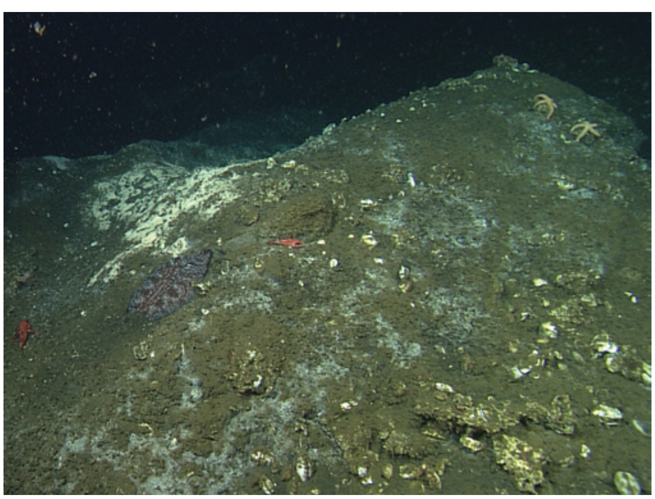


Figure 11: Fishes and invertebrates inhabit this mound in Barkley Canyon off the coast of Vancouver Island.

Peter Brewer's chemistry group studied a series of deep-sea sites that clearly show a progression from one that supports healthy fish populations, and a second that supports only low-oxygen life-forms that depend on assistance from microbes, to a third purely microbial community. The span of oxygen concentrations between these three locations is less than .33 milliliters per liter—the amount by which ocean oxygen levels are predicted to decline under climate warming of only two degrees Celsius. Thus the study provides an early warning of the likely impacts of climate change in the deep sea. The study sites are three seafloor mounds at about 850 meters depth ranging from offshore of Vancouver Island to the depths of the Santa Monica Basin offshore of Los Angeles. Each of these mounds is a site of methane venting, where the gas and fluid flowing through the top of the mound forms methane hydrates. In each case the sediments atop the mounds are oxygen-depleted and sulfide-rich. But the overlying seawater differs sufficiently in dissolved oxygen and so very different marine species inhabit each area.

In the first case, the seafloor of Barkley Canyon off Vancouver Island is dominated by clams, with abundant rockfish and sablefish populations (Figure 11). Atop the mound is a small crater where gas has vented. Instruments on the ROV revealed a temperature of 1.8 to 1.9 degrees Celsius and an oxygen concentration of about 0.35 milliliters per liter—close to the limit for support of fish populations. Equipment and markers left by scientists at this site quickly acquire a growth of marine organisms that settled on the fresh, exposed surface.

Brewer's group also studied two mounds venting methane in the Santa Monica Basin, each close to 850 meters depth. At one mound, no fish are present and equipment left at the

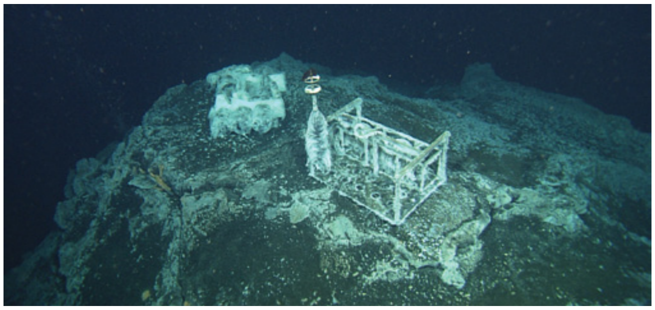


Figure 12: Bacteria and clams populate this undersea mound in Santa Monica Basin, where filamentous bacteria quickly settled and covered MBARI research equipment.

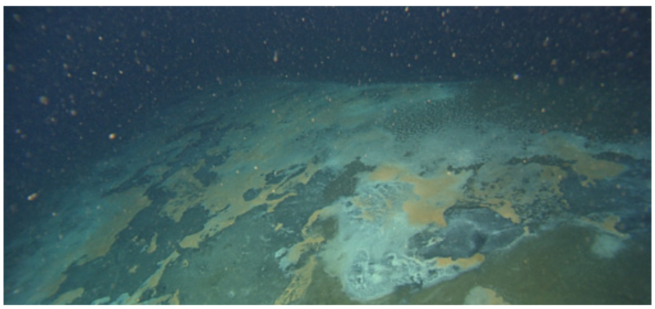


Figure 13: This deep mound in the Santa Monica Basin bears only orange and white mats of bacterial life.

site acquired long, waving strands of bacteria (Figure 12). An abundance of clams survive at this site by their association with microbial symbionts that allow them to gain energy by oxidizing sulfide from the sediments while scouring small traces of oxygen from the overlying seawater.

Atop a second mound in the Santa Monica Basin, only a few tens of meters deeper, even the sulfide-loving bacterial-assisted clams are absent. Only an eerie, white and orange, undisturbed bacterial mat is seen (Figure 13). There are no animals. Only the bacteria have the capacity to oxidize the leaking methane and gain energy from it.

The range of oxygen values and temperature in the water column spanned by these three sites, similar in depth and manner of formation, yields alarming insight into the changes ahead. As ocean warming occurs and oxygen levels decline there is a high probability of turning the northern site, which now supports a viable fish population, into something closely resembling the southern site where only microbes are found. The future that Brewer's work predicts parallels past events that Vrijenhoek's group has established.

Convening the experts on ocean acidification

Even as scientists at MBARI and elsewhere share their research on the important issues of climate change in professional publications, there is also a need to bring international experts together to further the ongoing conversation about the causes, effects, and adaptations to ocean acidification. The International Symposium on the Ocean in a High-CO_2 World has grown to be an important conference to foster such exchanges. In September 2012 MBARI, together with the Monterey Bay Aquarium and the Center for Ocean Solutions, welcomed over 500 scientists to the conference in Monterey. Since this conference series began in 2004, the symposium has led to extraordinary interest in the impacts of ocean acidification. The Monterey conference confirmed and expanded upon the study of this alarming phenomenon.

MBARI's Peter Brewer initiated the bid to host the conference in Monterey and then served on the international planning committee. MBARI's Jim Barry and George Matsumoto both served on the local organizing committee. Julie Packard, chair of the MBARI Board of Directors provided the opening remarks, and Brewer's invited talk (Figure 14) on the history of the science of ocean acidification drew a great deal of attention.

In addition to a historical perspective, the conference examined predictions of a future with rates of change in ocean acidification far exceeding anything experienced in Earth's geologic past. There is no comparable fossil record of ocean chemical changes at these rates, and many deep-sea species are found to be highly vulnerable.

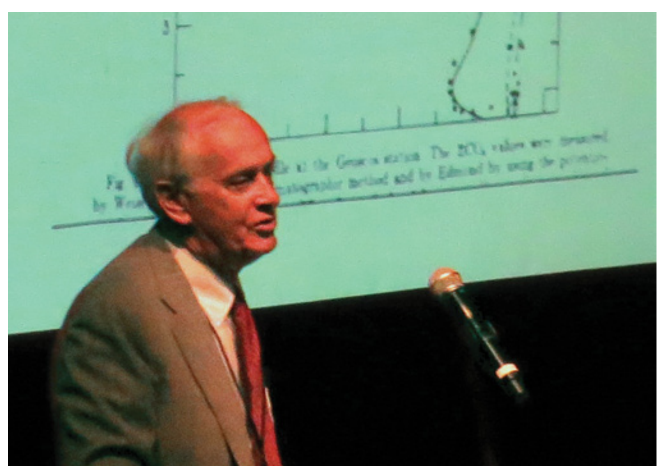


Figure 14: Peter Brewer presents the history of the science of ocean acidification at the 2012 International Symposium on the Ocean in a High CO_2 World.

An increasingly acidic ocean leads to a loss of carbonate ion concentration—the chemical basis for coral reef formation and for all carbonate-shelled animals. Many contributions at the conference demonstrated this vulnerability with particular concern for the cold polar waters. The first direct experiment on a controlled CO_2 addition to a coral reef system was reported, using a modification of MBARI's Free Ocean Carbon Dioxide Enrichment (FOCE) system. Fears that such ocean pH changes would negatively impact reef systems were confirmed.

New information was presented on wide-ranging consequences of ocean pH change well beyond the carbonate system, such as the stress and adaptations it causes in marine life. Humans rely on the ocean to take up some 90 percent of all the greenhouse gas heat generated in the atmosphere. Some 50 percent of all fossil fuel carbon dioxide ever produced now resides in the ocean. Without the benefit of the ocean's biological pump, the planet would face an even greater climate change. Opportunities such as this international meeting help to keep the dialog open among the scientists from around the world who are contributing to the understanding of the problem and raising the consciousness of policy makers, resource managers, and the general public who will ultimately inherit this issue.

Controlled, Agile, and Novel Observing Network

Project leads: James G. Bellingham, Francisco Chavez, Kanna Rajan, John Ryan, Chris Scholin, Ken Smith, Robert Vrijenhoek, Alexandra Z. Worden
Project manager: Francisco Chavez
Project team: Danelle Cline, Duane Edgington, Michael Godin, Kevin Gomes, Mike McCann, Tom O'Reilly, Thom Maughan, and members of all the research groups associated with the project leads
Collaborators: Fred Bahr, Central and Northern California Ocean Observing System, Moss Landing; David Foley, Southwest Fisheries Science Center, Pacific Grove, California

Benthic Rover

Project lead: Ken Smith
Project manager: Alana Sherman
Project team: John Ferreira, Rich Henthorn, Brett Hobson, Tom Marion, Paul McGill

Respirometer Upgrade

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

Molecular Ecology and Evolution

Project lead: Robert C. Vrijenhoek
Project manager: Shannon B. Johnson
Project team: Julio Harvey, Roman Marin III, John Ryan, Chris Scholin, Haibin Zhang
Collaborators: Asta Audzijonyte, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; Shana Goffredi, Occidental College, Los Angeles, California; Joe Jones, Environmental Genomics Core Facility, University of South Carolina, Columbia; Sigrid Katz and Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Elena Krylova, Shirshov Institute of Oceanology, Moscow, Russia; Mary McGann, U.S. Geological Survey, Menlo Park, California; Karen Osborn, Smithsonian Institution, Washington, D.C.; Heiko Sahling, University of Bremen, Germany; Rahel Salathé, Pennsylvania State University, State College; 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; Brock Woodson, University of Georgia, Athens

Ocean Chemistry of the Greenhouse Gases

Project lead: Peter Brewer
Project manager: Edward Peltzer
Project team: Andreas Hofmann, Peter Walz
Collaborators: Nancy Barr, MBARI; Melissa Luna, University of Washington, Seattle; Xin Zhang, Institute of Oceanology, Chinese Academy of Sciences, Qingdao

MBARI team for The Third International Symposium on The Ocean in a High-CO_2 World

Project lead: Peter Brewer
Project managers: James Barry, George I. Matsumoto
Collaborators: Adina Abeles, Center for Ocean Solutions; Ginger Hopkins, Monterey Bay Aquarium; Adina Paytan, University of California, Santa Cruz; Lauren Siring, Monterey County Convention and Visitors Bureau

Expeditions

A major expedition south to the Gulf of California in Mexico and a smaller research expedition north to the Arctic offered insights into the impacts of a changing climate.

Gulf of California

Opportunities to compare natural conditions and processes over time and space are essential to scientific inquiry, and the 2012 expedition to the Gulf of California provided both to MBARI's research teams (see foldout image following page 16). The Gulf's oxygen-depleted waters, seafloor gas venting, and tectonic activity provide an interesting contrast to the institute's home territory of Monterey Bay. This expedition also offered a chance to see how the Gulf's conditions have changed since MBARI last visited the area in 2003. The Gulf's low-oxygen and more-acidic waters are thought to be a harbinger of future ocean conditions, giving scientists a chance to see how marine life may adapt in response to projected changes. Unraveling the various causes and consequences of changing ocean conditions is challenging but critically important if we are to gain a realistic perspective on what the future holds.

MBARI worked closely with collaborators from several Mexican academic institutions, as well as the Mexican government, who shared their local knowledge on every segment of the expedition. The success of the three-month expedition is also a testament to the institute's expert and highly professional marine operations staff. The crews of the research vessels *Western Flyer* and *Zephyr*, ROV *Doc Ricketts* pilots, and the mapping AUV team, along with the group's entire support and logistical staff worked tirelessly to plan and execute every aspect of this complex expedition (Figure 15).

Southbound transit validates Monterey Bay findings

The *Western Flyer's* February 2012 transit from Monterey Bay to the Gulf of California (GOC) provided an opportunity to compare the coastal ocean of 2012 with that documented during the same transit in 2003. The results provide evidence of change.

The Pacific Ocean off western North America is a classic eastern boundary current region. The California Current flows southward as a broad, slow surface current from the coast of Washington to Baja California, where it turns offshore, back across the Pacific basin to Asia. A reverse countercurrent also flows northwards along the coast, inshore and beneath the California Current (see foldout illustration after page 16). This Inshore Countercurrent carries low-oxygen water from off Central and South America, and as it flows northwards it mixes with the California Current. Lower oxygen is associated with higher levels of carbon dioxide so these waters are also more acidic. Monterey Bay is embedded within

Figure 15: First Mate Andrew McKee, right, and Relief Deckhand Jason Jordan lower a bumper on the side of the R/V *Western Flyer* in preparation for docking in La Paz, which served as home port while the ship was in the Gulf of California.

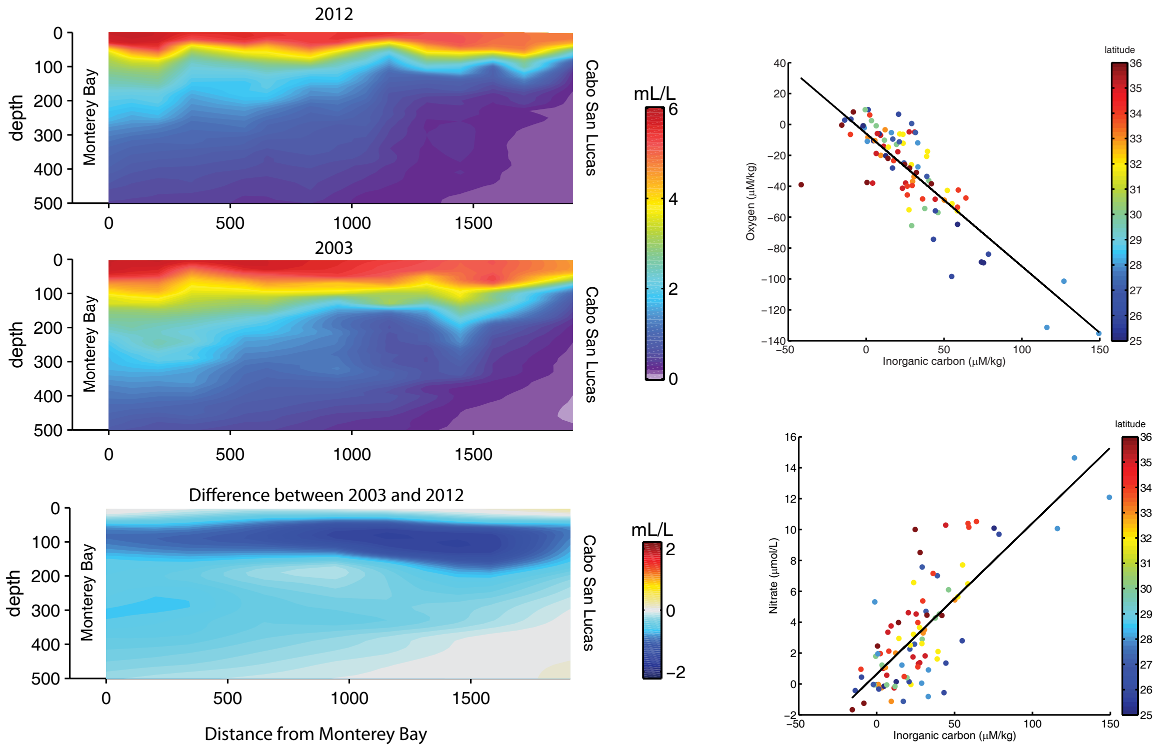


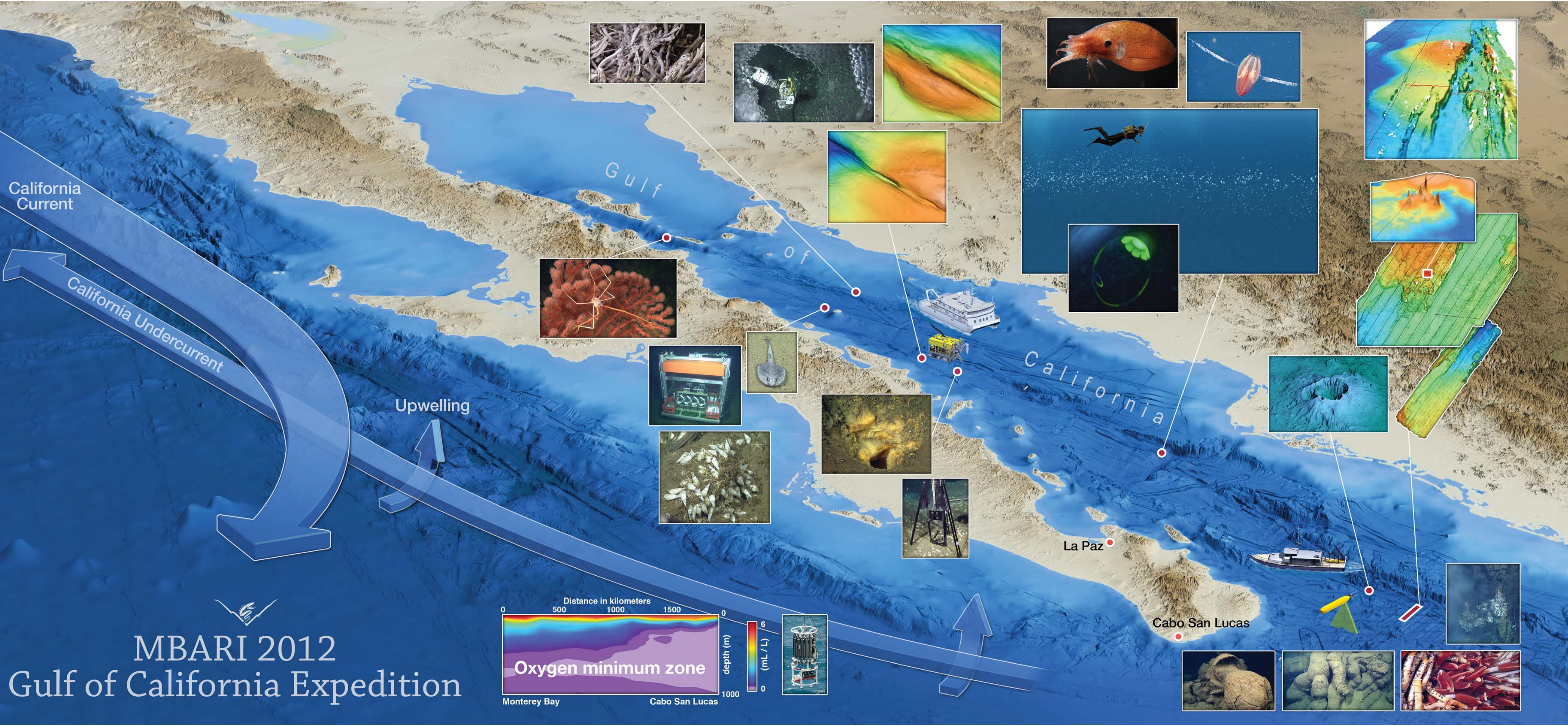
Figure 16: Oxygen concentration from the sea surface to 500 meters depth between Monterey Bay and Cabo San Lucas, Mexico, during 2012 transit (top left) and 2003 transit (middle left). The difference between 2012 and 2003 is displayed in the bottom left graph and shows that oxygen was significantly reduced in 2012, especially between 50- and 200-meter depth. The decrease was up to 30 percent in some cases. Decreased oxygen levels were associated with higher inorganic carbon (upper right graph) and nitrate (lower right graph). The end result is that waters with lower oxygen, higher carbon dioxide (and lower pH), and higher nitrate are presently being upwelled along the U.S. West Coast with uncertain consequences.

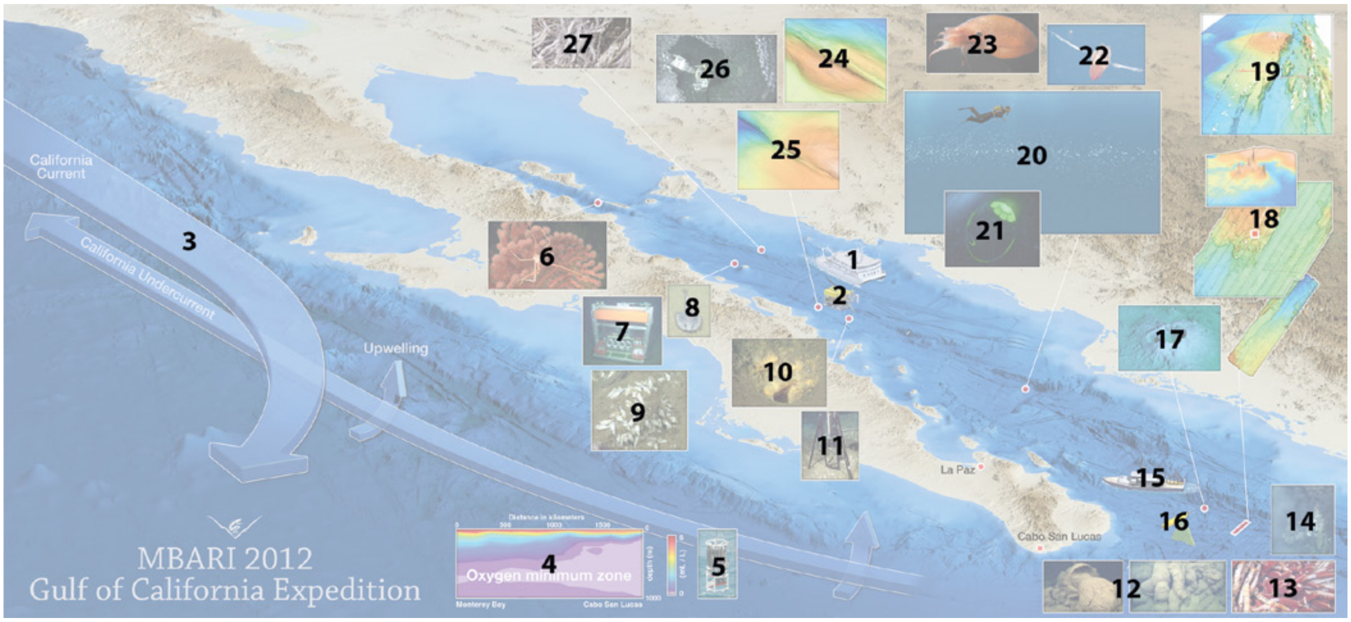
these currents—one from the north and the other from the south—and its ecosystems are profoundly affected by the varying mixtures of subarctic and subtropical waters.

These currents are driven by wind and so vary with weather, seasons, and El Niño events, and also on longer timescales. Since the 1997-98 El Niño, Monterey Bay has been much more biologically productive and every year its waters between depths of about 50 to 500 meters have been less oxygenated and more acidic than in previous decades. What drives the changes in Monterey Bay? Has the California Current become less oxygenated and more corrosive, or has the Inshore Countercurrent become stronger and less diluted? Either could decrease oxygen and increase acidity. Or are the changes more local, associated with coastal upwelling and biology? For example, as a region becomes more productive, more decomposing organic material sinks—further decreasing oxygen and increasing carbon dioxide levels at depth (see illustration on page 5). Understanding the cause of variations recorded in Monterey Bay over the past two decades will help to clarify what is driving change in the complicated, larger-scale system.

During the transit south, the ship stopped for measurements of many water properties at each degree of latitude between Monterey Bay and Cabo San Lucas. Researcher Francisco Chavez and his group then compared these measurements with equivalent ones from the 2003 transit. The most significant change was the reduced oxygen levels in 2012, particularly in the 50-to-200-meter-depth range (Figure 16). This is the depth range from which water is upwelled to the surface in Monterey Bay. Carbon dioxide, nitrate, and acidity also increased in this same depth range. These results show that the oxygen and acidity changes observed in Monterey Bay are widespread.

The observed differences in oxygen and carbon concentrations between the 2003 and 2012 transits are due to greater decomposition of organic material. The increased absorption of fossil-fuel derived carbon dioxide seems to be a small contributor to the higher carbon concentrations. Such changes are in agreement with the increased phyto-


California Current
California Undercurrent
Upwelling
Gulf
of
California
La Paz
Cabo San Lucas
Distance in kilometers
0
500
1000
1500
0
depth (m)
1000
Oxygen minimum zone
Monterey Bay
Cabo San Lucas
(mL / L)
6
0
MBARI 2012
Gulf of California Expedition



MBARI 2012 Gulf of California Expedition

MBARI's ships and research teams covered a wide range of territory—both geographically and scientifically—during a three-month expedition in the Gulf of California. Research vessel *Western Flyer* (1) and remotely operated vehicle *Doc Ricketts* (2) operated out of La Paz as a temporary home port, enabling seven science groups to reach their various points of interest. On the transit from Central California to the Gulf, the first team studied the California Current and Undercurrent systems (3), and the change in ocean chemistry as the waters became more oxygen-deprived (4) closer to Cabo San Lucas and the Gulf. The team used a rosette of water sampling bottles (5) mounted on a frame that included sensors to measure physical water properties.

Within the Gulf, benthic scientists found new species, such as this galatheid crab (6) , and used a Benthic Respirometer (7) to conduct experiments on the ability of pancake batfish (8) and other deep-sea animals to thrive in low-oxygen waters. Chemists found snails (9) and aggregates of yellow bacteria (10) where chemical-rich fluids are seeping out of the seafloor. The laser Raman spectrometer (11) was a key tool for measuring the chemical composition of seawater within the seafloor sediments.

Near the mouth of the Gulf, the scientists conducted remotely operated vehicle dives to study such features as different lava formations (12) and tubeworms (13) living at hydrothermal vents (14). Research vessel *Zephyr* (15) was host to the *D. Allan B.* autonomous underwater vehicle (16), which was used to map details of the seafloor in many sections of the Gulf. The sonar data gathered by the vehicle were processed aboard ship to create the maps that pinpointed areas of volcanic activity (17) and hydrothermal vents (18 and 19) for further study with the remotely operated vehicle.

Among the finds of the midwater biologists during bluewater dives (20) and remotely operated vehicle operations were a fluorescent jelly (21), an undescribed comb jelly (22), and a brooding octopus (23). In the earthquake fault zone in the central area of the Gulf, faults were clearly depicted in new high-resolution maps (24 and 25), and researchers saw bubbles emanating from the seafloor (26) and large clumps of tubeworms (27).

plankton growth observed in Monterey Bay over the past decade, slower rates of ocean ventilation in northern latitudes, and the increasing atmospheric carbon dioxide levels reported worldwide. Thus the California-to-Mexico transits confirm and broaden observations made in Monterey Bay, illustrating that local conditions are indeed reflective of much larger scale phenomena.

Stratified waters force marine life into narrow layers

The Gulf of California (GOC) supports an amazing ecosystem with animals adapted to extreme conditions of low oxygen and high temperature, which may be representative of future ocean conditions. The habitat also hosts high concentrations of otherwise rare species and unique predator-prey interactions. Vertical mixing in the Gulf is limited as a result of reduced circulation patterns and other physical constraints, so the water becomes stratified, or divided into layers. Temperature, salinity, light, and oxygen all undergo rapid changes from the surface down to deeper waters.

One effect of these rapid changes over short vertical distances is that organisms are forced into narrow depth ranges to remain in the layer with their preferred habitat. During ROV and scuba dives, Steve Haddock and his research team witnessed many such layers. Especially dramatic were the zones with iridescent copepods shining sapphire blue light back into the camera and flapping gastropods called sea butterflies which sometimes were the only living things visible in the water (Figure 17).

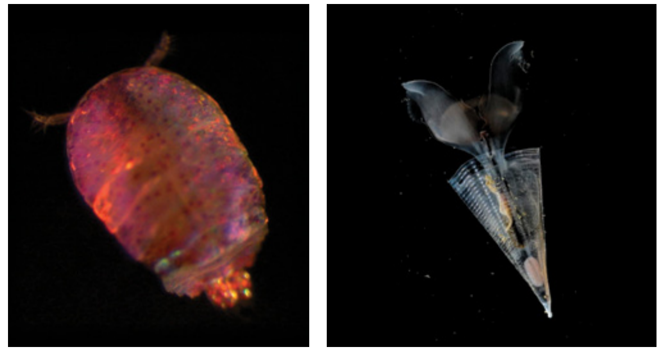
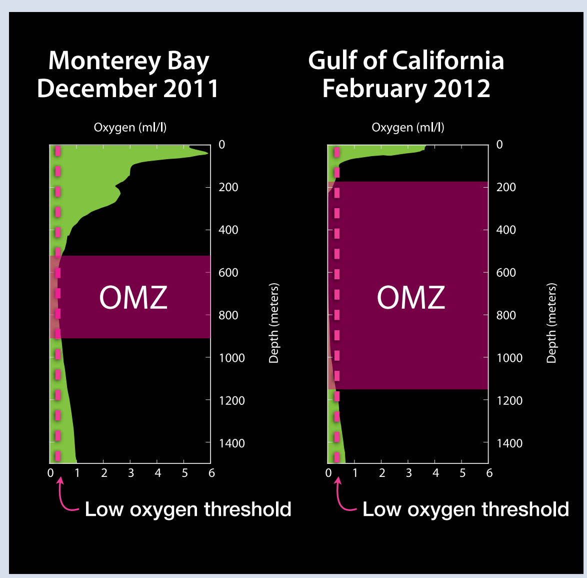


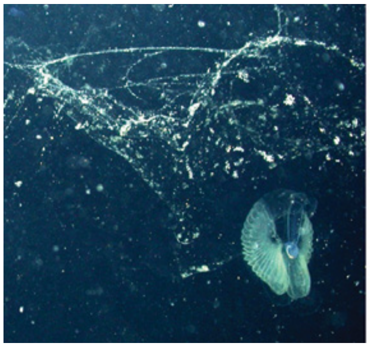
Figure 17: The iridescent copepod *Sapphirina*, left, is only about five millimeters (two-tenths of an inch) long and the sea butterfly *Clio*, is about one centimeter (less than half an inch) long.

The particularly extreme changes in oxygen in the Gulf, characteristic of semi-enclosed basins, seem to affect the distributions of many organisms—more so than other physical factors. For comparison, off the west coast of the United States, oxygen is substantially reduced between about 600 and 800 meters depth. This area is known as the oxygen minimum zone (OMZ), where oxygen concentration drops below 0.5 milliliters per liter (see sidebar). In some areas of the Gulf of California, oxygen drops to these levels by 100 meters, and is even notably low within scuba diving depths. As a result, organisms that might typically live at 200 meters are squeezed up to depths of 30 meters in the Gulf. The most conspicuous of these was the larvacean, *Bathochordaeus* (Figure 18). These tadpole-shaped creatures filter water through the large mucus "houses" they construct. In Monterey waters, scientists are accustomed to

Oxygen minimum zone

The oxygen minimum zone (OMZ) is an area below the surface of the ocean, but above the seafloor, where the concentration of oxygen in the water is extremely low. Oxygen content is usually highest at the sea surface, and diminishes gradually with depth, then increases again. In Monterey Bay, the OMZ begins at about 600 meters deep, where oxygen content is less than 10 percent of that at the surface. In the Gulf of California it starts much shallower, at about 200 meters deep. The OMZ also extends much deeper in the Gulf waters than in Monterey Bay. In these graphs, the green areas show oxygen concentration measurements from the ocean surface to depths of 1,400 meters in Monterey Bay (left) and the Gulf of California. Many animals cannot survive in the OMZ, so as the zone expands, they may be pushed further toward the surface or the seafloor. For the few animals that thrive in low oxygen, this change in ocean chemistry expands their habitat.





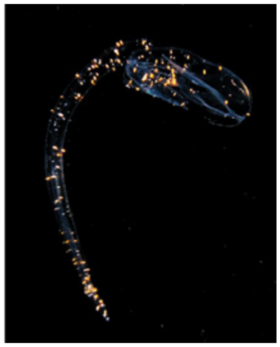


Figure 18: The tadpole-like larvacean *Bathochordaeus* within its mucus feeding filter (left) and free swimming (right) is about five centimeters (two inches) long.

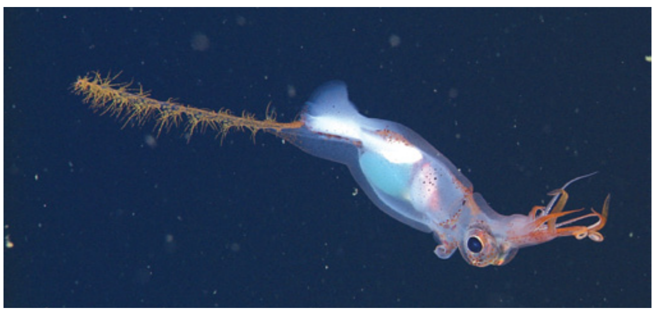


Figure 19: Cephalopods in the Gulf include the swordfish squid *Planctoteuthis* (above), which is about 13 centimeters (five inches) long, not including its tail, and this egg-bearing member of the family Gonatidae (below), which is about 76 centimeters (30 inches) long, not including the egg sac (brown material to the left of the animal).

seeing these larvaceans during deep-water ROV dives, so it was disorienting to come across them during relatively shallow scuba dives, where the water temperature was eight to 10 degrees Celsius (about 14 to 16 degrees Fahrenheit) warmer than they would occur off California.

These kinds of adaptations and changes of distributions are potentially indicative of challenges that animals elsewhere will face as ocean conditions change. By studying this natural distribution, we can see what physiological tolerances are possible for species typically found in the deep sea.

The diversity of organisms in the Gulf also shows some surprising trends. The researchers found high numbers of a few species, rather than a large diversity of animals at each depth, perhaps because some simply could not cope with the environmental extremes. Furthermore, species that are rarely seen on typical California dives—even during trips far offshore—were commonly encountered in the Gulf. Among these, cephalopods had strong representation, including the octopus *Japetella*, which sports a bioluminescent ring around its mouth; *Planctoteuthis*, which has a distinct Christmas-tree-like appendage; and members of the family Gonatidae, which carry around large egg masses for up to nine months (Figure 19). Many of the squids were undoubtedly feeding on the abundant lanternfish and dragonfish which made up much of the catch in net trawls during the expedition.

In addition to documenting the region's biodiversity, researchers also examined the bioluminescence and fluorescence characteristic of many of the Gulf's inhabitants. They found transparent jellies filled with fluorescent remains of digested prey, and additional species of siphonophores (a kind of elongate jelly) that use tiny fluorescent spots to attract prey to its powerful stinging tentacles. Collectors became intimately familiar with siphonophores, which delivered powerful stings to any exposed skin (usually near the diver's mouth!) during blue-water scuba dives.

Adapting to harsh seafloor conditions

The effects of depleted oxygen were also apparent in the Gulf during studies of seafloor animals by Benthic Ecologist Jim Barry and his colleagues. Benthic investigations focused on comparing seafloor communities in the Guaymas Basin in the central Gulf where conditions are typical of the Eastern Pacific, with the more unusual conditions in the northern Gulf. Near 1,000 meters depth in the Guaymas Basin, temperatures are low (about 4.5 degrees Celsius) and oxygen levels are very low (0.1 to 0.2 milliliters per liter)—quite similar to the oxygen minimum zone (see sidebar on page 17) throughout the tropical to temperate Eastern Pacific. In contrast, the Delfin and Salsipuedes Basins

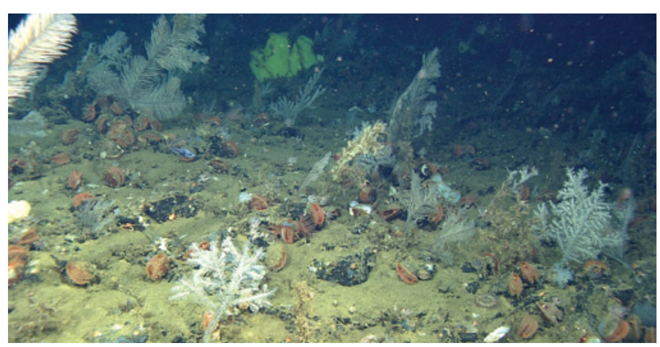


Figure 20: The rich seafloor animal community at Guaymas Basin.

in the northern GOC have quite different conditions at the same depth, with temperatures of 11.5 degrees Celsius and oxygen levels of 0.9 to 1.5 milliliters per liter. These disparate conditions allowed researchers to compare the composition and function of deep-sea benthic communities separated by only 240 kilometers (150 miles), but each characterized by very different environments.

The unique conditions in the northern GOC are related to the circulation pattern of waters near the northern end of the Gulf. A surface oscillation of the water (like the slosh produced by a child in a bathtub) produces a large tidal range (nearly eight meters) in the upper Gulf. The shape of the basin causes this large tidal surge to flow over the shallow shelf in the upper Gulf, then drain into the northern basins. Northwest winds may add to this phenomenon by causing some down-welling of surface waters along the northwestern coast of the Gulf.

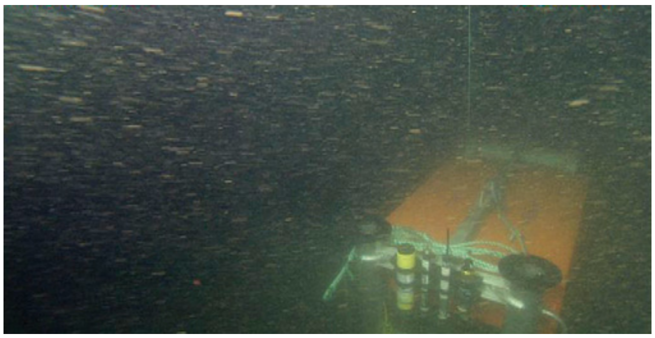


Figure 21: A "storm" of turbid water near the seafloor in the Delfin basin in the Northern Gulf of California.

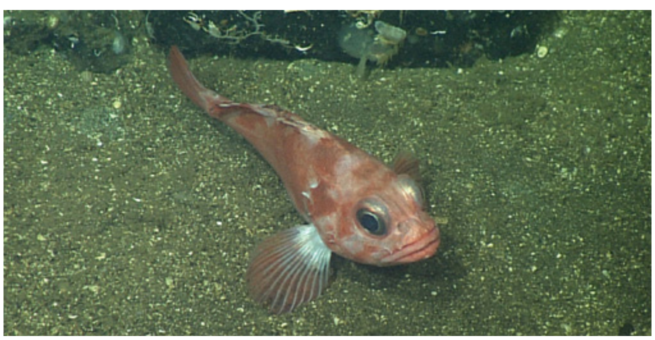


Figure 22: The splitnose rockfish, *Sebastes diploproa*, is about 35 centimeters (14 inches) long.

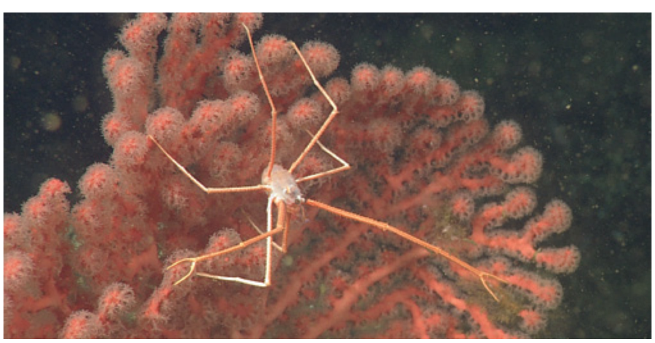


Figure 23: A new galatheid crab. The body is about three centimeters (one inch) long.

The R/V *Western Flyer* and remotely operated vehicle (ROV) *Doc Ricketts* enabled the benthic research team to perform surveys and collect samples of seafloor animals, deploy and recover the Benthic Respirometer System, and search for sulfide seeps using Chemist Ken Johnson's In Situ Ultraviolet Spectrophotometer sensor. Biological surveys in the Guaymas Basin showed abundant life near 1,000 meters depth (Figure 20), despite the low temperature and very low oxygen levels. Dives in the Delfin and Salsipuedes Basins found warmer and more oxygenated waters, as expected, but also highly turbid waters and very strong currents (Figure 21).

Discoveries made during these benthic surveys included geographic or bathymetric range extensions for a number of species. For example, splitnose rockfish (*Sebastes diploproa*) (Figure 22) and aurora rockfish (*S. aurora*) were observed at greater depths or further south than previously known. Several new species were also discovered. Some of the worms found in the sediments during the cruise are likely new discoveries. Other animals, including the small batfish (*Dibranchus* sp.) that was the focus of some respiration studies and a new species of galatheid crab (Figure 23) have been seen before but have not been described for science.

To understand better how seafloor animals will fare as ocean chemistry becomes more acidic, researchers used the Benthic Respirometer System (see page 10) to compare metabolism in urchins, brittle stars, and the small batfish. In addition to measuring respiration at the environmental conditions typically found in either the Guaymas or northern basins, conditions in some chambers were altered by adding seawater enriched with carbon dioxide to reduce the pH and simulate the acidic ocean of the future. Results indicate that the batfish responds most strongly to high oxygen levels and less so to reduced pH, indicating that oxygen is the more important environmental constraint on its metabolism.

The major conclusions from studies of the benthos in the Guaymas and northern GOC basins highlight the strong effect of low oxygen levels in the severe oxygen minimum

Figure 24: AUV Specialist Doug Conlin and AUV Group Leader Hans Thomas prepare the AUV *D. Allan B.* for launch.

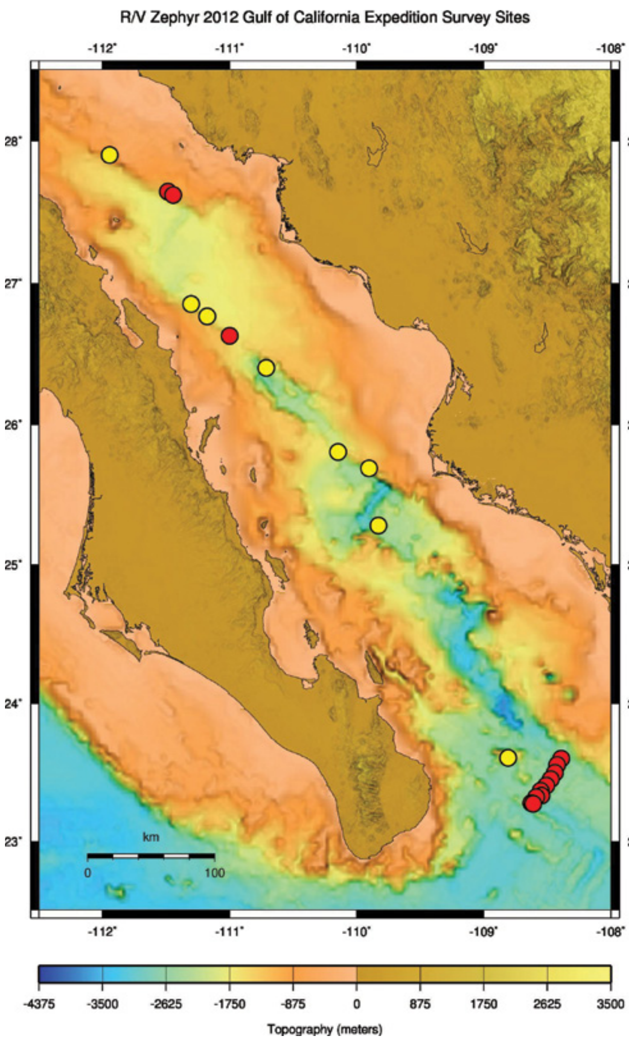


Figure 25: *D. Allan B.* survey locations during the 2012 Gulf of California expedition. The red dots mark the sites of maps shown elsewhere in this section.

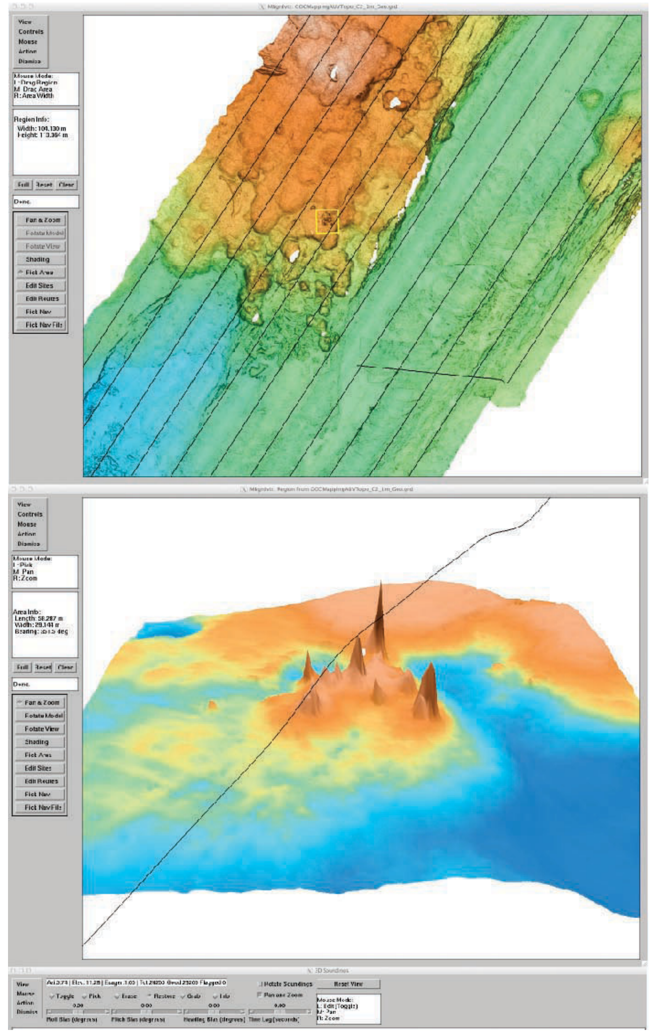


Figure 26: Hydrothermal vent chimneys identified from AUV bathymetric surveys. Display of bathymetry (top) after initial editing of mapping data with area of interest marked by yellow box. Lines indicate the AUV track. Three-dimensional perspective with no vertical exaggeration of the area of interest (bottom) where spikes indicate apparent vent chimneys.

zone on metabolism of benthic animals, and the likely role of oxygen and temperature in extending the depth range of some deep-sea organisms in the Gulf. Lastly, the entire research team was tantalized by the unusual warm, high-oxygen conditions found in the northern basins, which leave far more questions unanswered than answered.

Precise, just-in-time seafloor mapping

Many of the ROV dives made during the 2012 Gulf of California expedition were successful because of the detailed seafloor maps created by MBARI's autonomous underwater vehicle (AUV) team. A small cadre of MBARI personnel and Mexican collaborators on the research vessel *Zephyr* conducted high-resolution, autonomous seafloor surveys

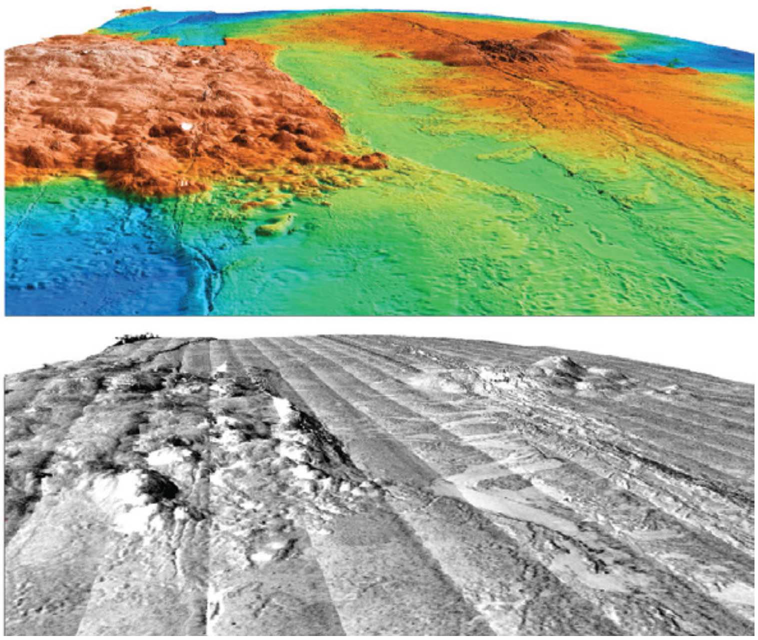


Figure 27: Perspective view with no vertical exaggeration looking northeast across a large sheet flow on the Alarcón Rise. Top, one-meter-resolution multibeam bathymetry with shading by illumination. Bottom, one-meter-resolution backscatter mosaic from chirp sidescan sonar data reveals variations in fine-scale texture of the lava flows. Linear depressions on the seafloor are artifacts of data collection.

using the AUV *D. Allan B.* (Figure 24), then quickly made the detailed maps available to the science teams aboard the R/V *Western Flyer* so they could plan ROV dive strategies.

The mapping team, led by Software Engineer David Caress and AUV supervisor Hans Thomas, completed 22 successful AUV missions during six cruise segments in March and April (Figure 25). These surveys produced maps of seafloor topography with details showing features as small as one meter across, along with subbottom profiles—images that show the structure of the layers of sediment below the seabed down to a 10-centimeter resolution. The coupling of the AUV and ROV dive programs meant that shipboard data processing and rapid communication of results were high priorities (Figures 26 and 27).

Detecting gases in the seafloor

Methane gas is present in huge quantities on Earth. In the atmosphere, methane is a critical heat-trapping gas. But the vast majority of methane that leaks from the interior of the Earth to the seafloor is consumed by organisms before it can ever get out of the sediments. This is one of the fundamental processes that hold our climate in balance. Observations of methane and the microbes and higher animals that utilize methane as a source of energy allow for better understanding of the Earth's methane budget.

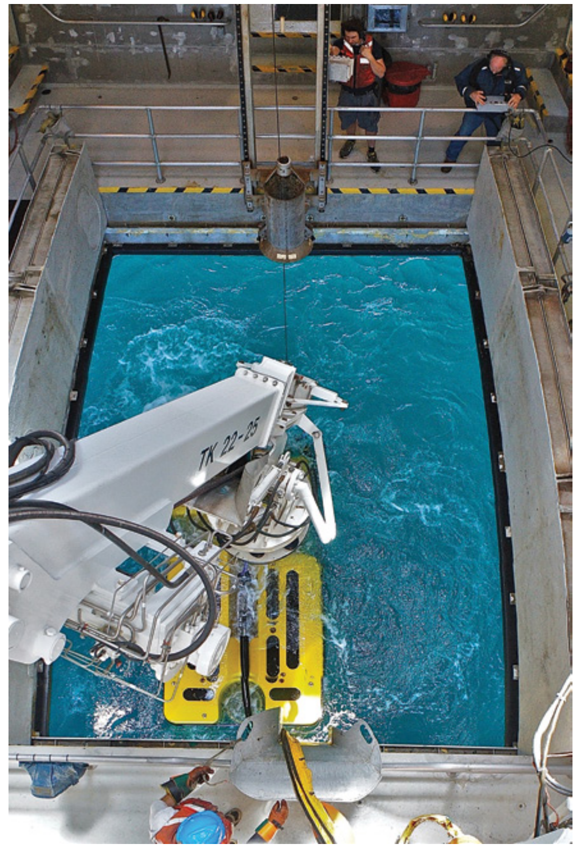


Figure 28: Recovering the ROV *Doc Ricketts* following a dive to investigate the chemistry of the deep seafloor.

During the 2003 Gulf of California expedition, Peter Brewer and his laboratory group used the newly developed deep-ocean laser Raman spectrometer to investigate the composition of the gas hydrates. Pairing high-resolution AUV mapping with the advanced chemical investigations using the second-generation laser Raman technology in 2012 brought MBARI exploration of ocean chemistry into a new mode of investigation.

The chemists' goals during this expedition were to test the detection limits for the new laser Raman system, investigate the sediment pore-water chemistry around the active methane gas vents, and explore seafloor features that the AUV mapping had revealed. The combination of bathymetry and subbottom profiler data served to identify sites of likely fluid and gas venting, and the biological communities found at such sites.

The science team used the ROV (Figure 28) to explore the Gulf's axial valley and a transform fault site—a spot where tectonic activity created cracks in the seafloor at right angles to the spreading center—and found methane and cold seeps, in addition to sulfur (Figure 29). Black mud, large fields of chemosynthetic clams, and fuzzy mats of bacteria were signs of chemicals venting from below. The Raman probe, inserted into the sediment (Figure 30) in a field of live clams, returned a signal clearly showing methane in the pore water within the sediment. The science team gathered water and sediment samples along with data, to be analyzed in the lab later for a clearer picture of the chemical activity in the area. These scientific observations and experiments conducted in situ enable researchers to directly test hypothesis and theories about seafloor geochemical processes.

Figure 29: This soft blob of bacteria pulsed as fluid flowed through the vent opening in the seafloor. The color indicates these microbes were feeding on sulfur. The absence of giant clams and tubeworms in the area suggests this was a fairly new vent as older ones usually teem with such life.

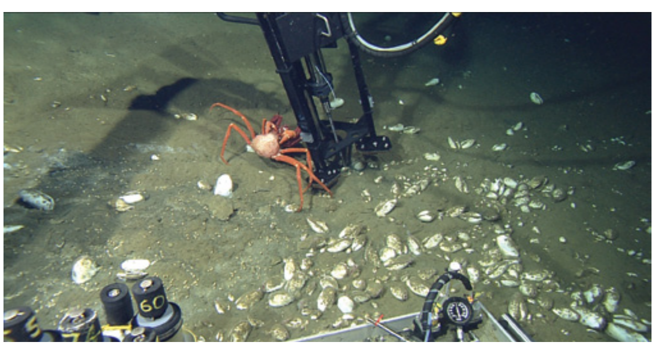


Figure 30: The laser Raman spectrometer inserted into the sediments in a clam field. The team "reached new lows" when it used a longer probe to measure chemical components as deep as 55 centimeters into the seafloor. The full analysis of the spectra obtained by the instrument will be carried out in the laboratory at a later date.

Exploring fault zones and fluid vents

Studies of faults and gas venting help expand the understanding of marine ecosystems and provide important information in coastal risk assessment programs. An understanding of fault movements in the GOC will provide insight into the fault activity further north along the San Andreas Fault and across all of California. The first objective for Geologist Charlie Paull and his team was to explore the fault zones with particular emphasis on identifying evidence of recent seafloor deformation. A second objective was to better understand the distribution and impact of fluid venting on the seafloor formations and biological communities, both directly along the active transform fault and elsewhere. It was of particular interest to assess whether the fault acts as a conduit for fluid flow.

First the active trace of the transform fault was identified on the AUV bathymetric map as a distinct line (Figure 31). Although other ridges occur on the seafloor within the surveys, many appeared to be features related to older inactive branches of the fault. The appearance of the active fault trace varied from subtle, as a horizontal relief of only a few centimeters in some places, to scarps tens of meters high and troughs tens of meters deep (Figures 31 and 32). In places where the relief across the active fault was minimal,

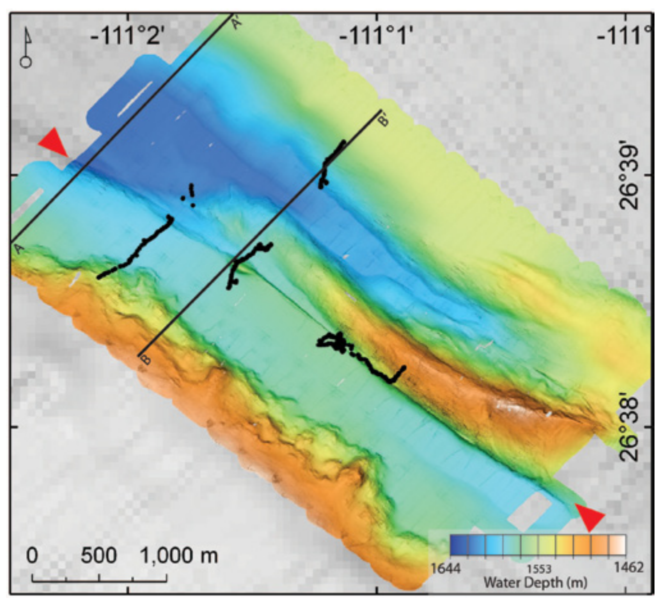


Figure 31: Color view of new high-resolution bathymetry from one AUV dive, superimposed on previous bathymetric map in grayscale, of the active transform fault in the Gulf. Red arrows mark the presumed active strand of the fault having a northwest to southeast orientation; the survey also showed some secondary fault lines. Black dots outline the paths of ROV dives. Lines A-A' and B-B' indicate locations of recorded seismic profiles.

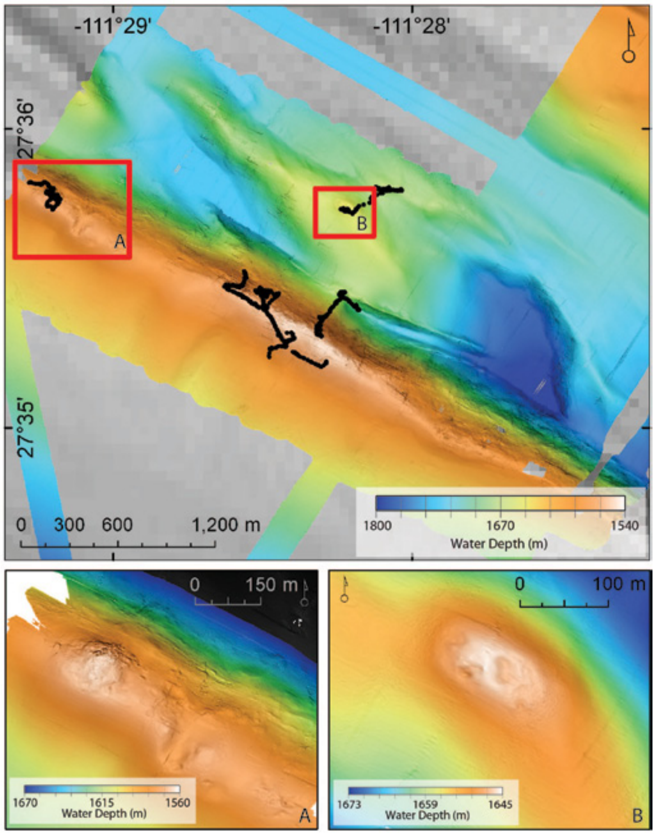


Figure 32: Color view of new high-resolution bathymetry from another AUV dive superimposed on previous bathymetric map in grayscale of a different section of the active transform fault in the Gulf. Black dots mark the paths of ROV dives. The ROV dives revealed that the distinctive morphology and inflated seafloor seen in the more detailed AUV maps (A and B) are associated with methane-derived carbonates and communities of chemosynthetic organisms.

it was frequently possible to locate the surface expression of this plate margin recorded as a small scarp on the ROV video (Figure 33). The simplicity of locating the plate was remarkable. Without the AUV-generated maps, it would have been impossible to locate the active trace of the fault based solely on ROV observations or subbottom profiles (Figure 34). Knowledge of the precise location of the plate boundary guided ROV transects to sample sediments and pore water, collect gas, and measure sediment temperatures.

Sediment temperatures indicated that the geothermal gradient in the vicinity of the fault is almost 20 times more pronounced than the average, although it decreases very quickly away from the fault. Sediment cores taken with the ROV reveal evidence of physical deformation resulting from fault movements (Figure 35). However, no evidence of active fluid venting was found along the fault trace during this expedition.

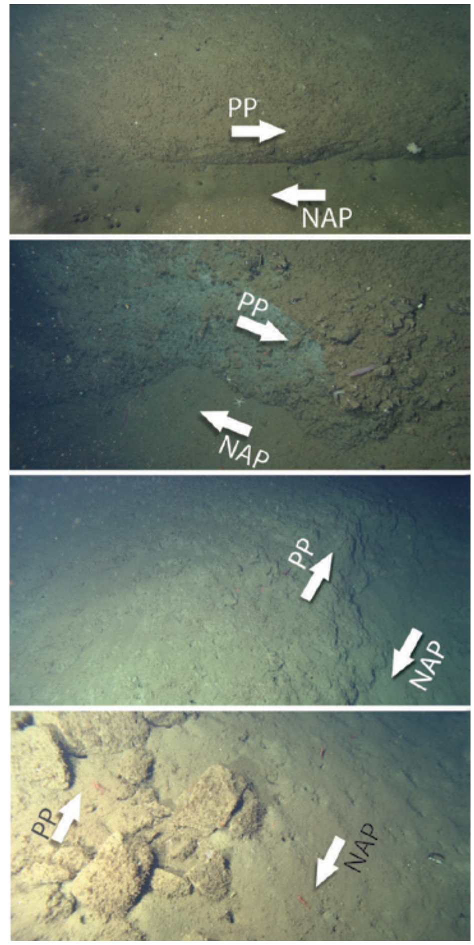


Figure 33: Small scarps on the Gulf of California seafloor where the transform fault separates the Pacific tectonic plate (PP) and the North American plate (NAP). These were identified as the part of the plate boundary because they follow the straight line of steeper scarps and troughs further along the fault trace in the AUV-generated maps.

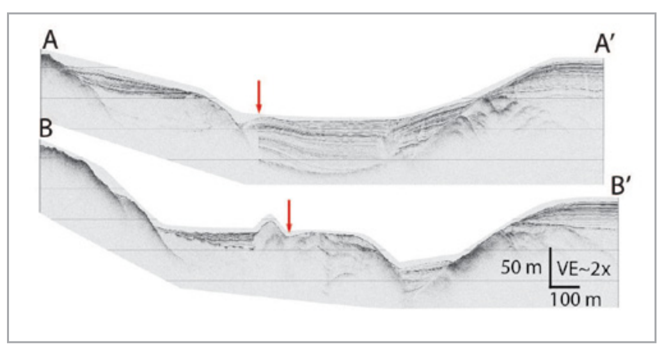


Figure 34: Subbottom profiles showing structure beneath the seafloor across the transform fault seen in figure 31. The location of the active strand of the fault (red arrow) would be difficult to identify based on subbottom profiler data alone.

Figure 35: Images of segments from three sediment cores (approximately eight centimeters in diameter) taken in the vicinity of the active fault. Core A shows tilted sediment layers. Core B shows highly deformed layers. Core C was taken directly within the fault and does not show any distinct internal layering.

Analysis of the sediment samples is enabling interpretation of the geologic history and development of the fault zones. Two recurring rock characteristics were observed. The seafloor within the deeper small basins was covered with sediments rich in plankton fossils, which apparently entered the basins as sedimentary flow down a steep slope. These deposits correspond with the layered sediment sequences shown in the subbottom profiles (Figure 34) and are relatively recent deposits. Older deposits of firm mudstone, filled with dolomite, a re-crystalized carbonate mineral, were also common. The presence of dolomite indicates that these rocks have undergone extensive alteration, which is unusual for marine sediments near the seafloor. The widespread exposure of significantly altered sediments on the floor of the Gulf shows that this area is not experiencing significant modern sediment accumulation. These samples also help elucidate how the position of the active fault has shifted over time.

The AUV-generated maps also revealed distinctive patches of rough seafloor on the northeast flank of the Guaymas Basin. These patches, up to 100 meters across, occur on the higher crests away from the fault traces. Closer examination with the ROV showed that this rough topography consists of broken and irregular blocks of methane-derived carbonates, separated by seafloor craters and open cracks one to two meters deep. Beds of living chemosynthetic organisms were common within these cracks and craters. In some places, streams of methane bubbles were trapped by overhanging slabs within the cracks to form a web of gas hydrate-coated bubbles. One hypothesis is that the seafloor in these areas has been raised by the formation of gas hydrate at depth.

The recognition that these patches of rough topography are associated with fluid venting enabled the research team to identify previously unknown seepage sites based on the remote sensing data collected with the AUV. This proved to be an extremely effective way to direct biological sampling by MBARI's molecular ecology group.

Spectacular lava flows and hydrothermal chimneys

The Gulf of California is marked with abundant signs of volcanic activity but the lava-strewn seafloor has been grossly understudied. MBARI's expedition offered a chance to fill in some of the missing information about this volatile territory.

Marine Geologist David Clague and his team focused their segment of the expedition on the Alarcón Rise and nearby Alarcón Seamount volcanic chain (Figure 36). The new AUV maps were valuable for targeting ROV dives on lava flows, faults, and hydrothermal chimneys.

The Alarcón Rise—a 50-kilometer-long segment of the East Pacific Rise that spans the mouth of the Gulf of California—is comprised of pillow, lobate, and sheet lava flows (Figure 37) that vary dramatically along its axis. The southern third of the rise is dominated by an extensive young sheet flow that erupted along an eight-kilometer-long fissure. Just north of this large sheet flow are a young flat-topped cone, an older low shield, and numerous smaller pillow mounds. The northern section of the rise is highly fractured and contains a steep, rugged lava dome.

This dome was the most surprising discovery. Clague's team knew that it was a high-priority region to explore with the ROV as soon as they saw it on one of the new AUV maps. The irregular-shaped feature looked more like rugged, thick, pasty flows common on land rather than smoother

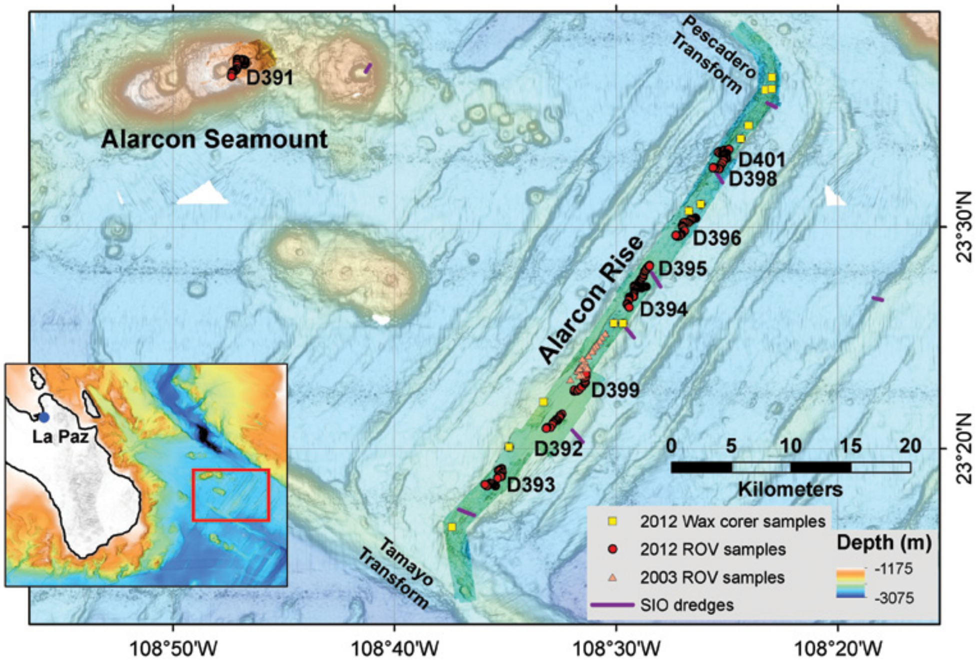


Figure 36: Map of the Alarcón Rise and Alarcón Seamount volcanic chain showing one-meter resolution AUV bathymetry superimposed on 100-meter resolution shipboard bathymetry. The sites of all samples taken in the area are shown as well as locations of 10 ROV dives identified by dive numbers (D393-D401).

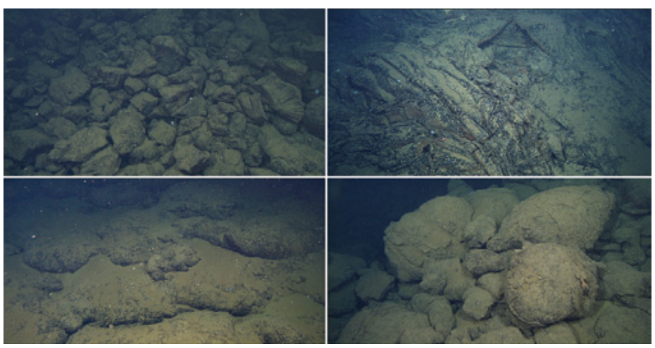


Figure 37: Lava formations seen on the Alarcón Rise, clockwise from upper left: talus, sheet flow, pillow flow, and lobate flow.

features usually encountered along mid-ocean ridges. The dives revealed steep slopes, blocky flows, talus blocks, and abundant gravel. Chemical analyses of the rock samples confirmed that the dome is composed of lava with high silica content unlike any previously collected from a mid-ocean ridge, making this a very significant find (Figure 38). These silica-rich lavas are more typical of explosive, continental settings like Mount Saint Helens. Even more intriguing, preliminary analysis suggests there was no contamination by continental material during their formation, which means that these unusual rocks were formed by processes occurring within the deep-sea ridge system. By studying these samples, the team aims to gain an understanding of how such structures could form at a mid-ocean ridge and how explosive their eruptions might be.

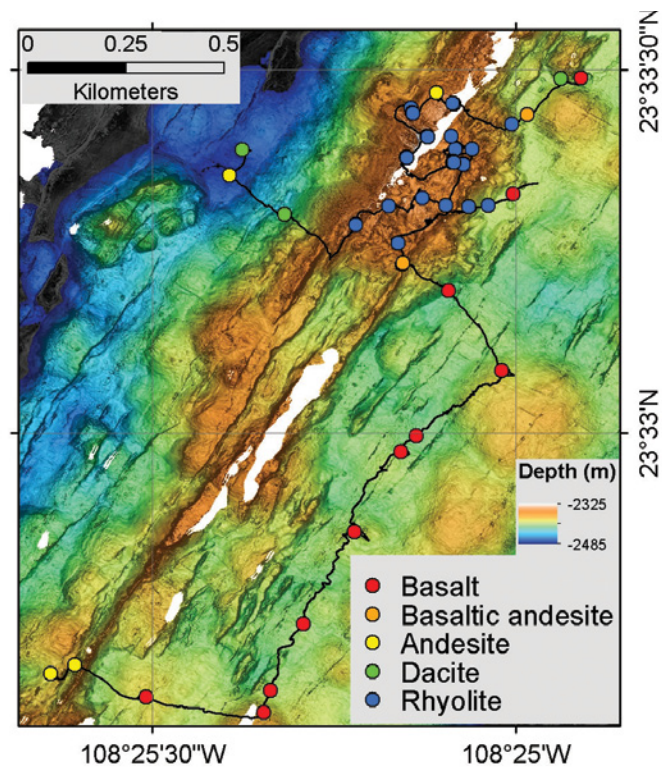


Figure 38: AUV bathymetric map of the rugged dome discovered on Alarcón Rise. Lava sample sites color coded by rock type show the main dome is composed of rhyolite, a silica-rich lava (blue dots). Younger basalt flows (red dots) are located to the east of the dome.

The maps of the rest of the rise revealed features more typical of a mid-ocean ridge system. Lava flow boundaries are distinguishable on the AUV maps, so it was possible to plan ROV dives that could traverse a maximum number of flow segments to collect volcanic rocks and sediment cores. The glasses from the lava samples were analyzed chemically and the data are being used to confirm and refine flows on the AUV map. The shells of foraminifera—tiny animals with calcium carbonate shells—extracted from the base of the sediment cores are being carbon dated to provide minimum ages for the sampled flows. This information, along with the AUV maps and ROV dive observations, will help unravel the history of the entire Alarcón Rise. The wide range of lava compositions and flow morphologies along the rise make it an ideal location to explore fundamental volcanic processes that should be applicable along the global mid-ocean ridge system, something of interest to geologists worldwide.

The AUV maps also allowed Clague's team to examine the distribution of active and inactive hydrothermal vents along the rise. The team identified numerous chimneys in two active vent fields (Figure 39). Active venting ranged from high-temperature black smokers (more than 300 degrees Celsius or 572 degrees Fahrenheit) to low-temperature seeps. Vibrant biological communities surround the active vents, including dense clusters of bright red giant tubeworms (*Riftia pachyptila*), carpets of bacterial mats, galatheid crabs, and large clams (*Calyptogena magnifica*). These communities resemble vent communities further south along the East Pacific Rise more than communities within the Gulf of California. Genetic comparisons between these communities will provide a better understanding of the evolution and distribution of vent species along the global ridge system.

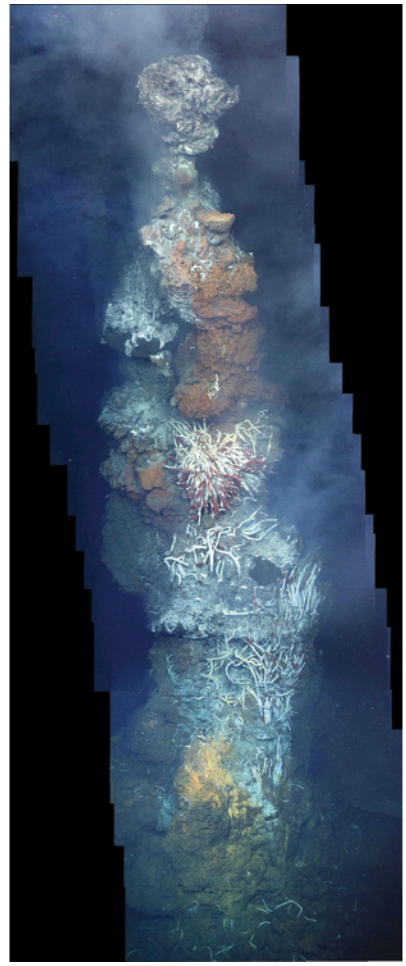


Figure 39: Mosaic of overlapping video frames shows a 13-meter-tall active hydrothermal vent on Alarcón Rise.

Shedding light on species distributions

The diverse shallow-water animals of the GOC—from the endangered vaquita dolphin to migratory whales and sea turtles—hint that the deep-sea faunas found farther north at the Guaymas Basin hydrothermal vents and nearby cold-water hydrocarbon seeps could also be unique. The Guaymas Basin vents occur on a thick (600-meter) layer of sediment rich in hydrocarbons, whereas vents to the south along the East Pacific Rise—a 9,000-kilometer-long, fast-spreading mid-ocean ridge—occur on recently erupted basalts. Except for the giant *Riftia* tubeworms, very few species appeared to be present at other eastern Pacific vent and seep sites. Now, as a consequence of the 2003 and 2012 expeditions to the Gulf, MBARI scientists have learned that the Gulf habitats are directly connected on evolutionary and ecological time scales with coastal seeps along the North American margin. The newly discovered hydrothermal vents at Alarcón Rise host essentially the same fauna found at basaltic vents along the East Pacific Rise, connecting to the south. The *Riftia* tubeworms, vesicomyid clams, and crabs found at Alarcón are genetically identical to those occurring along the East Pacific Rise, but of those species, *Riftia* alone also occupies the sedimented vents in Guaymas Basin. In addition, the Guaymas Basin hot vents host annelid worms and molluscs that also occur at nearby hydrocarbon seeps along the Guaymas Transform Fault (Figure 40).

A number of animals once proclaimed to be "vent endemics" are now known to inhabit seeps as well, and they are connected genetically to populations occurring along the North and Central American margins from Costa Rica

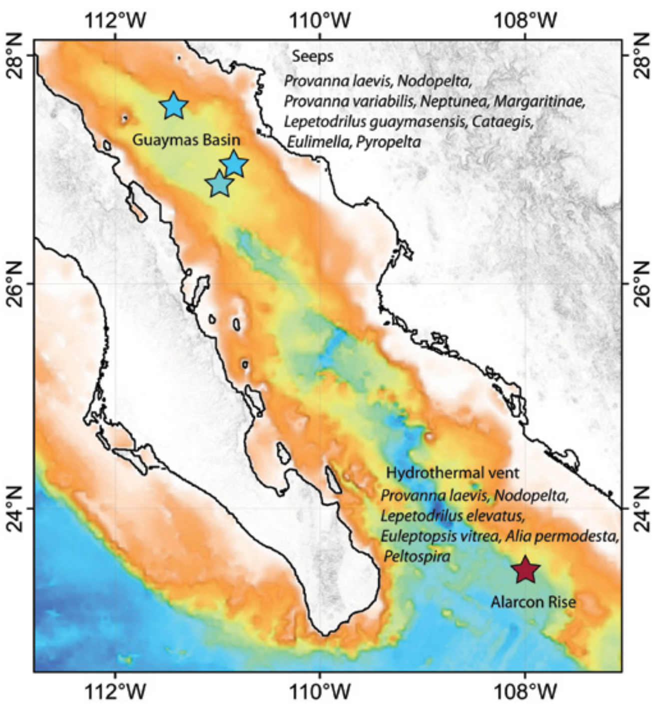


Figure 40: Dominant animal species observed at a newly discovered hydrothermal vent on the Alarcón Rise (red star) and cold-water hydrocarbon seeps to the north (blue stars).

through Monterey Bay and Oregon to Washington. For example, the snail *Provanna laevis*, once considered endemic to Guaymas Basin vents is now known to occur at vents along the Juan de Fuca and Gorda Ridges in the Northeast Pacific and in seeps from Monterey Bay to the Costa Rica margin. The new samples obtained from the Gulf also identified significant range extensions for a number of deep-sea species and discoveries of several new annelid worm species that remain to be named. DNA-barcode libraries and photographs from this research will aid future researchers in the identification and enumeration of deep-sea animals. Such exploratory ventures lead to discoveries that foster understanding of how widely distributed species are connected and interdependent.

Building an ROV to explore the Arctic

The Arctic region is a key site for assessing impacts associated with changing climate, both in past geological history and the present. Expanding research into the scientifically significant higher latitudes was the impetus for the building of a small remotely operated vehicle (ROV). While the Arctic Ocean is commonly acknowledged as one of the least explored parts of the Earth, ROVs and other seafloor imaging tools have rarely been available for scientists to explore the depths in the western Arctic. Many ROVs are extremely expensive to use, require substantial crews to operate, occupy considerable deck space, and can only be mobilized in major ports. MBARI's new "mini ROV" fills the need for a small, easy-to operate vehicle that is practical on multidisciplinary expeditions, which are the norm for high-latitude cruises.

A more specific motivation for building the mini ROV was to support further Arctic research by Charlie Paull and his Canadian colleagues. The group's goal is to understand the dynamics of the decomposition of sub-surface gas hydrate and permafrost, evaluate whether these are coupled with sea-level and climate cycles, and determine the potential impacts that decomposition has on the seafloor. During cruises in 2003 and 2010, the researchers documented that methane was escaping from the mid-shelf and along the shelf edge in the Canadian Beaufort Sea. The venting gas is inferred to be coming from permafrost or deeper gas hydrate deposits that are still warming from relatively warm Arctic Ocean water that flooded the truly cold permafrost in the area at the end of the last glacial period. While remote sensing suggested that gas might be venting on the slope, that area of the slope was too deep to sample with the available ROVs.

Thus, a 2012 cruise was planned with the mini ROV to trace acoustically defined gas plumes to their seabed source, appraise the character of gas release, image the sites, identify the associated biological communities, and sample the escaping gas.

Engineers Dale Graves and Alana Sherman developed the system from concept through a field deployment with all required core functions in only 18 months, with support from the Geological Survey of Canada and by recycling instruments and ROV components already available at MBARI. By June the new mini ROV was completed and shipped off to Canada to be loaded onto the Canadian icebreaker *Sir Wilfrid Laurier* for a fall Arctic Ocean expedition (Figure 41).

The mini ROV provides MBARI with a "flyaway" ROV system capable of operating to one-kilometer (3,280 feet) depth on ships of opportunity. The core vehicle includes high-definition video, three auxiliary video cameras, sonar, a conductivity-temperature-depth (CTD) sensor, and a multi-purpose tool sled. The core vehicle was designed as a generic platform that can be used for a wide variety of science applications. A science/operations team of just three people can deploy the vehicle. The small size and easy mobilization are definite advantages in shipping and operating off ships with limited space. Training MBARI staff or testing the control system can be done in MBARI's test tank without sending a ship to sea.

Paull, Graves, and Sherman joined the *Sir Wilfrid Laurier* in the Canadian islands, where they completed eight dives as deep as 780 meters. The mini ROV successfully completed all the cruise objectives, including the sampling of the gas escaping from the continental slope in the Canadian Arctic (Figure 42). These efforts have produced what is arguably the best documentation of gas venting anywhere in the Arctic Ocean, adding significantly to the understanding of how these vents affect the stability of the seafloor, and therefore the potential for large submarine landslides, which in turn could trigger a tsunami.

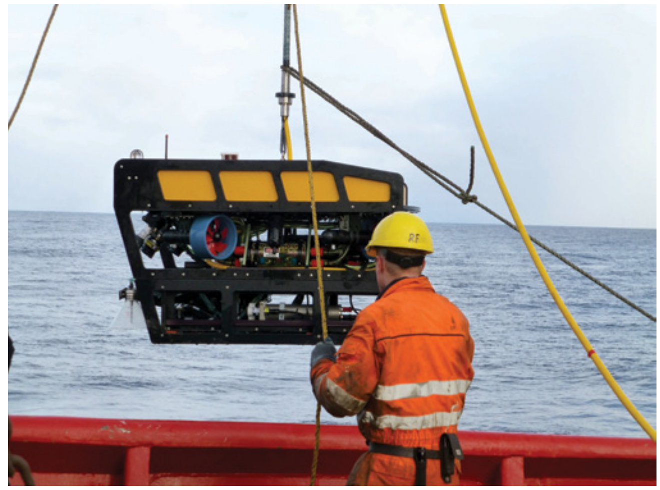


Figure 41: The new mini ROV is launched into the Arctic Ocean from the Canadian icebreaker *Sir Wilfrid Laurier*.

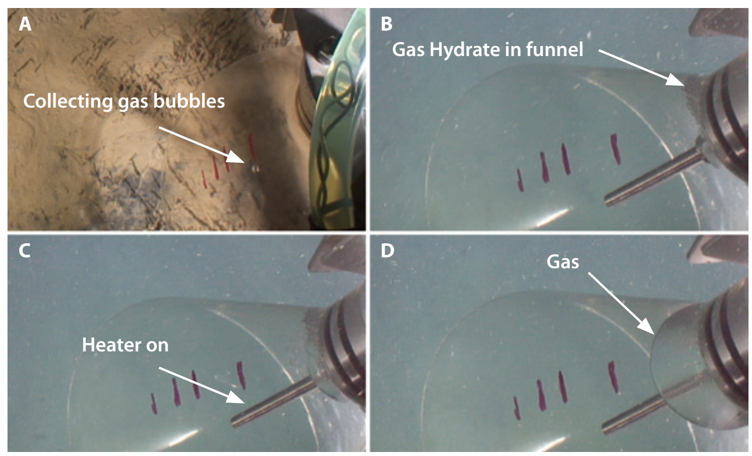


Figure 42: The mini ROV collected gas venting from the seafloor on the continental slope at 460-meters depths in the Arctic Ocean. A.) Methane bubbles emanating from the seafloor were captured in a funnel mounted on the mini ROV. At these ambient pressures and temperatures, individual gaseous methane bubbles became coated with a solid gas hydrate skin. B. & C.) Multiple bubbles collected at the top of the funnel. D.) A heater (the round rod extending into the funnel) was used to decompose the hydrate-coated bubbles to form a pure gas. A sample of the gas was then withdrawn into a cylinder via remote control of the mini ROV.

California Current

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Gernot Friederich, Jules Friederich, Monique Messié, Reiko Michisaki, Chris Wahl
Collaborators: Martín Hernández Ayón and Gabriela Y. Cervantes, Universidad Autónoma de Baja California, Ensenada; Marguerite Blum, University of California, Santa Cruz; Carmen Castro, Higher Council for Scientific Investigations, Vigo, Spain; Curt Collins, Naval Postgraduate School, Monterey, California; Dana Lacono, Alexander Limardo, Erich Rienecker, and Haibin Zhang, MBARI; Jason Smith, Stanford University, California

Midwater Research in the Gulf of California

Project lead/manager: Steven Haddock
Project team: Lynne Christianson, Hendrik Jan Ties Hoving, George Matsumoto, Meghan Powers, Kyra Schlining
Collaborators: Stephanie Bush, University of Rhode Island, Kingston; Rebeca Gasca, El Colegio de la Frontera Sur, Chetumal, Mexico; Karen Osborn, Smithsonian Institution, Washington, D.C.; Erik Thuesen, Evergreen State College, Olympia, Washington

Benthic Ecology Studies in the Gulf of California

Project leads: James Barry, Ken Johnson
Project manager: Kurt Buck
Project team: Bob Herlien, Linda Kuhnz, Chris Lovera, Josi Taylor, Patrick Whaling
Collaborators: Adriana Gaytán-Caballero and Yossellin Tapia De la O, Universidad Nacional Autónoma de México, Mexico City

Gulf of California Seafloor Mapping

Project leads: David Caress, Hans Thomas
Project manager: Hans Thomas
Project team: Krystle Anderson, David Clague, Doug Conlin, Eve Lundsten, Julie Martin, Jennifer Paduan, Charles Paull, Duane Thompson
Collaborators: Beatriz Eugenia Mejia Mercado, Ana Cristina Sanchez Garcia, and Alejandro Hinojosa, Center for Scientific Research and Higher Education at Ensenada, Baja California, Mexico; Carolina Nieves-Cardoso and Miguel Santa Rosa-del Rio, Universidad Autónoma de Baja California, Ensenada, Mexico

Deep-Sea Chemistry

Project lead: Peter Brewer
Project manager: Ed Peltzer
Project team: Nancy Barr, Peter Walz
Collaborators: Martín Hernández Ayón and Gabriela Y. Cervantes, Universidad Autónoma de Baja California, Ensenada; Abbey Chrystal and Joseph Murray, University of California, Santa Cruz

Faults, Seeps, and Vents of the Gulf of California

Project lead: Charles Paull
Project manager: Roberto Gwiazda
Project team: Krystle Anderson, David Caress, Eve Lundsten, Hans Thomas
Collaborators: Teresa Cardoza, Ken Johnson, Shannon Johnson, Josh Plant, Susan von Thun, Robert Vrijenhoek, and Kris Walz, MBARI; Scott Dallimore, Geological Survey of Canada, British Columbia; Brian Edwards and Mary McGann, U.S. Geological Survey, Menlo Park, California; Luis Terán González, Mexican Geological Survey, Sonora, Mexico; Juan Carlos Herguera, Center for Scientific Research and Higher Education at Ensenada, Baja California, Mexico; Sigrid Katz and Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Thomas Stevens, University of London, United Kingdom

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: David Caress, Lonny Lundsten, Julie Martin, Ryan Portner
Collaborators: Julie Bowles, University of Wisconsin, Milwaukee; Juan Carlos Braga, University of Granada, Spain; Paterno Castillo, David Hilton, and Edward Winterer, Scripps Institution of Oceanography, La Jolla, California; Brian Cousens, Carleton University, Ottawa, Canada; Brian Dreyer and Don Potts, University of California, Santa Cruz; Fred Frey, Massachusetts Institute of Technology, Cambridge; Paul Fullagar, University of North Carolina, Chapel Hill; Tom Guilderson, Lawrence Livermore National Laboratory, Livermore, California; Rigoberto Guardado France, Carolina Nieves-Cardoso, Hiram Rivera Huerta, Miguel Santa Rosa del Rio, and Ronald Spelz Madero, Universidad Autónoma de Baja California, Ensenada, Mexico; James Hein, Mary McGann, and James Moore, U.S. Geological Survey, Menlo Park, California; Christoph Helo, University of Mainz, Germany; Rosalind Helz, U.S. Geological Survey, Reston, Virginia; Tessa Hill and Rob Zierenberg, University of California, Davis; Sichun Huang, Harvard University, Cambridge, Massachusetts; Anthony Koppers, Oregon State University, Corvallis; Kathie Marsaglia, California State University, Northridge; Larry Mastin and David Sherrod, U.S. Geological Survey, Vancouver, Washington; Craig McClain, University of North Carolina, Durham; Michael Perfit, Florida State University, Tallahassee; Willem Renema, Leiden University, the Netherlands; John Smith, University of Hawaii, Honolulu; John Stix, McGill University, Montreal, Canada; Dorsey Wanless, Woods Hole Oceanographic Institution, Massachusetts; Jody Webster, University of Sydney, Australia; Guangping Xu, Colorado State University, Fort Collins

Gulf of California Expedition

R/V Western Flyer
Master: Ian Young
Crew: Paul Ban, Dan Chamberlain, Cole Davis, Eric Fitzgerald, George Gunther, Craig Heihn, Jason Jordan, Olin Jordan, Andrew McKee, Patrick Mitts, Matt Noyes, Lance Wardle, and Shaun Summer

ROV Doc Ricketts
Chief Pilot: Knute Brekke
Crew: Ben Erwin, Eric Martin, Randy Prickett, Bryan Schaefer, Mark Talkovic, and Robert Waters

R/V Zephyr
Master: Aaron Gregg
Crew: Paul Ban, Jim Boedecker, Phil Sammet, and Perry Shoemake

Mini ROV

Project lead: Charles Paull
Project manager: Dale Graves
Project team: Chad Kecy, Alana Sherman

Weird and Wonderful

When a novel species or peculiar-looking creature is revealed in ROV videos of the deep, classic questions of their ecology arise. What food is available? How does that one eat? How do behaviors and metabolism contribute to survival in cold, dark depths? Why did some adapt to live in regions with very low oxygen? We are left to wonder if our weird and wonderful discoveries can inspire others to learn and care about the ocean.

The vampire that doesn't eat what you think

The vampire squid's very name conjures up images of a vicious predatory animal. But a close study of deep-sea video and live animals in the laboratory, as well as the stomach contents of dead animals, has shown that these amazing creatures actually survive on a diet of marine waste—bits of dead bodies, mucus, and feces. MBARI Postdoctoral Fellow Henk-Jan Hoving and Senior Scientist Bruce Robison determined that, unlike its relatives the octopuses and squids, which eat live prey, the vampire squid uses two thread-like filaments to capture bits of organic debris that sink down from the ocean surface into the deep sea (Figure 43). The soft-bodied, passive creature, about the size, shape, and color of a football, inhabits the deep waters of all the world's ocean basins at depths where there is almost no oxygen, but also relatively few predators. After collecting live animals with MBARI's remotely operated vehicles (ROVs), Hoving found that if he placed bits and pieces of microscopic animals into a tank with a vampire squid, the food particles would stick to one of the string-like filaments that the animal sometimes extends outward from its body. The vampire squid would then draw the filament through its arms, removing the particles from the filament and enveloping them in a glob of mucus. Finally, the animal would transfer the glob to its mouth and consume it.

The organic material that forms the bulk of the vampire squid's diet would not seem to be particularly nutritious. However vampire squids complement their frugal diet with an extremely energy-efficient lifestyle and unique adaptations. Their bodies are neutrally buoyant, so they don't have to expend energy to stay at a particular depth. Even better, they don't have to swim to find food, but simply extend their filaments to collect food that drifts past them. Perhaps best of all, vampire squids don't have to expend much energy avoiding predators, because they live at depths where there is so little oxygen that few other animals can survive.

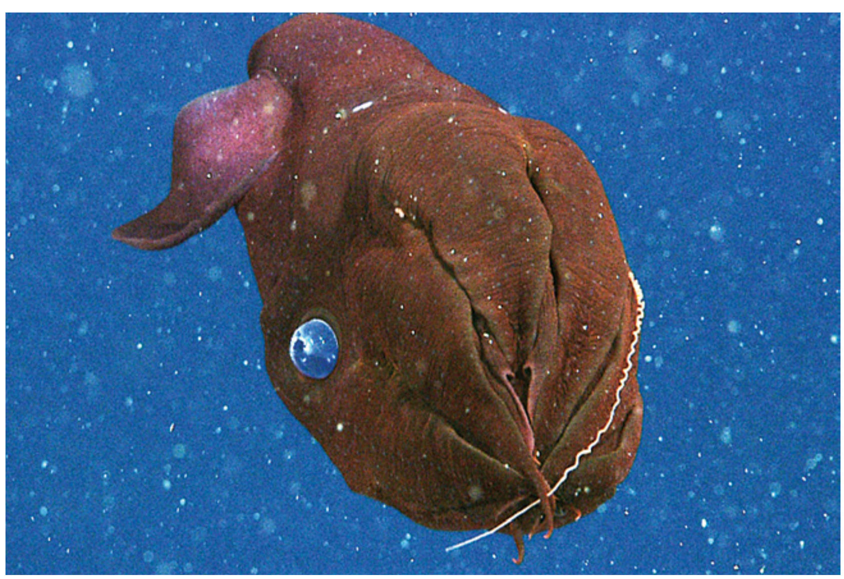


Figure 43: This close-up view shows a vampire squid using its arms to scrape food off of one of its filaments.

Extraordinary new sponge is carnivorous

The mysteries of the deep never cease to capture the public's imagination. When MBARI Research Technician Lonny Lundsten and his colleagues reported this past year on a delicate-looking sponge that actually feasts on the animals around it, the story spread like wildfire. By year's end, well over two million people had visited the MBARI YouTube channel to take a look at this unusual animal that can grow as big as 60 centimeters (two feet) across.

Chondrocladia lyra is called the harp sponge because its basic structure, called a vane, is shaped like a harp or lyre (Figure 44). Each vane consists of a horizontal branch supporting several parallel, vertical branches. Yet despite its delicate appearance, this sponge is a deep-sea predator. The harp sponge captures tiny animals that are swept into its branches by deep-sea currents. Typical sponges feed by straining bacteria and bits of organic material from the seawater they filter through their bodies. However, carnivorous harp sponges snare their prey—tiny crustaceans—with the barbed hooks that cover the sponge's branching limbs. Once the harp sponge has its prey in its clutches, nearby cells engulf and slowly begin to digest it. This unique method of feeding in carnivorous sponges is an adaptation to the food-poor deep sea.

Using MBARI's remotely operated vehicles (ROVs), researchers collected two sponges and made video observations of 10 more, finding sponges with up to six vanes radiating out from the organism's center. Scientists believe the harp sponge has evolved this elaborate candelabra-like structure in order to increase the surface area it exposes to currents, much like sea fan corals. The harp sponge is an extraordinary example of the kind of adaptations that animals make in order to survive in the hostile environment of the deep seafloor.

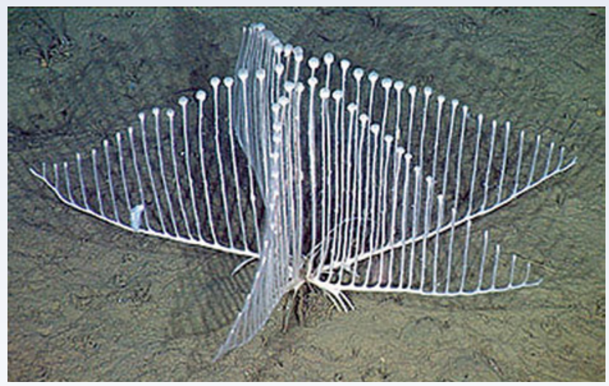


Figure 44: The recently described carnivorous sponge, *Chondrocladia lyra*. The "harp sponge" is found off the coast of California at depths between 3,300 and 3,500 meters (10,800–11,500 feet).

Upside-down fish carries a long lure

Most of what is known about the unusual whipnose anglerfish (*Gigantactis gargantuan*) comes from about a dozen females, all collected in the North Pacific at depths of 500 to 1,300 meters. The fish has been seen as big as 41 centimeters (16 inches). Previously the only time another research team observed this anglerfish, it was swimming upside down. Since it was swimming just above the seafloor, it was thought to be trolling for benthic invertebrates. During an expedition off of Monterey Bay in 2012, Steve Haddock's group spotted this specimen in 700 meters of water, 2,700 meters above the seafloor (Figure 45). Although far from the bottom, the fish observed by Haddock also maintained the upside-down posture. The fish can vibrate its glowing lure and can also pull it back over its head. How it gets its prey anywhere near its mouth remains a mystery!

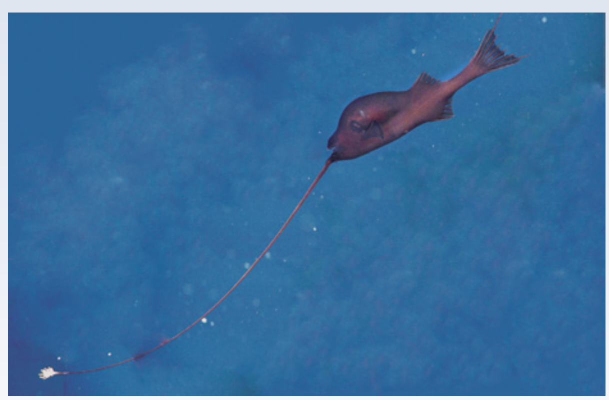


Figure 45: The lure of the whipnose anglerfish is very long, with a bioluminescent tip.

A fish that doesn't swim well

While exploring the seafloor in the middle of the Gulf of California, scientist Jim Barry and his team found that some fishes were unexpectedly abundant, including an odd fish called the pancake batfish (*Dibranchus* sp.), which is roughly 15 centimeters (six inches) long (Figure 46). The diversity and abundance of fishes and invertebrates was expected to be fairly low at 950-meter depths, owing to the pronounced low oxygen levels in the oxygen minimum zone (OMZ). Nevertheless, the pancake batfish was common, albeit one of the oddest looking creatures encountered. True to its name, the pancake batfish appears as "flat as a pancake" as if it were roadkill. As expected from its shape, it is a very poor swimmer. Consequently, these batfish were easy to capture with the ROV suction sampler to investigate further. It appears these fish obtain sufficient oxygen through their large gills to support their mostly sedentary behavior in the bathyal depths of the Gulf of California.

Figure 46: The flattened pancake batfish was abundant on the seafloor near Isla Tortuga in the Gulf of California.

Dance and science: An unconventional pas de deux

In 2010, MBARI entered into an unconventional experiment with local dance company SpectorDance. Together the collaborators posed the following questions: Can live performance deepen understanding and foster public dialogue on the complex issues threatening ocean health? Can merging science and dance reach broader audiences? The result was *Ocean*, a 35-minute performance piece that weaves material from filmed interviews with leading ocean scientists, high-definition video, original music, and choreography together into a multi-sensory composite piece (Figure 47). Topics highlighted by the piece include marine pollution, changing ocean chemistry, storm patterns, extinction of species, the food web, the interconnectedness of all things, sustainable practices from indigenous cultures, and hope for the future. By bringing together information and inspiration, *Ocean* offers an innovative and exciting way to deliver science, a critical step toward making informed decisions regarding responsible stewardship of the world ocean.

In 2011-2012, *Ocean* was performed by dance professionals 13 times throughout Monterey County—in addition to onsite educational programs at several local schools. *Ocean* was also presented at TEDx Monterey and at the Smithsonian Institution in Washington, D.C. Each performance included a brief introductory presentation by an MBARI researcher and ended with an informal question and answer session. These sessions were both entertaining and educational, and helped to alleviate some of the challenges of bringing the climate change story to a diverse audience.

For the artist/dancer, scientific information fuels the imagination and opens a door for the power of dance to make a difference. For the scientist, art/dance provides a fresh way to address the task of making complex research results accessible and understandable for the general public. The crossing of disciplines has exciting potential to create new languages for fostering communication and understanding.

Figure 47: Paige Guthormsen, Lilly Nguyen, and Maria Basile perform a dance segment as part of the SpectorDance *Ocean* program.

On the Horizon

Research cruises far from Moss Landing allow MBARI scientists to study natural phenomena, potential hazards, and human impacts that don't occur in our local waters. The coming year will be busy with a wide range of expeditions on MBARI ships and on other vessels. With ever-increasing interest in the use of autonomous systems at sea, MBARI engineers are also developing and refining the capabilities of the AUV fleet.

Distant field missions in 2013

Both MBARI research vessels, our remotely operated vehicles (ROVs), and autonomous underwater vehicles (AUVs) will travel south and north to revisit areas of the deep seafloor where MBARI researchers had previously discovered sites of gas and oil venting and volcanic eruptions, as well as suspected weapon dump sites (Figure 48).

Heading south

MBARI research vessel *Rachel Carson* will conduct AUV mapping surveys in Southern California as part of Chemist Peter Brewer's research program. Target areas include active gas vents and oil seeps, as well as designated chemical weapon dump sites near the Channel Islands. The seafloor off the coast of Santa Monica is an extraordinary region for observing the consequences of low oxygen and high fluxes of methane and hydrogen sulfide, making it a good location for learning about fundamental seafloor processes that could become more widespread in the future. By sending the AUV in advance, subsequent ROV dives can focus on specific sites where seafloor features indicate that gas venting is likely. Piggybacking on this project, Molecular Ecologist Bob Vrijenhoek will also use the new bathymetric maps to guide collections of invertebrate animals from chemosynthetic communities that occur at any newly identified seeps, as part of a study on the role of seeps in the dispersal of chemosynthetic species.

The Southern California mission also provides the first opportunity for MBARI's large institutional initiative, CANON (see page 4), to venture far afield from Monterey Bay. Researchers will employ the long-range AUV and the water-sampling AUV in concert with other instrumentation to research harmful algal blooms (HABs). This collaborative project with the Ecology and Oceanography of Harmful Algal Blooms program of NOAA will allow comparisons of the HAB ecology in central and southern California. No single study has yet attempted to directly compare these environments, and therefore no comprehensive theory or model exists regarding the development and progression of HABs along the California coast.

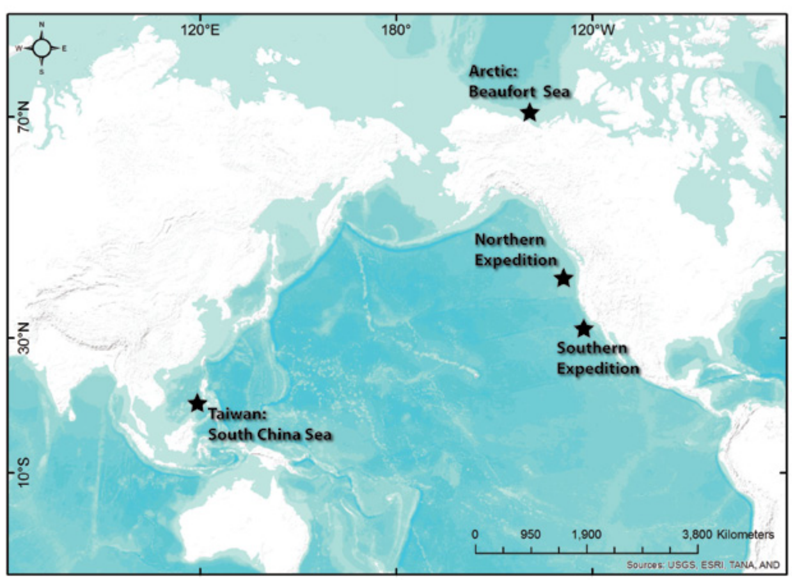


Figure 48: MBARI research vessels will sail to the Pacific Northwest and to Southern California in 2013. Expeditions to the South China Sea and the Beaufort Sea will utilize the mapping autonomous underwater vehicle *D. Allan B.* on ships from other institutions.

Northward expedition

David Clague's focus on submarine volcanism will utilize existing AUV high-resolution maps for the selection of sites for ROV dive observations and sampling. His team plans to complete their sampling of lava flows and volcaniclastic sediments at Axial Volcano on the Juan de Fuca Ridge west of Oregon.

Peter Brewer is planning experiments to resolve geochemical changes that relate to how microbes decompose oil at an oil- and gas-venting site off Eel River in Northern California. His team will study changes in the chemistry of the pore water (the seawater in the sediments) as it moves through the seafloor as well as measuring the oil/gas phase of droplets as they rise through the water toward the sea surface.

Following up on high-resolution mapping of the undersea Eel Canyon, Charlie Paull will explore and sample gas-venting sites and the massive seafloor scour off the western end of that canyon. Seafloor deposits of methane hydrates, an icy form of methane and other gas molecules trapped in a cage of frozen water molecules, are potential threats to the stability of seafloor sediments.

International collaborations

Working with international collaborators, Paull will extend this research on hydrates and seafloor stability further west into the South China Sea on a Taiwanese research vessel. Because the South China Sea is known to have significant gas formation and venting, and because floods in the area regularly force large flows of sand from rivers into submarine canyons, this is a rare opportunity to couple the two areas of research to learn how they are interrelated.

Paull is also set to return to the Arctic Ocean, where the seafloor is undergoing perhaps the most dramatic warming of all the seafloor on Earth. In the fall, Paull will conduct AUV mapping surveys of several active methane gas vents, coupled with targeted sampling with MBARI's small portable mini ROV (See story page 27). This joint effort with the Geological Survey of Canada aims to determine if the increased gas venting stems from deep gas hydrate deposits or the decomposition of permafrost that was flooded at the end of the last glacial period. The AUV will be used to document gas-venting structures, areas of unstable seafloor, and other seafloor features that appear to be unique to the margins of the Arctic Ocean.

Autonomous vehicle fleet grows more sophisticated

MBARI engineers are busy working on several projects to enhance the capabilities of the institute's AUV fleet. To begin with, a second mapping AUV is being built in-house to meet the increasing demand for high-resolution seafloor maps (Figure 49).

The imaging AUV, which collects high-resolution color images that allow identification of seafloor animals to the species level and visual records of significant seabed features, is slated for several upgrades. New terrain-based navigation techniques are being developed for collecting images over complex seafloor terrain. The imaging AUV will also be used in tandem with the mapping AUV for exploring sections of the seafloor never seen before, providing maps and images of the same site (Figures 50 and 51).

Figure 49: A side-by-side view of MBARI's two deep-water mapping AUVs. The original vehicle is shown on the right, configured for benthic-imaging surveys. The new vehicle, shown on the left with syntactic foam modules in place, is designed for depths as great as 6,000 meters.

While previously confined to taking pictures of the seafloor, the imaging AUV's capabilities will now be expanded into the midwater, with a new nosecone video camera system. Tests in 2013 will determine if the AUV can successfully fly at slower speeds for video transects that until now have been collected with remotely operated vehicles. By adding the AUV to the midwater team's arsenal of tools, the researchers will be able to add to their 19-year time series of midwater video without relying on access to a research vessel. An additional benefit is that the AUV is not as noisy as the ROV, and therefore may catch more animals on camera.

Another new MBARI AUV development, funded by NASA, focuses on the ability to map and explore free-drifting icebergs in the Antarctic. This vehicle is unique in that it will map to both sides and above and below the AUV, then use those maps to autonomously navigate back to a site of interest and perform optical imaging. This system is being developed and tested in Monterey Bay.

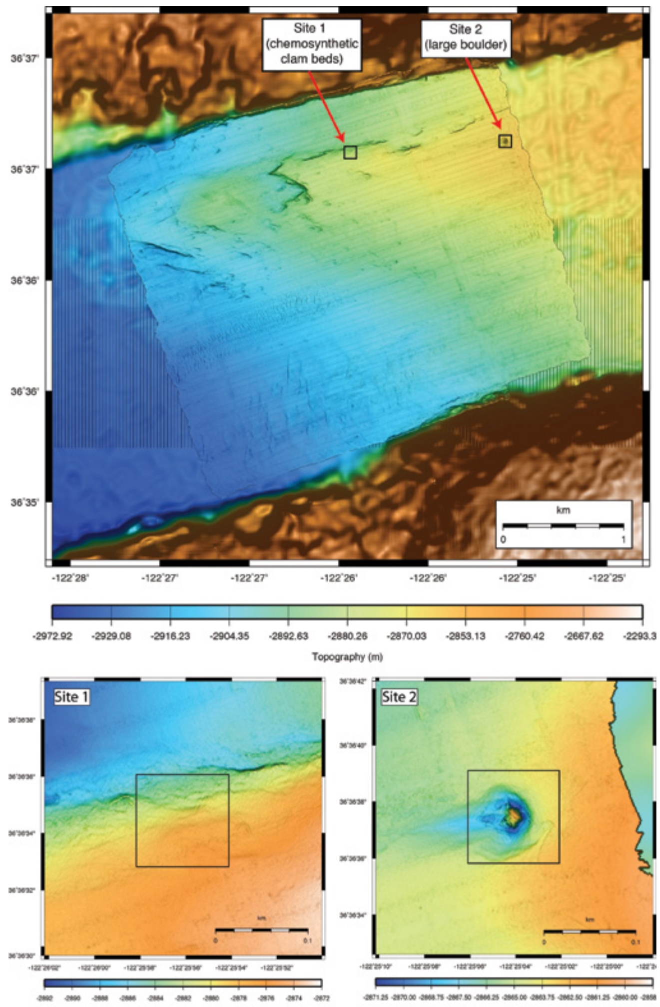


Figure 50: Bathymetric map of seafloor from 400 kHz multibeam data collected at test site by the imaging AUV in November.

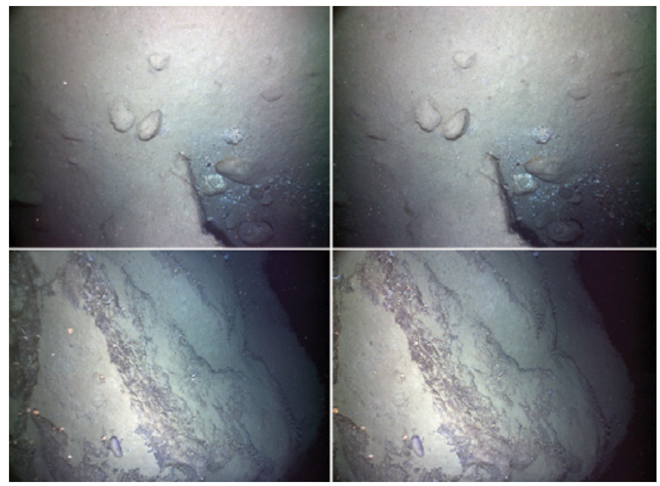


Figure 51: Example of paired stereo images taken with cameras pointing straight down from the ROV toolsled during ocean imaging tests in Monterey Bay. Top images show rocks exposed in scour pit adjacent to a large boulder, and bottom images show the top and edge of a large boulder.

Behind the Scenes:
Outfitting a New Coastal Research Vessel

An intense four-month effort by more than two dozen staff members turned a former oil-field supply vessel into a first-rate research ship with wide-ranging flexibility for carrying out science and engineering development missions. The ship was christened the *Rachel Carson* after the pioneering environmental scientist and author (see box on opposite page).

The R/V *Rachel Carson* spent its early years supplying fuel, food, and pipes to the oil rigs in the Gulf of Mexico. Its large, flat, open back deck was perfect for mounting various ocean research equipment—an ROV and its winch and crane, an AUV and its crane, a science lab, and a workshop for the crew—and the option of moving things around should the institute's needs change. With its ample deck space, the R/V *Rachel Carson* is now equipped to run ROV and AUV missions, launch moorings and other science instruments, and serve as host to engineering development projects that need quick access to the sea (Figure 52).

With the commissioning of this new ship, MBARI moves its seagoing operations to a two-vessel fleet. The R/V *Western Flyer* remains the institute's regional vessel, capable of spending weeks at sea and traveling up and down the West Coast of North America. The R/V *Rachel Carson* serves as a coastal vessel, which means it will stay a bit closer to home. And yet, with 12 berths on this new ship and enormous fuel tanks, it can also work away from port for days at a time should that be necessary.

The *Rachel Carson* replaces the R/V *Point Lobos*—the long-time support ship for ROV *Ventana* operations—and the R/V *Zephyr*, host to the AUV system since 2001. Both these ships have been retired.

MBARI purchased the ship late in 2011; by the end of that year the ship had sailed through the Panama Canal and up the West Coast, arriving at a San Francisco Bay shipyard for its second round of improvements. One engine was rebuilt and another was overhauled—with Chief Engineer Mark Aiello and Bosun Greg Maudlin at the shipyard to oversee the work. New generators and a new hydraulic system were installed.

By May the ship was brought to Moss Landing, where marine operations staff, the engineering group, and the information systems group jumped in to work on the conversion (Figure 53). Captain Aaron Gregg was tied up with the final missions of the R/V *Zephyr*, but when the *Zephyr* was laid up he, too, was able to turn his attention to the new ship (Figure 54).

The first challenge in the area that was to become the ROV control room was to insulate the space from the

Figure 52: The R/V *Rachel Carson* sets sail from Moss Landing with ROV *Ventana* and AUV *D. Allan B.* on its deck.

Figure 53: Electro-Mechanical Technician Paul Coenen installs deck wiring on the R/V *Rachel Carson*.

Figure 54: Chief Engineer Mark Aiello and Master Aaron Gregg position deck plates on the ship.

noise of the bow thrusters situated directly below. The plumbing that passes through the control room walls up to the living areas above was also upgraded before the rooms were sealed in. Once that was complete, Technical Support Manager Craig Dawe handcrafted the control room's wooden counters and work areas so wiring could begin (Figure 55).

Up on the bridge, Engineer Craig Okuda oversaw the complete rewiring of both the forward station and aft steering station, and the installation of additional marine equipment, such as radar and depth sensors. The air conditioning and wiring systems were improved and a plan was devised to pass power, hydraulics, and signals from the engine room to the main deck. Two vans were installed on the back deck—one as a workshop for the ROV and AUV crews

Rachel Carson

At a time when there were few jobs for women in science or writing, Rachel Carson pursued both to share her love of the natural world and educate the public about environmental issues. Carson worked tirelessly to piece together research about how chemicals applied to kill pests were in turn having a serious effect on other animals, and that these chemicals could enter the food web and be passed on to humans. Her book *Silent Spring* had a profound impact on the environmental movement, as she argued for a more cautious approach to the application of pesticides.

Carson (1907-1964), who was trained as a marine biologist, served as an editor for the U.S. Fish and Wildlife Service while spending her spare time writing magazine articles and books on environmental issues.

MBARI's Board of Directors chose to name the new coastal vessel after this remarkable person to honor women in science and to call attention to the institute's work to enhance the scientific understanding of the ocean in a time of increasing human impact.

Rachel Carson, influential writer and scientist, at the microscope.

and the other as a science wet lab. A dry lab was outfitted inside the ship to provide scientists and engineers a place for their computer-based work.

By October, the ship was operational; it was time to go to sea. "There's a stage where people need to start working it to see what needs to be improved," said Deputy Director of Marine Operations Chris Grech, who managed the project.

The ship's first mission (Figure 56) couldn't have been better timed for MBARI's long-range AUV (LRAUV) team as one of their vehicles had failed to resurface during a recent mission. The *Rachel Carson* with ROV *Ventana* successfully located and recovered the errant LRAUV—a major accomplishment for using the new system for the first time.

The ship has since taken on a regular schedule of science and engineering missions. While a few improvements will be made the next time the ship is in the shipyard, scientists are happy with the new vessel. The ship can operate in weather that would have kept the *Point Lobos* dockside. A full schedule is on tap for 2013, including several multi-day missions. While the immediate schedule skews toward AUV work, Grech said he is looking forward to more synergistic opportunities to combine ROV and AUV operations on the same mission. The very presence of the ROV makes the AUV program safer, evidenced by the very first mission. By having an ROV at the ready, the AUV can be safely recovered—an advantage not lost on the insurance company which provides a more reasonable rate knowing the vehicles can be recovered.

The change from three vessels to two makes for a more cost-effective and flexible seagoing fleet. MBARI is looking forward to the next 25 years of R/V *Rachel Carson* operations.

Coastal Vessel Conversion

Project leads: Peter Brewer, Steve Etchemendy
Project manager: Chris Grech
Project team: Mark Aiello, Paul Ban, Jim Boedecker, Pete Braccio, Mike Burczynski, Paul Coenen, Doug Conlin, Mike Conway, Craig Dawe, John Ferreira, Eric Fitzgerald, Frank Flores, David French, Kevin Gomes, Aaron Gregg, Greg Maudlin, Vincent Nunes, Craig Okuda, D.J. Osborne, Kim Reisenbichler, Erich Rienecker, Rich Schramm, Farley Shane, Hans Thomas, Duane Thompson

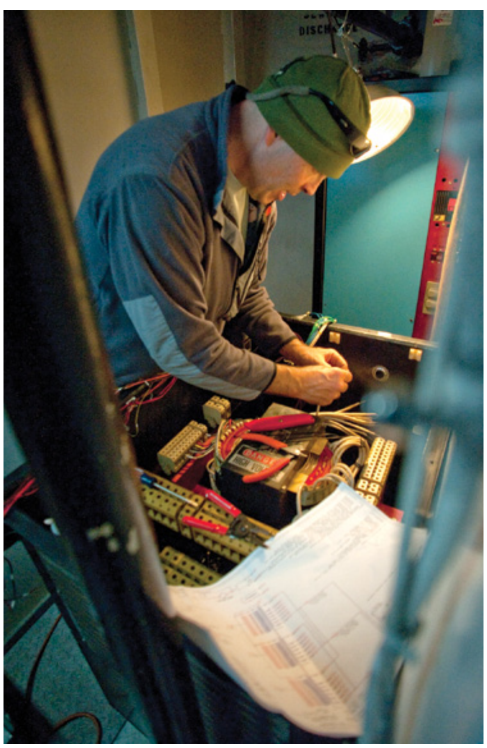


Figure 55: ROV Pilot/Technician D.J. Osborne attaches wiring in the ship's control room.

Figure 56: The control room during the R/V *Rachel Carson*'s first mission. Postdoctoral Fellow Jordan Stanway, in the orange vest, anxiously watches for the missing long-range AUV, while Osborne (in rear) guides the vehicle and Marine Operations Technician Erich Rienecker controls the main camera.

Making the most of a special gift

During its 12 years of service to MBARI, the research vessel *Zephyr* traveled up and down the West Coast of North America for many seafloor mapping missions, launched AUVs for complex ecological studies off Monterey Bay, and gave MBARI engineers and scientists easy access to the sea to test and develop new instruments and platforms. The 25-meter-long (79 feet) *Zephyr* conducted a total of 550 missions, mostly as the host ship for the institute's growing autonomous underwater vehicle program.

The ship came to MBARI as a generous gift from the San Francisco Bar Pilots Association. It was renovated inside and out, with the addition of a dry lab inside and an AUV launch-and-recovery system on deck.

Originally, MBARI accepted the gift of the R/V *Zephyr* to enable accelerated development of the *Dorado*-class AUVs, with the notion that it might last for two or three years. With the R/V *Western Flyer* and R/V *Point Lobos* each engaged in 150 to 170 days of ROV work a year, the institute realized that the *Zephyr* was ideal for local operations with a flexible schedule, enabling the frequent tests required to achieve reliable AUV operating systems. As each new AUV gained reliability, science missions were added to the schedule, until the *Zephyr* and AUVs became full-time science assets. Using the *Zephyr* to venture more than 250 nautical miles out to sea to map Axial Seamount or to venture to the Gulf of California was not in the original plan, but rather a result of successful trips to local seamounts (Pioneer and Davidson). As the institute realized what a seaworthy boat it had received, the staff pushed the envelope each succeeding year.

The *Zephyr* sailed its last MBARI mission in 2012, and will soon be moving on to a new home.

The research vessel *Zephyr* was key to the success of MBARI's autonomous underwater vehicle development program.

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; Stephen Riser, University of Washington, Seattle

Sixteen profiling floats equipped with chemical sensors were built and deployed to monitor the major biogeochemical cycles. Floats were deployed in the Arctic Ocean, the Southern Ocean, the oxygen minimum zone of the Eastern Tropical North Pacific (ETNP), the ultra-oligotrophic South Pacific, the California Current, the North Atlantic, the North Pacific, and the Bay of Bengal. MBARI now has a total of 30 such instruments in the world ocean. Two profiling floats in the ETNP and one in the Arabian Sea show interesting coupling between production at the surface and nitrate consumption in the oxygen minimum zone. A new float in the California Current will monitor nutrient cycling, net community production, and carbon export for the next five years. The team also continues to support a chemical sensor network in Elkhorn Slough and the nearshore waters of Monterey Bay. This network has operated for nearly 10 years and is allowing an unprecedented view of the impacts of land/ocean coupling on the nitrogen cycle. Measurements in 2012 were 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, Judith Connor, T. Craig Dawe, David French, Kim Fulton-Bennett, Steven Haddock, Hendrik Jan Ties Hoving, Linda Kuhnz, Chris Lovera, Lonny Lundsten, Thom Maughan, Craig Okuda, Bruce Robison, Kyra Schlining, Nancy Jacobsen Stout, Josi Taylor, Susan von Thun
Collaborators: Rita Bell, Alicia Bitondo, Lisa Borok, Paul Clarkson, James Covel, Bret Grasse, Humberto Kam, Enrique Melgoza, Sonya Sankaran, Kim Swan, and Jaci Tomulonis, Monterey Bay Aquarium, California

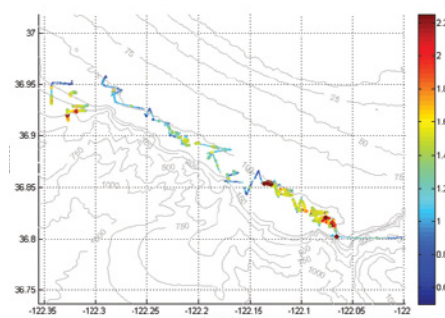
This collaboration between the Monterey Bay Aquarium (MBA) and the Monterey Bay Aquarium Research Institute (MBARI) included the new *Jellies Experience* exhibit, updating the *Mysteries of the Deep* auditorium program, and an upcoming cephalopod exhibit. MBARI staff participated in the *World Ocean Day* and *Community Day* celebrations at the aquarium and provided lectures and tours for MBA staff and volunteers. The highly successful International Symposium on the Ocean in a High CO_2 World was held in late 2012, co-sponsored, organized, and staffed by both organizations and the Center for Ocean Solutions. Several MBARI researchers mentored students in the aquarium's Watsonville Area Teens Conserving Habitats program and provided a venue for the students' end-of-year symposium for friends and family. MBARI engineers also worked with the MBA White Shark Research Program to design and develop a prototype camera system.

MBARI scientists worked closely with Monterey Bay Aquarium staff to ensure the accuracy of the new *Jellies Experience* exhibit, which includes these soft-coral polyps.

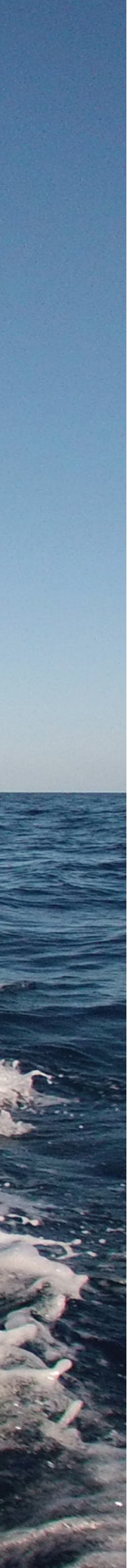
Autonomous Ocean Sampling Networks

Project lead/manager: James G. Bellingham
Project team: Michael Godin, Thomas Hoover, Dorota Kolber, Yanwu Zhang

Efforts focused on learning how to autonomously map ocean features. The team also supported two Controlled, Agile, and Novel Observing Network (CANON) field programs. Algorithms developed by the team for detecting upwelling fronts enabled the long-range AUV (LRAUV) to conduct a four-day study on the evolution



Tests using a new method of tracking with the *Tethys* LRAUV resulted in acquisition of a longer stretch of data from a patch of phytoplankton.



of an ocean front. A different set of algorithms was used to track an algal bloom for approximately 24 hours as the bloom advected across Monterey Bay. Using the *Dorado* AUV, the front-detection algorithms were combined with water-sampling methodologies to capture a series of water samples on either side of the upwelled front. These different approaches to adaptive sampling, one for characterizing populations, the other for following aggregations of organisms, are key to strategies for developing future time-series studies of microbial populations. As the year came to a close, the first operations coordinating two LRAUVs were conducted, opening the door to future intensive observation programs.

Autonomous Underwater Vehicle (AUV) Infrastructure Support

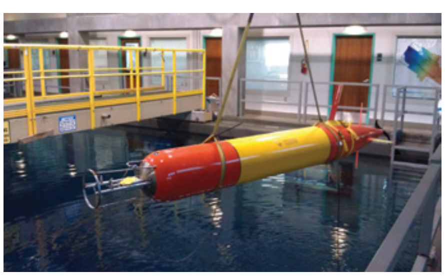
Project leads: David Caress, John Ryan
Project manager: John Ryan
Project team: Mike McCann

Improvements and upgrades were made to the mapping AUV data systems. Continuing maintenance and development of MB-System, the primary software used for processing and visualization of seafloor mapping data, supported research at MBARI as well as researchers in the greater marine geological community. Development of the Spatial Temporal Oceanographic Query System enabled effective integration of AUV data with a variety of other data, all managed using an intuitive graphical interface. Methods were developed for quantitative analysis of particle size data and integration of these results with other data acquired by a novel sensor on the AUV for particle imaging and sizing.

Benthic Exchange Events

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

A sensor created at NPS for measuring ocean turbulence was integrated onto LRAUV *Daphne*, tested, and deployed for a field program—the first to use two LRAUVs. The field work was timed to occur in conjunction with deployment of NPS, MLML, and U.S. Geological Survey instruments. Challenges associated with that integration of the turbulence instrumentation included its high data rates, stability of the vehicle with the long probes at the front of the vehicle, and handling of the fragile turbulence sensor. Data from the first turbulence sensor experiment are being analyzed.

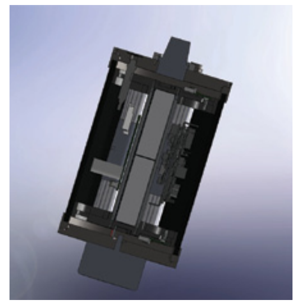


The *Daphne* LRAUV with integrated turbulence sensor is hoisted over the test tank.

Benthic Event Detectors

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

The Benthic Event Detector (BED) is being developed to determine the magnitude, timing, and dynamics of sediment debris flow events in upper Monterey Canyon. In 2012, the BED team conducted a design review and began fabrication of six instruments to be tested in the upper canyon. The team also hopes to employ a Wave Glider AUV on the sea surface for geolocation and transfer of data from the event detectors when they are on the seafloor. After gaining valuable data from prototype deployments, the team will participate in a larger collaborative experiment.

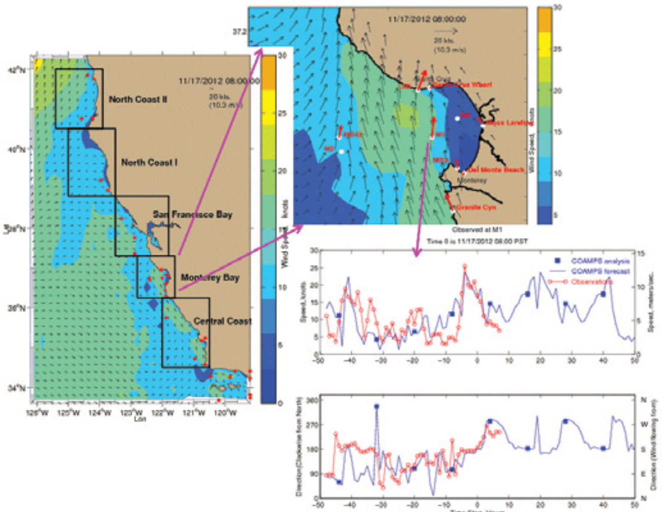


Drawing of the BED housing that will be encased in foam and placed on the canyon floor to detect and measure sediment debris flows.

Central and Northern California Ocean Observing System (CeNCOOS)

Project lead/manager: Leslie Rosenfeld
Project team: Fred Bahr, Jennifer Patterson, Janine Scianna
Collaborators: 15 principal investigators from 13 institutions

CeNCOOS is a collaboration that enables sustained and coordinated measurements, models, forecasts, and products to inform decisions about the ocean off Central and Northern California. Almost 50 research, academic, government, for-profit, and non-profit member organizations support a network of ocean observing technologies. CeNCOOS also supports a regional atmospheric model and ocean circulation models for Monterey Bay, the waters off California, and a larger domain covering the whole West Coast. Data from these instruments and models are available via the CeNCOOS website, and from MBARI and CeNCOOS-partner servers, and are incorporated into a variety of informational products for users including shellfish growers, marine-protected-area managers, and the State Water Resources Control Board. The CeNCOOS group is working to



The CeNCOOS website (http://www.cencoos.org) displays measured coastal and offshore winds and model current and forecast winds for the CeNCOOS region.

integrate data access and display with neighboring observing systems, to help address California Current System-wide issues such as ocean acidification and harmful algal blooms.

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; Stephen Riser and Dana Swift, University of Washington, Seattle

Team efforts were focused on continued adaptation of the Honeywell Ion Sensitive Field Effect Transistor pH sensor for operation at high pressure in the deep ocean and the development of robust fluidic systems for multi-step, in situ chemical analyses. The performance of the pressure-tolerant pH sensor was validated in the first profiling float with pH sensors deployed in the ocean. This float was deployed in October near the Hawaii Ocean Time-series station and has sufficient battery power to run for five years. Through its first 100 days of operation, there was no detectable drift in the sensor and precision is on the order of 0.002 pH units. Field tests also began in Elkhorn Slough on an improved dissolved ammonium analyzer, based on the Johnson lab's Digital Submersible Chemical Analyzer.

Coastal Profiling Float

Project leads: Ken Johnson, Gene Massion
Project manager: Gene Massion
Project team: Luke Coletti, Sergey Frolov, Josh Plant, Wayne Radochonski

The team developed a draft set of requirements for a new coastal profiling float, evaluated existing technology, and analyzed several conceptual designs. The most risky element of the conceptual designs was the buoyancy engine, so the group developed a benchtop version of the preferred buoyancy engine design and evaluated its performance, with positive results. A design for a profiling float rated for 100-meter depths has been completed, built, and tested in the lab. A Matlab model application was developed to help the team use advantageous currents to keep the float in Monterey Bay. In addition, the team purchased a standard Argo Autonomous Profiling Explorer (APEX) float to serve as a benchmark for development work. The project team also completed a real-time tracking program that monitors the position of deployed floats relative to marine protected areas, the shoreline, and the open ocean to provide an alert when recovery of a float may be required.

Prototype of MBARI coastal profiling float.

Collaborative Multi-Robot Exploration of the Coastal Ocean

Project lead/manager: Kanna Rajan
Project team: Rishi Graham, Frederic Py
Collaborators: Matthew Bernstein and John Dolan, Carnegie Mellon University, Pittsburgh, Pennsylvania; Jnaneshwar Das and Gaurav Sukhatme, University of Southern California

The intent of this National Science Foundation project is to elucidate the basic principles governing environmental field model synthesis based on the integration of adaptive robot sampling with human decision-making. In doing so, the project will generate a broad set of principles for multi-robot environmental field exploration coupled with human decision-making. The project will also foster new ways to enable adaptive robotic sampling in the context of a dynamic environment using automated plan execution driven by machine learning techniques for in situ decision-making.

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

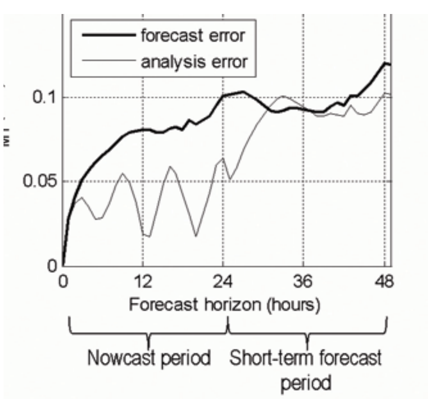
Project leads: David Caress, David Clague
Project manager: David Clague
Project team: Julie Martin, Jennifer Paduan
Collaborators: Alden Denny and Deborah Kelley, University of Washington, Seattle; Brian Dreyer and James Gill, University of California, Santa Cruz

MBARI mapping AUV data from 2008 and 2011 have been merged with overlapping data collected with a NOAA AUV a few years before. The resultant map has strong spatial accuracy and the MBARI data provide resolution of one meter. The team assembled a database of all mapped hydrothermal chimneys at the Endeavour site, examined their distribution along the ridge, identified the youngest lava flows, and evaluated the faulting that dominates this ridge segment. The ages of 40 lava flows were determined, with the goal of establishing the recurrence interval of eruptions and age of the axial valley formation. The population of mapped hydrothermal chimneys far exceeds the number of chimneys previously identified from dives with submersibles. Most past hydrothermal activity is limited to the central section of the axis where five vent fields are active today. The final report on this project was submitted to the National Science Foundation in 2012.

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
Collaborator: Raphael Kudela, University of California, Santa Cruz

To enable greater autonomy for underwater vehicles, the team developed a system that provides a comprehensive view of surface ocean currents by assimilating data from an AUV while it is underway. This approach bypasses communication bandwidth and delay limitations by assembling both synoptic and local data on a vehicle. In 2012 the team tested the system in computational experiments. The tests showed improvements in predicting currents up to 25 kilometers away from the vehicle. Within the first 10 kilometers, assimilation of data improved the initial predictions, as well as forecasts of up to six hours.



Results of compact ocean model to improve forecasts of ocean surface currents.

Core Conductivity-Temperature-Depth (CTD) Data

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

This project team continued to support the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. They migrated underway and profiling CTD equipment from the R/V *Point Lobos* to the R/V *Rachel Carson* and also installed a new raw seawater system. Numerous improvements were made to the user interface for real-time remotely operated vehicle (ROV) data display. Validation of ROV oxygen-sensor data continued and now includes Winkler titrations. New quality control measures are being implemented.

Core Mooring Data

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

This project team continues support of the collection, processing, and archiving of several core data streams from the MBARI moorings.

Core Navigation Data

Project leads: David Caress, John Ryan
Project manager: David Caress
Project team: Knute Brekke, Mike Burczynski, Ben Erwin, Linda Kuhnz, Eric Martin, Mike McCann, D.J. Osborne, Randy Prickett, Bryan Schaefer, Rich Schramm, Mark Talkovic

The project team maintained ROV and ship navigation hardware, developed software for automated data processing and archiving, edited ROV navigation data, and monitored data quality.

Core Outline Video Annotation

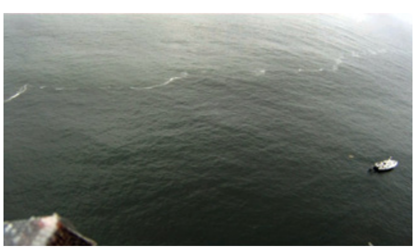
Project lead: John Ryan
Project manager: Nancy Jacobsen Stout
Project team: Linda Kuhnz, Lonny Lundsten, Brian Schlining, Kyra Schlining, Susan von Thun

In 2012, video lab staff annotated approximately 550 hours of ROV video; the Video Annotation and Referencing System (VARS) database currently contains over four million observations. The system was updated with linear and area measurement features, providing the ability to measure the sizes of animals, detritus, geological features, and other objects on video. In collaboration with several projects across the institute, the annotation team continued to prepare for the integration of digital still and video files from a growing number of imaging platforms (such as AUVs, the Benthic Rover, and fixed time-lapse cameras) into the VARS workflow. The team also directed effort towards resolving critical quality assessment and control issues in VARS.

Distributed Autonomy

Project lead: Kanna Rajan
Project manager: Thom Maughan
Project team: Danelle Cline, Rishi Graham, Tom O'Reilly, Frederic Py, Hans Thomas
Collaborators: John Dolan, Carnegie Mellon University, Pittsburgh, Pennsylvania; Maria Fox, Kings College, London, United Kingdom; Ricardo Martins, Jose Pinto, and João Sousa, University of Porto, Portugal; Raja Sengupta, University of California, Berkeley; Ryan Smith, Queensland University of Technology, Australia; Gaurav Sukhatme, University of Southern California, Los Angeles; Transition Robotics, Inc.

In addition to participating in CANON field experiments (see page 5), the group participated in field exercises off the southern coast of Portugal. A significant event was the use of the Teleo-Reactive Executive (T-REX) system on two small, portable AUVs from the University of Porto to dynamically survey and collect upper-water-column data. In doing so, T-REX was demonstrated outside the context of MBARI vehicles and operations. In Monterey Bay, the group demonstrated the use of three different unmanned aerial vehicles (UAVs) from the deck of the R/V *Zephyr*. Using a simple high-resolution camera and flying the UAV in manual control mode, the team was able to discern and follow a coastal front. This is significant for providing near-synoptic views as a basis for finding and tracking dynamic coastal features.



R/V *Zephyr* and the trace of an ocean front separating two different water masses. Image was taken from a human-controlled, unmanned aerial vehicle from the University of California, Berkeley.

Education And Research: Testing Hypotheses (EARTH)

Project lead/manager: George I. Matsumoto
Project team: Kevin Gomes, Dana Lacono
Collaborators: Lisa Adams, Kennesaw State University, Georgia; Jennifer Dorton, University of North Carolina, Wilmington; Debra Hernandez, Southeast Coastal Ocean Observing Regional Association, Charleston, South Carolina; Lundie Spence, Centers for Ocean Sciences Education Excellence South East, Charleston, South Carolina

A successful EARTH teacher workshop held at the University of North Carolina, Wilmington, generated many educational activities. Discussions for further dissemination of EARTH materials and workshop format resulted in three professional development workshops facilitated by previous EARTH participants. Planning began for the next two EARTH workshops, with co-hosts the Center for Dark Energy and Biosphere Initiative and the Center for Microbial Oceanography: Research and Education for the 2013 workshop and the Pacific Islands Ocean Observing System for 2014.

Enhancing Detection Chemistries for Investigating Microbial Ecology

Project leads: Roman Marin III, Christina Preston, Chris Scholin, William Ussler III
Project manager: James Birch
Project team: Holly Bowers, Elif Demir-Hilton
Collaborators: Alexandria 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, University of Washington, Seattle; Dianne Greenfield, University of South Carolina, Columbia; Steve Hallam, University of British Columbia, Canada; Blythe Layton and Steve Weisberg, Southern California Coastal Water Research Project, Costa Mesa, California; Victoria Orphan, California Institute of Technology, Pasadena; Julie Robidart and Jonathan Zehr, University of California, Santa Cruz; Robert Vrijenhoek, MBARI

This project team is developing techniques to automate end-to-end biochemical analyses from sample collection to application of multiple molecular analytical analyses to assess the presence, abundance, and metabolic activity of marine microbes. In 2012, the team experimented with methods for concentrating target organisms, extracting and purifying DNA and RNA, and devising new assays for detecting specific microbes and their genes.

The Feasibility of Delay Tolerant Networking for Ocean Platform Connectivity

Project leads: Mark Chaffey, Kanna Rajan
Project manager: Mark Chaffey
Project team: Thom Maughan, Tom O'Reilly, Frederic Py
Collaborators: Ricardo Martins and João Sousa, University of Porto, Portugal

The team began researching the feasibility of using an at-sea communications gateway to increase the volume of data that can be forwarded from MBARI's various sampling vehicles back to land. Such a communications gateway could offer a cost-efficient, large-volume data pipeline connecting equipment at sea with mission planning and data-processing applications on shore. Laboratory and field tests with a software application that implements a delay-tolerant networking (DTN) design and Linux/Windows file synchronization showed that the gateway concept is technically feasible with available off-the-shelf hardware and software. The study concluded that there is substantial value in MBARI developing this infrastructure, initially to support MBARI's Oceanographic Decision Support System and Controlled, Agile, and Novel Observing Network field programs and subsequently for keeping researchers informed during long-endurance over-the-horizon oceanography on robotic platforms.

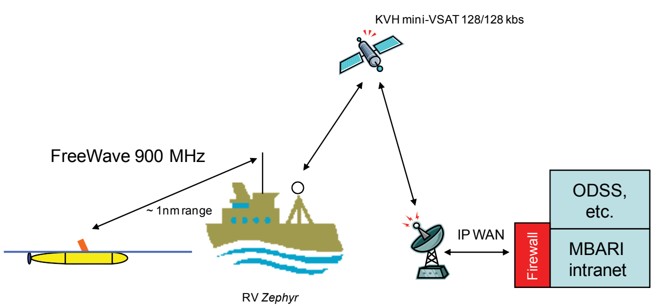


Diagram of how the delay-tolerant networking design will transfer data from sea to shore.

Feasibility Study to Develop Safety Guidelines for the Failure Modes of Lithium Batteries

Project lead: James G. Bellingham
Project manager: Ed Mellinger
Project team: Jon Erickson, Ken Smith

This project focuses on understanding the parameters for safe operations of lithium polymer and lithium ion batteries in MBARI systems. Lithium battery chemistries are widely used for mobile electronics applications and are the focus of significant industry investment. In 2012 the team established working relationships with battery experts at Lawrence Livermore National Laboratory, the Naval Postgraduate School, and industry. Plans for a joint project with those experts have been developed, and efforts are underway to help those partners raise funds to participate in the project.

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 Wisconsin-Milwaukee; William Chadwick, Oregon State University, Newport; Brian Dreyer and James Gill, University of California, Santa Cruz; Robert Embley, National Oceanographic and Atmospheric Administration, Newport, Oregon; Kenneth Rubin, University of Hawaii, Honolulu; Adam Soule, Woods Hole Oceanographic Institution, Massachusetts

Researchers synthesized MBARI high-resolution AUV mapping data and lava flow chemistry and ages to evaluate variations in magma generation and eruptions in space and time on the Juan de Fuca Ridge. The study focuses on three sites where historic eruptions have been documented: CoAxial (eruptions between 1982 and 1991, and in 1993), North Cleft (eruption in 1986), and Axial (eruptions in 1998 and 2011). Radiocarbon dating of foraminifera from sediments on top of the flows and analyses of volcanic glasses and lava samples were compared with each other and with relative age determined from ROV observations and flow relations inferred from mapping data. The team determined that at Axial Seamount lavas have switched from lower-temperature crystal-free lavas to higher-temperature crystal-rich lavas and back in the past 1,500 years.

Forecasts and Projections of Environmental and Anthropogenic Impacts on Harmful Algal Blooms in Coastal Ecosystems

Project lead/manager: Fred Bahr
Project team: Jennifer Patterson, Janine Scianna
Collaborator: Raphael Kudela, University of California, Santa Cruz

Glider data were telemetered to a base station at MBARI and made available to the Southern California Ocean Observing System. These data were used to monitor water quality conditions during the temporary redirection of the Orange County Sanitation District's outfall.

Genetically Encoded Luminescence for In Vivo Imaging

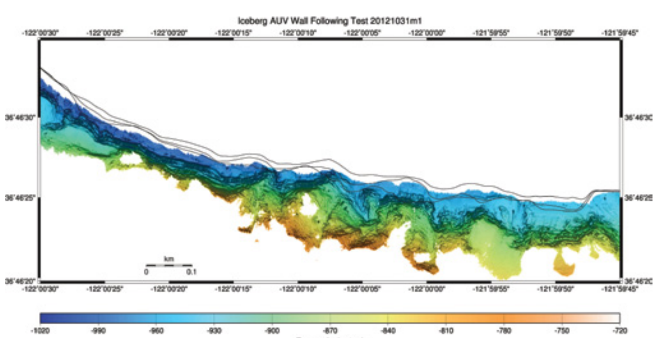
Project lead/manager: Steven Haddock
Project team: Warren Francis, Meghan Powers
Collaborators: Andy Baxevanis and Christine Schnitzler, National Institutes of Health, Bethesda, Maryland; Mikhail Matz, University of Texas, Austin

The team has been working on the biosynthesis pathway for the light-emitting compound luciferin in the bioluminescent copepod *Gaussia*. More recently they succeeded in completing a detailed characterization of the luminous system of a ctenophore (comb jelly) and a polychaete worm. Their research continues with the goal of discovering the chemical and genetic underpinnings of bioluminescence in novel systems.

Iceberg AUV

Project leads: Brett Hobson, Steve Rock, Ken Smith
Project manager: Brett Hobson
Project team: David Caress, François Cazenave, Doug Conlin, Rich Henthorn, Eric Martin, Rob McEwen, Paul McGill, Hans Thomas, Duane Thompson

MBARI engineers and adjunct Steve Rock's Aerospace Robotics Laboratory group at Stanford University began building a new AUV that can map the submerged portion of free-drifting icebergs off Antarctica and use those maps to autonomously return to sites of interest. The project is funded by NASA's Astrobiology Science and Technology for Exploring Planets program because the iceberg-relative navigation and autonomous return-to-site techniques may be applicable to future space missions, while also supporting science investigations of icebergs by MBARI scientists. The new vehicle has been designed with a side-looking sonar configuration. The sonar and wall-following algorithms were tested at a vertical wall inside Monterey Canyon using the existing mapping AUV.

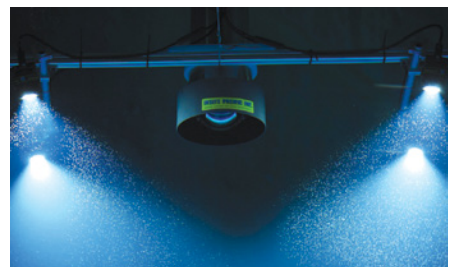


Bathymetric map of a wall in Monterey Canyon created as test of capabilities of the new Iceberg AUV. The three black lines show the path of the AUV during tests at three different depths along the wall.

Investigations of Imaging for Midwater Autonomous Platforms

Project leads: Dale Graves, Hendrik Jan Ties Hoving
Project manager: Kim Reisenbichler
Project team: David French, Michael Risi, Bruce Robison, Rob Sherlock, Todd Walsh

The team explored the feasibility of employing unobtrusive, autonomous imaging systems to study the midwater. A rudimentary red-LED-illuminated video system was tested both on a midwater mooring and on a wire from the ship. The system shows potential for the temporal analysis of the abundance of some common zooplankton and marine snow (detritus particles). Testing of the low-power LED lighting configuration, in a pattern practical for AUV installation, was conducted during midwater transects from the ROV *Doc Ricketts*. These transects compared favorably with those recorded using the standard lighting configuration. This proof of concept demonstrated that the camera and lighting technology are available to develop a midwater AUV imaging system of video quality comparable to that obtained using an ROV.



Test of the midwater AUV imaging module in the MBARI test tank using four off-the-shelf white LED lights and the ROV high-definition video camera.

Legacy Data Systems Transitions

Project leads/managers: Kevin Gomes, Todd Ruston
Project team: Pat Allen, Peter Braccio, Neil Conner, Mike McCann, Rich Schramm, Cathy Sewell

Due to the end of hardware or software support from manufacturers, some data processing software systems needed to be migrated to new hardware or systems. This entailed a significant amount of "software archaeology" to identify dependencies and architectures that had not been visited in many years and, where necessary or prudent, to adjust or re-implement them to run in modern environments. The team successfully retired a number of deprecated technologies in 2012.

Lagrangian Sediment Trap/Vertical Profiler

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

Building on the successful development and deployments of Lagrangian sediment traps in the Antarctic, the project team began to develop a device more suitable for use along the coast of California. The team selected and began testing an acoustic profiler to be included on the new instruments to image particle density while drifting or profiling vertically through the water column. Two shallow-water units were built.

Long-Range AUV: Testing and Initial Operations

Project leads: James G. Bellingham, Brett Hobson
Project manager: Brett Hobson
Project team: Mark Chaffey, Jon Erickson, Michael Godin, Rich Henthorn, Thomas Hoover, Brian Kieft, Denis Klimov, Rob McEwen, Ed Mellinger, Yanwu Zhang

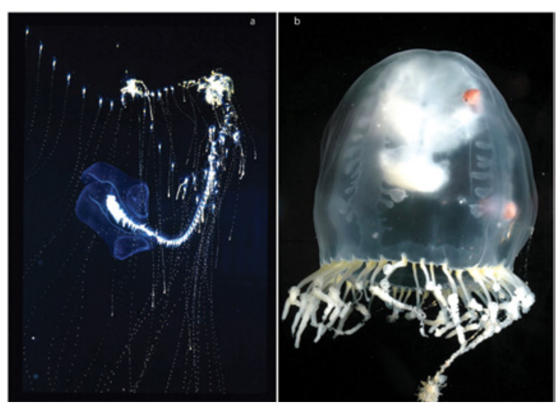
The building of a second LRAUV, *Daphne*, was completed and tested, and the vehicle carried out its first at-sea operations. Both LRAUVs participated in the spring and fall CANON field programs. The vehicles were also used to support AUV docking tests and observations of turbulent mixing near the seafloor. Substantial changes were made to the vehicle's sensor handling capabilities, including a turbulence package built by the Naval Postgraduate School and a commercial acoustic Doppler current profiler with very high spatial resolution. The year included several firsts: the operation of two LRAUVs at the same time, multi-day tracking of an ocean front, and operations coordinating LRAUV and Environmental Sample Processor drifter deployments.

Coordinated operations of long-range AUVs *Tethys* and *Daphne* were held for the first time in September.

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 and Richard Young, University of Hawaii, Manoa; William Gilly, Hopkins Marine Station of Stanford University, Pacific Grove, California; Steven Haddock, George I. Matsumoto, and Ken Smith, MBARI; Erika Montague, Schmidt Ocean Institute, Palo Alto, California; Karen Osborn, Smithsonian Institution, Washington, D.C.; Kevin Raskoff, Monterey Peninsula College, Monterey, California; Tracey Sutton, Virginia Institute of Marine Science, Gloucester Point; Louis Zeidberg, California Department of Fish and Game, Monterey

Research on the oxygen minimum zone documented significant changes in the depth distributions of several mesopelagic species and coupled these shifts to concurrent reductions of oxygen concentration in their habitat. These data were then matched with results from the midwater respirometers (see page 8) to establish the link between oxygen and depth distributions. The results clearly show that as oxygen decreases, animals move into new depth ranges, which results in fragmentation and reassembly of midwater communities, establishing new patterns of competition and interaction. The team also focused on squid studies that revealed many previously hidden aspects of the life histories of deep-living squid. Among these is the discovery that the vampire squid, *Vampyroteuthis*, is now the only known cephalopod to feed on sinking detritus instead of hunting for living prey (see page 30). Progress was also made in determining squid growth patterns and ages, which are longer in deep-sea species than their shallow-water counterparts.

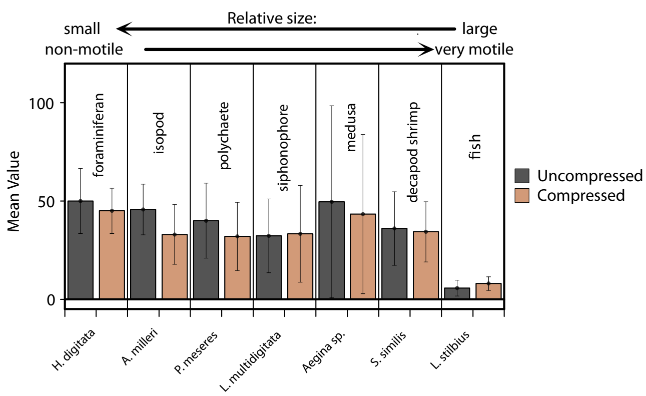


Siphonophores like *Praya*, left, and medusae like this undescribed species, right, use long tentacles to capture prey. *Praya* is about a full meter long (three feet) when stretched out; the body of this medusa is only about 6.5 centimeters (2.5 inches).

Midwater Time Series

Project lead: Bruce Robison
Project manager: Rob Sherlock
Project team: Kim Reisenbichler, Kristine Walz
Collaborators: Danelle Cline, Steven Haddock, Hendrik Jan Ties Hoving, Brian Schlining, Kyra Schlining, Rich Schramm, and Susan von Thun, MBARI

The team worked toward automated recognition of mesopelagic organisms while continuing to make transects for the Midwater Time Series. Lights and camera configurations that will be used when running transects from an autonomous platform were tested. Transects were conducted with the ROV *Doc Ricketts* configured normally (with widespread halide lights and recording on high-definition tapes) and with much smaller, closely-set LED lights as the AUV will be configured. These comparisons are vital to making the transition to an AUV-based time series.



No significant differences were found in comparisons of annotations of animals on compressed and uncompressed video of nine midwater transects.

Monterey Accelerated Research System (MARS)

Project leads: Steve Etchemendy, Gene Massion
Project manager: T. Craig Dawe
Project team: Ken Heller

The MARS cabled observatory ran continuously in 2012—other than periods offline for routine maintenance—serving up data and providing power to science and engineering experiments. Users included Oregon State and Harvard Universities' benthic microbial fuel cells, the University of California, Berkeley Seismological Laboratory's Monterey Ocean Bottom Broadband seismometer, the University of Minnesota's Calibrator Linked In Situ Timed Observatory, and MBARI's Free Ocean CO_2 Enrichment experiment and photographic benthic observing system.

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 research team noted that 2012 began as a cool La Niña year with a very weak warming/El Niño developing in the late fall, then fizzling toward year end. An effort to synthesize accumulated Monterey Bay Time Series datasets from physics to ecology began in 2012 and should mature in 2013.

Mooring Maintenance

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

The new hybrid M2 mooring (a collaborative project with the National Data Buoy Center) was recovered and an engineering review was completed.

Multi-University Research Initiative/Adaptive Sampling and Prediction (ASAP)

Project lead/manager: Fred Bahr
Collaborators: Steve Ramp, Soliton Ocean Services, Inc., Carmel Valley, California; Igor Shulman, Naval Research Laboratory, Stennis Space Center, Mississippi

The Naval Research Laboratory Innovative Coastal Observing Network model was used to assimilate glider data from the ASAP experiment. These model runs were then analyzed to compute heat fluxes around the ASAP region. Surface heat fluxes from aircraft flights over the region were used for the surface boundary and upwelling and relaxation conditions were compared.

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

Project lead: Francisco Chavez
Project manager: Gernot Friederich
Project team: Jules Friederich, Chris Wahl
Collaborators: Jan Bottenheim and Stoyka Netcheva, Environment Canada, Toronto; Paty Matrai, Bigelow Laboratory for Ocean Sciences, East Boothbay, Maine; Donald 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

Climate change is expected to rapidly and dramatically impact the Arctic Ocean. MBARI has developed a low-cost, high-precision system for measuring the partial pressure of carbon dioxide in the atmosphere, then deployed it on buoys moored in sea ice to help monitor Arctic conditions. The project team has also been developing the capability to add sensors to measure conditions (CO_2, pH, oxygen, fluorescence, temperature, and salinity) in seawater under the ice. A total of eight 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.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter G. Brewer, William Kirkwood
Project manager: Edward Peltzer
Project team: Jon Erickson, Anna Gallagher, Andreas Hofmann, Peter Walz
Collaborators: Martín Hernández Ayón and Gabriela Cervantes, Universidad Autónoma de Baja California, Mexico; Abbey Chrystal, Joseph Murray, and Adina Paytan, University of California, Santa Cruz

In addition to participation in the Gulf of California expedition (see page 20) and the Ocean in a High CO_2 World symposium (see page 12), the team developed a modification to the laser Raman spectrometer pore-water probe. The new tool will allow further investigation of chemical changes in marine sediments, and may help detect leakage of carbon dioxide sequestered in geologic reservoirs in the deep seafloor.

Ocean Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Rich Henthorn, Brett Hobson, Eric Martin, Hans Thomas

This project is developing a low-altitude, high-resolution seafloor mapping capability that combines multibeam sonar with stereo photographic imagery. The team designed and constructed new camera housings with corrective optics for achieving a 90-degree field of view, implemented new dual xenon strobes, and integrated the complete system onto ROV *Doc Ricketts*. Multibeam and camera survey data were collected at two sites in the deep axis of Monterey Canyon (both at about 2,850 meters depth). Both surveys were conducted from about two meters off the seafloor. At that altitude, the multibeam bathymetry swath was more than seven meters wide and the camera images were four meters wide. These data sets provide a test bed for the team's development of data processing tools and for the adaptation of vision- and terrain-aided navigation algorithms for real-time survey application.

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; Carol Blanchette, Gretchen Hofmann, and Libe Washburn, University of California, Santa Barbara; Brian Gaylord, Tessa Hill, Ann Russell, and Eric Sanford, University of California, Davis; Margaret McManus, University of Hawaii, Honolulu; Stephen Palumbi, Hopkins Marine Station of Stanford University, Pacific Grove, California; Pete Raimondi, University of California, Santa Cruz

This research on the responses of urchins and mussels to ocean acidification has documented a dynamic oceanographic mosaic 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. The mussels and urchins appear to have the capacity to acclimate to the different conditions of ocean acidity observed, although their long-term adaptation remains uncertain. MBARI provided the pH sensors used at intertidal sites from Oregon to Southern California and led the oceanographic studies off Central California.

Ocean Observatories Initiative (OOI) Cyberinfrastructure (CI)

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

This team provided advice and input on various aspects of the cyberinfrastructure system of the Ocean Observatory Initiative, a National Science Foundation-funded environmental observatory. The team participated in several design review sessions, evaluated the OOI concepts, and provided documentation, reports, source code, and design artifacts for technologies that were developed at MBARI. They provided advice on how to integrate the MBARI-developed PUCK protocol into observatory instruments to enable automatic instrument integration, operation, and data processing. MBARI engineers developed workflow schemes for interactive quality-control and developed software for applying calibration information to OOI data. The group also helped demonstrate various OOI-CI components and advanced the design and implementation of the framework, which played an important role in the Initial Operating Capability demonstration in November.

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, John Ferreira, Rich Henthorn, Brett Hobson, Christine Huffard, Linda Kuhnz, Paul McGill, Brian Schlining, Susan von Thun
Collaborators: Jeffrey Drazen, University of Hawaii, Manoa; Amanda Kahn, University of Alberta, Edmonton, Canada; Mati Kahru and Janet Sprintall, Scripps Institution of Oceanography, La Jolla, California; Henry Ruhl, National Oceanography Centre, Southampton, United Kingdom; Timothy Shaw, University of South Carolina, Columbia; Stephanie Wilson, Bangor University, United Kingdom

Detritus collected with this Sedimentation Event Sensor is deposited onto a microscope slide, which is then photographed in situ.

Long-term studies at Station M in the abyssal northeastern Pacific are designed to further understand how organic carbon production and export from the surface waters influences seafloor community dynamics. In 2012, the Benthic Rover was deployed autonomously and successfully recorded sediment community oxygen consumption over a one-year period (see page 7). During the year Station M instruments recorded the second largest seasonal flux of organic material sinking to the seafloor in the past 24 years, from a spring salp bloom at the sea surface over a period of three months. The newly developed Sedimentation Event Sensor was deployed at Station M, providing fine-scale temporal resolution of sedimentation. The team is examining possible relationships between major sedimentation events in the spring and fall, benthic community responses, climate indices, and surface ocean production, and working to increase the deployment longevity of the monitoring instruments.

Philippine Sea

Project lead/manager: Fred Bahr
Collaborators: Tarun Chandrayadula and John Colosi, Naval Postgraduate School, Monterey, California; Steve Ramp, Soliton Ocean Services, Inc., Carmel Valley, California

Mooring data from the Philippine Sea Acoustics Experiment 2010 were processed and quality controlled. Post-deployment calibrations were applied. Isotherm (contours indicating areas of equal temperature seawater) and isopycnals (contours of equal density seawater) were then computed from the mooring data to aid in analysis of the data.

Photographic Benthic Observing System (PhoBOS) Upgrade

Project lead: T. Craig Dawe
Project manager: David French
Project team: Shannon Johnson
Collaborator: Sigrid Katz, Scripps Institution of Oceanography, La Jolla, California

PhoBOS was upgraded with new lighting on a remote stand and a recalibrated CTD sensor. The camera system enables observations of larval *Osedax* deposition. Following a malfunction in the system, the package was recovered and found to have a flooded housing. The fault has been identified and is being resolved.

Picophytoplankton Ecology and Dynamics

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, Shuangchun Yan
Collaborators: Craig Everroad, NASA Ames Research Center, Moffett Field, California; Stephen Giovannoni, Oregon State University, Corvalis; Patrick Keeling, University of British Columbia, Vancouver, Canada; Adam Monier, Takuvik, University of Laval, Quebec City, Canada

The research team worked intensively on understanding the genomes of eukaryotic phytoplankton and their interaction with the environment. In addition to developing a method for analyzing diversity of photosynthetic eukaryotes in the field, the team applied these methods to the most abundant photosynthetic organism on the planet, the marine cyanobacterium *Prochlorococcus* and its close relative *Synechococcus*. Using this approach they discovered two new types of *Synechococcus* in the moderately nutrient-rich waters just outside of Monterey Bay, as well as other trends in the phytoplankton community. Together the two new groups comprise 36 percent of all *Synechococcus* sequences in these waters—representing significant characters that were previously not known. Through sequencing the complete plastid genome of an uncultured alga, the researchers were able to analyze the genome content and track where this alga lives using samples from around the globe. Importantly, they found that although this alga is very small it was present in deep-sea sediments indicating it had sunk, bringing atmospheric CO_2 fixed by photosynthesis to the seafloor.

PowerBuoy

Project lead/manager: Andrew Hamilton
Project team: François Cazenave, Peter Corr-Barberis, Jon Erickson, John Ferreira, Scott Jensen, Paul McGill, Wayne Radochonski, Jose Rosal

The PowerBuoy project is working to develop a proof-of-concept system for the conversion of wave energy to electrical energy for powering oceanographic instrumentation. The device that has been developed is designed to provide an average of 400 watts of electrical power. The system is similar in size to traditional oceanographic buoy systems, which are capable of providing 50 watts on average when powered by solar and wind. The project performed three test deployments in 2012 and the capability of the system was increased with each subsequent deployment.

The PowerBuoy system is loaded onto a ship for a test deployment in Monterey Bay.

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

This project focused on developing and refining two key technologies that will improve the ability of AUVs and ROVs to revisit benthic sites to monitor them for change. The first is terrain-relative navigation. This is a method for correlating altitude profiles collected during a mission against pre-stored bathymetry maps. An important feature of the method is that it does not require external positioning aids or GPS updating. The second is the fusion of video and Doppler velocity log information to enable precise local area navigation (for example within a 50-meter-square grid) to support video and sonar surveys. Work in 2012 focused on fusing this capability into the ROV control systems as an automated pilot aid as well as enabling its use during AUV surveys.

A Regional Comparison of Upwelling and Coastal Land Use Patterns on the Development of Harmful Algal Bloom Hotspots along the California Coast

Project lead/manager: John Ryan
Project team: James Birch, Frederic Py, Kanna Rajan, Chris Scholin
Collaborators: Holly Bowers, Kevin Gomes, Scott Jensen, Roman Marin III, Christina Preston, Frederic Py, and Brent Roman, MBARI; David Caron, Burt Jones, and Gaurav Sukhatme, University of Southern California, Los Angeles; Yi Chao, Remote Sensing Solutions, Barnstable, Maine; Meredith Howard, Southern California Coastal Water Research Project, Costa Mesa, California; Raphael Kudela, University of California, Santa Cruz; George Robertson, Orange County Sanitation District, Fountain Valley, California; Leslie Rosenfeld, Central and Northern California Ocean Observing System and MBARI; Jason Smith, Moss Landing Marine Laboratories, Moss Landing, California

This project is focused on comparative studies of harmful algal bloom ecology in “hotspots” along the California Coast: San Pedro Bay and Monterey Bay. During fall 2012, this project supported a multi-institution effort to study the ecological responses to a massive diversion of sewage into shallow waters of San Pedro Bay.

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; Fei Chai, University of Maine, Orono; Yi Chao, Remote Sensing Solutions, Barnstable, Maine; Eric Danner, John Field, Steve Lindley, Bruce MacFarlane, and Brian Wells, Southwest Fisheries Science Center, Santa Cruz, California; William Peterson, Southwest Fisheries Science Center, La Jolla, California; 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 in the U.S. This project brought 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 on the number of fish returning to rivers the year before, has been considerably improved by the SAFARI team. 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. A significant advance over the past year has been the demonstration that the coupled physical-biological numerical models can simulate the temporal and spatial distribution of krill—important information for fisheries management.

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; Roger Nisbet, University of California, Santa Barbara

This project couples the physical-biological oceanic model developed under the SAFARI project with models of the San Francisco estuary and the upper Sacramento River. The corresponding physical (temperature) and biological (food supply) solutions will eventually drive a dynamic energy budget for Chinook salmon. The resulting coupled models will be used to explore what causes variation in salmon growth and maturation, and the impacts of current and future water management, climate variability, and global change.

Seafloor Mapping and MB-System

Project lead/manager: David Caress
Project team: Krystle Anderson, David Clague, Doug Conlin, Eve Lundsten, Eric Martin, Julie Martin, Jennifer Paduan, Charles Paull, Hans Thomas, Duane Thompson
Collaborators: Dale Chayes, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York; Christian Ferreira, University of Bremen, Germany

The project team continued to improve MBARI's seafloor mapping data processing capabilities (MB-System), archived data of interest to MBARI researchers, and disseminated these data. Several updates to MB-System were released, incorporating new features and bug fixes. During 2012 MB-System was in active use at 41 U.S. and 68 foreign academic institutions, 11 U.S. and 40 foreign government agencies, and 37 companies, making this software one of the most widely used technologies derived from MBARI. The MBARI seafloor mapping database, allows MBARI scientists to generate up-to-date models of the seafloor that incorporate all of the available sonar data. The Lamont-Doherty Earth Observatory, the Scripps Institution of Oceanography, and the National Geophysical Data Center currently use MB-System as a foundation for seafloor mapping databases. MBARI's mapping AUV was used for high-resolution bathymetry and subbottom profiler surveys in a variety of settings during 2012 (see page 18).

Second Deep-Water Mapping AUV Build

Project leads: David Caress, Hans Thomas
Project manager: Hans Thomas
Project team: Doug Conlin, Eric Martin, Duane Thompson

The project team began integrating many in-house components into a second AUV mapping system. In 2012, the team purchased all long-lead items for the vehicle, assembled the mid-body, and designed a prototype of a battery. The new vehicle will be completed in 2013 and will be used for geophysical mapping, benthic imaging, and other projects.

Self-Contained Plankton Imager

Project leads: Steven Haddock, Ken Smith
Project manager: Chad Kecy
Project team: François Cazenave, Mark Chaffey, Andrew Hamilton, Chad Kecy, Michael Risi

A working prototype of the Self-Contained Plankton Imager (SCPI) camera system was completed in 2012 following a full study of the various imagers, lighting system, and options for overall system design. The prototype—including camera, light, and battery modules—is designed to quantify zooplankton autonomously. As a low-cost, easy-to-fabricate imaging system, it should be feasible to have more than one system in operation, providing insight into the spatial distribution of the plankton.

Prototype of the self-contained plankton imager.

Streaming Data Middleware

Project lead/manager: Duane Edgington
Project team: Kent Headley, Bob Herlien, Tom O'Reilly
Collaborators: Tony Fountain and Sameer Tilak, University of California, San Diego

MBARI's involvement in this project will be to apply the Open Source Data Turbine, a real-time data-streaming engine, to Free Ocean Carbon Dioxide Enrichment (FOCE) experiments.

Support Engineering Upgrades and Explorations

Project lead: Rich Schramm
Project manager: Kevin Gomes
Project team: Mike McCann

The team began simplifying and enhancing the process for the flow of data from MBARI's moorings, as part of this institutional infrastructure project.

SURF Center (Sensors: Underwater Research of the Future)

Project leads: James Birch, Chris Scholin
Project manager: James Birch
Project team: Holly Bowers, Elif Demir-Hilton, Kevin Gomes, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, John Ryan, William Ussler III
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Thierry Baussant, International Research Institute of Stavanger, Norway; Alexandria 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, University of Washington, Seattle; Peter Girguis, Harvard University, Cambridge, Massachusetts; Dianne Greenfield, University of South Carolina, Columbia; Steven Hallam, University of British Columbia, Vancouver, Canada; David Karl, University of Hawaii, Manoa; Blythe Layton and Steve Weisberg, Southern California Coastal Water Research Project, Costa Mesa, California; Stephanie Moore and Vera Trainer, Northwest Fisheries Science Center, Seattle, Washington; Mary Ann Moran and Vanessa Varaljay, University of Georgia, Athens; Victoria Orphan, California Institute of Technology, Pasadena; George Robertson, Orange County Sanitation District, Fountain Valley, California; Julie Robidart and Jonathan Zehr, University of California, Santa Cruz; Robert Vrijenhoek, MBARI; Cody Youngbull, Arizona State University, Phoenix

Funding from the David and Lucile Packard Foundation was utilized synergistically with funds from the Gordon and Betty Moore Foundation, the National Science Foundation, the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, industry, and various states to continue to develop, deploy, enhance, and transfer the second-generation Environmental Sample Processor (2G ESP). In 2012, the SURF Center oversaw the first global deployments of a 2G ESP network. One instrument located in a shellfish-growing area in New Zealand was programmed to detect both harmful algal bloom species and bacteria associated with sewage effluents. In parallel, commercially-produced versions programmed to detect harmful algal bloom species were located in Puget Sound, Washington, and in the Gulf of Maine. In the fall, the 2G ESP was used to monitor treated sewage effluents in Southern California. The 2G ESP was also deployed on a drifting buoy as part of the fall CANON cruise. In all cases, information gleaned from those installations, along with a command and control capability, was available in real-time via a wireless communication network. Development also continued on the third generation ESP, which is aimed at realizing a smaller instrument suitable for use on the long-range AUV and other free-ranging platforms.

Shallow-Water Free Ocean Carbon Dioxide Enrichment Experiment (swFOCE)

Project leads: James Barry, Peter G. Brewer, George I. Matsumoto
Project manager: William Kirkwood
Project team: Kent Headley, Chad Kecy, Thom Maughan, Tom O'Reilly, Edward Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborators: Larry Crowder, Center for Ocean Solutions, Stanford University, California; Brock Woodson, Hopkins Marine Laboratory of Stanford University, Pacific Grove, California

The FOCE project team has been developing technical concepts for an open-source technology reference design (called xFOCE), focusing on making FOCE cost-effective and easy to adopt by other organizations conducting ocean acidification studies. An xFOCE concept design review was held and testing of the major components continued. The xFOCE website was launched with a forum section to allow xFOCE users to share tools and techniques and an xFOCE workshop was held in France. The team worked with the Center for Ocean Solutions on a shallow-water FOCE installation at Hopkins Marine Station, conducted several enclosure tests, and evaluated mechanical design concepts. The team purchased the shore side components for swFOCE and began testing and integration. The deep FOCE experiment was recovered in 2012 following an 18-month deployment on the MARS cabled observatory. Equipment failures prevented closed loop control during the last several months of the deployment, but the high-resolution pH sensor developed in the FOCE program performed well in that environment.

George Matsumoto and Kim Reisenbichler prepare the shallow-water FOCE equipment for a test in Moss Landing Harbor.

Technology Transfer Observatory Software

Project leads: Kevin Gomes, Kent Headley, Bob Herlien, Tom O'Reilly
Project manager: Duane Edgington
Project team: Paul Coenen, Thom Maughan, Craig Okuda, Rich Schramm

Collaborators: Paul Barter, Chris Cornelisen, Andrew Mahon, and Rowan Strickland, Cawthron Institute, Nelson, New Zealand; Luis Bermudez, Open Geospatial Consortium, Herndon, Virginia; Arne Bröring, 52°North Initiative for Geospatial Open Source Software GmbH, Muenster, Germany; Joaquin del Rio, Antoni Manuel, and Daniel Toma, Universitat Politècnica de Catalunya, Barcelona, Spain; Tony Fountain, Peter Shin, and Sameer Tilak, University of California, San Diego; Janet Fredericks, Woods Hole Oceanographic Institution, Massachusetts; Martyn Griffiths, Bruce Howe, Roger Lukas, Ethan Ross, and Fernando Santiago-Mandujano, University of Hawaii, Honolulu; Mohammad Ali Jazayeri and Steve Liang, University of Calgary, Canada; John Liu, Tsinghua University, Beijing, China

The project team continued several collaborations to transfer MBARI observatory technologies—software infrastructure middleware (SIAM), PUCK protocol, Shore-Side Data System (SSDS), and OASIS mooring technology—to external observatory projects, industry groups, and standards organizations. The University of Hawaii credited MBARI's SIAM and SSDS software with providing key data collection and archiving capabilities on the ALOHA mooring. The Cawthron Institute in New Zealand deployed a second mooring based on MBARI's OASIS mooring controller. As part of the design, Cawthron developed a new instrument driver, which they have provided to MBARI as part of the two-way mooring technology transfer. The team implemented the MBARI-developed Open Geospatial Consortium PUCK protocol as part of a pH instrument license agreement with a commercial partner as well as for other applications. The team also released SIAM as open-source software after streamlining the software and improving SIAM documentation.

Testing of Student-Developed Marine Systems

Project leads: William Kirkwood, Chris Kitts
Project manager: William Kirkwood
Collaborators: Thomas Adamek, Sreekanth Dayanidhi, Arjun Menon, and Chase Traficanti, Santa Clara University, California

This project encourages students on a number of technical developments on seagoing systems. The SeaWASP, a small waterplane-area twin-hull (SWATH) platform for shallow-water multibeam mapping, had two successful missions in Lake Tahoe, as well as a number of missions in the Santa Clara reservoir. In a second project, the SeaWASP acted as a hub while three autonomous kayaks operated in unison around it. The work successfully demonstrated the algorithms developed allowing the kayaks to react to an oncoming threat and create a protective barrier. A third project involved the ROV autonomous control system to execute preplanned, precision, three-dimensional movements. A fourth project was initiated to rewrite the fault-tolerant software for a new AUV tailcone and to improve on the functionality of the fault-tolerant recognition software.

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 project team added features to enhance the Video Annotation and Reference System (VARS) with software written to summarize spatial and temporal distributions of video annotations. For example, the system can generate histograms of data on the depth distribution or seasonal observations a particular species of squid. Weekly processing of all the data in the VARS database was established to keep the contents current. The VAAP system and its accompanying web portal, the Deep-Sea Guide, were released internally for MBARI staff to test and use. Staff feedback was used to improve speed and usability.

Zooplankton Biodiversity and Biooptics in the Deep Sea

Project lead/manager: Steven Haddock
Project team: Lynne Christianson
Collaborators: William Browne, University of Miami, Florida; Robert Condon, Bermuda Institute of Ocean Sciences, St. George's; Casey Dunn and Stefan Siebert, Brown University, Providence, Rhode Island; Mikhail Matz, University of Texas, Austin; Claudia Mills, Friday Harbor Laboratories, Washington; Karen Osborn, Smithsonian Institution, Washington D.C.; Philip Pugh, National Oceanography Centre, Southampton, United Kingdom; Bruce Robison, MBARI; Brad Seibel, University of Rhode Island, Kingston; Erik Thuesen, Evergreen State College, Olympia, Washington

Biodiversity studies of gelatinous animals—ctenophores, siphonophores, radiolarians, and hydromedusae—were advanced by both morphological and molecular studies. The team completed sequencing from a range of specimens, correlated with vouchered specimens, and developed a computational pipeline for extracting relevant sequence data from transcriptome data sets. These will be merged to form the most thorough picture yet of comb jelly relationships and siphonophore diversity. The results of these studies will establish baselines for marine communities, and be useful in evaluating the true extent of (and potential changes in) biodiversity of the open ocean, by far the earth's largest habitat.

Awards

Peter Brewer

Einstein Visiting Professorship, Chinese Academy of Sciences

Steven Haddock

Kavli Fellow, National Academy of Sciences, Kavli Frontiers of Science Symposium

William J. Kirkwood, Thomas G. Maughan

Patent issued, Wireless Power and Data Transfer Device for Harsh and Extreme Environments

Linda Kuhnz

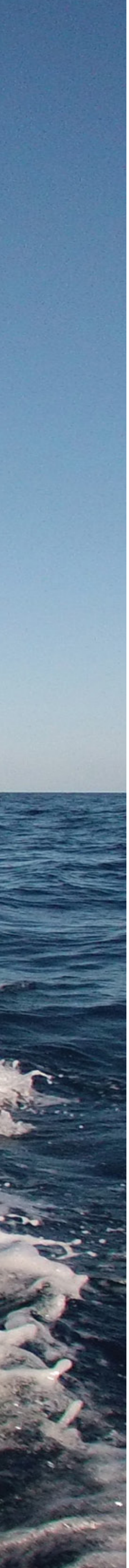
MBARI YouTube video on “Deep-sea snowblower vents” awarded Labby Multimedia Award “Honorable Mention” by *The Scientist* magazine.

Alexandra Z. Worden

Marine Microbiology Investigator, Gordon and Betty Moore Foundation

David Packard Distinguished Lecturer Dana Yoerger

MBARI President and Chief Executive Officer Chris Scholin, left, presents the 2012 David Packard Distinguished Lecturer medal to Dana Yoerger, senior scientist of the Deep Submergence Laboratory at Woods Hole Oceanographic Institution. Yoerger presented a talk at MBARI in November titled “Technology for scientific deep-sea exploration: Where have we been, where are we now, and where are we going?”



Invited Lectures

James Barry

Association for the Sciences of Limnology and Oceanography, Salt Lake City, Utah

Ross Sea Conservation Workshop, La Jolla, California

Keynote Address, Xiangshan Science Conference, Bejing, China

United Kingdom Ocean Acidification Research Program, Exeter

University of California, Santa Cruz

Monterey Bay Aquarium, Monterey, California

Chesapeake Biological Laboratory, Solomons, Maryland

Research Center for Marine Geosciences, Kiel, Germany

Biological Impacts of Ocean Acidification, Kiel, Germany

James G. Bellingham

Association for the Sciences of Limnology and Oceanography, Salt Lake City, Utah

Catch the Next Wave: Meeting Ocean Challenges, London, United Kingdom

Electric Vehicles Land, Sea & Air USA, San Jose, California

University of California, Berkeley

Plenary Speaker, Mine Warfare Technology Symposium, Monterey, California

National Marine Sanctuary Foundation, Capitol Hill Ocean Week, Washington, D.C.

Association for Unmanned Vehicle Systems International, Las Vegas, Nevada

Keynote Presentation, Bluefin Robotics Fifteenth Birthday, Quincy, Maine

Keynote Presentation, International Workshop on Underwater Networks, Los Angeles, California

James Birch

Micro Total Analytical Systems, Okinawa, Japan

Peter G. Brewer

American Association for the Advancement of Science, Vancouver, Canada

Geophysical Colloquium, Max-Planck-Institut für Meteorologie, Hamburg, Germany

Exploration of the Sea and the North Pacific Marine Science Organization Symposium, Yeosu, Korea

David Dryssen Symposium on Marine Sciences, Gothenburg, Sweden

Ocean University, Qingdao, China

Institute of Oceanology, Qingdao, China

Northwestern Polytechnical University, Xi'an, China

Graduate University of the Chinese Academy of Sciences, China

Third International Symposium on The Ocean in a High CO_2 World, Monterey, California

BNP Paribas Foundation, Villefranche-sur-mer, France

François Cazenave

Moss Landing Marine Laboratories, California

Francisco Chavez

Association for the Sciences of Limnology and Oceanography, Salt Lake City, Utah

National Aeronautics and Space Administration, Seattle, Washington

University of California, Santa Barbara

Peruvian Ocean Sciences, Lima, Peru

Open Science Symposium, Qingdao, China

David Clague

Keynote Presentation, American Geophysical Union Chapman Conference, Waikoloa, Hawaii

American Geophysical Union, San Francisco, California

Judith Connor

National Steinbeck Center, Salinas, California

Monterey Bay Aquarium, Monterey, California

Ministry of Foreign Affairs, Santiago, Chile

Steven Haddock

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

Silicon Valley Space Business Roundtable, Menlo Park, California

Keynote Presentation, International Conference on Bioluminescence and Chemiluminescence, Ontario, Canada

Portland State University, Oregon

Keynote Presentation, Monterey Bay National Marine Sanctuary Currents Symposium, Seaside, California

Hendrik Jan Ties Hoving

University of Groningen, Netherlands

Monterey Bay Aquarium, Monterey, California

Scripps Institution of Oceanography, La Jolla, California

Ken Johnson

Association for the Sciences of Limnology and Oceanography, Salt Lake City, Utah

Ed Ricketts Memorial Lecture, Monterey Bay National Marine Sanctuary Currents Symposium, Seaside, California

European Geosciences Union, Vienna, Austria

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

Hopkins Marine Station of Stanford University, Pacific Grove, California

Environmental Sensors Conference, Anglet, France

Argo Data Management Team meeting, Hyderabad, India

U.S. Ocean Carbon and Biogeochemistry Time Series Workshop, St. George's, Bermuda

Shannon Johnson

San Jose State University, California

Ocean Institute, Dana Point, California

Monterey Peninsula College TRiO Program, Santa Cruz, California

Moss Landing Marine Laboratories, California

Taewon Kim

Seoul National University, Korea

National Fisheries Research and Development Institute, Busan, Korea

Ewha University, Seoul, Korea

William Kirkwood

Plymouth Marine Laboratory, United Kingdom

Automar Research Network Symposium, Girona, Spain

Lonny Lundsten

California State University, Monterey Bay, Seaside

George I. Matsumoto

Monterey Bay Aquarium, Monterey, California

SpectorDance, Marina, California

Smithsonian Institution, Washington, D.C.

Tribal Marine Science Workshop, Seldovia, Alaska

Pacific Whale Foundation, Maui, Hawaii

Earth System Science Education Alliance, Monterey, California

Keynote Presentation, National Professional Science Master's Association, Monterey, California

California State University, Monterey Bay, Seaside

Monique Messié

International Council for the Exploration of the Sea and the North Pacific Marine Science Organization Conference for Early Career Scientists, Calvià, Majorca, Spain

Charles Paull

University of California, Santa Cruz

Integrated Ocean Drilling Program, Kananaskis, Alberta, Canada

University of California, Davis

Keynote Address, Deep Sea and Sub-Seafloor Frontier, Sitges, Spain

Gordon Research Conference, Ventura, California

International Symposium on Polar Sciences, Jeju Island, Korea

Central Geological Survey, Taipei, Taiwan

National Taiwan University, Taipei, Taiwan

American Geophysical Union, San Francisco, California

Edward Peltzer

Modesto Junior College, California

Ryan Portner

Stanford University, California

American Geophysical Union, San Francisco, California

Frederic Py

University of Porto, Portugal

University of California, Berkeley

Kanna Rajan

Center for Applied Autonomous Sensor Systems, Orebro University, Sweden

Google, Mountain View, California

Office of Naval Research Autonomy Architectures Summit, Arlington, Virginia

University of Porto, Portugal

Association for the Advancement of Artificial Intelligence, St. Paul, Minnesota

University of California, Berkeley

Sternberger Lecture, University of Rhode Island, Kingston

Keynote Presentation, International Federation of Automatic Control Workshop on Navigation, Guidance, and Control of Underwater Vehicles, Porto, Portugal

University of Genoa, Italy

North Atlantic Treaty Organization Undersea Research Center, La Spezia, Italy

Indraprastha Institute of Information Technology, Delhi, India

Naval Science and Technology Laboratory, Vishakapatnam, India

Bruce Robison

Plenary Presentation, Conference on the Sea: Exploring the Deep Pelagic Realm, São Paulo, Brazil

Plenary Presentation, Australian Marine Sciences Association and the New Zealand Marine Sciences Society, Hobart, Tasmania, Australia

Commonwealth Scientific and Industrial Research Organization, Hobart, Tasmania, Australia

BLUE Ocean Film Festival, Monterey, California

Leslie Rosenfeld

Stanford University, California

University of California, Santa Cruz

John Ryan

Institut de Ciències del Mar, Barcelona, Spain

Optical Remote Sensing of the Environment Conference, Monterey, California

Kyra Schlining

TEDx Monterey, California

Christopher Scholin

Sandia National Laboratory, Livermore, California

Defense Threat Reduction Agency, Washington, D.C.

Institute for Systems Biology, Seattle, Washington

Monterey Bay National Marine Sanctuary, Monterey, California

Stanford Energy and Environment Symposium, Stanford University, California

Innovative Ventures Laboratory, Seattle, Washington

Hopkins Marine Station of Stanford University, Pacific Grove, California

National Science Foundation Research Coordination Network, San Francisco, California

Esther Sumner

Society of Economic Paleontologists and Mineralogists (Society for Sedimentary Geology), American Association of Petroleum Geologists, Long Beach, California

Josi Taylor

California State University, East Bay, Hayward

Hopkins Marine Station of Stanford University, Pacific Grove, California

William Ussler III

Deep-Sea and Sub-Seafloor Frontier Conference, Sitges, Spain

Robert C. Vrijenhoek

National Oceanography Centre, Southampton, United Kingdom

Alexandra Z. Worden

Bay Area Biosystematists, San Jose, California

International Society for Microbial Ecology, Copenhagen, Denmark

Keynote Lecture, International Chrysophyte Symposium, Prague, Czech Republic

University of California, Davis

American Association for the Advancement of Science, Vancouver, Canada

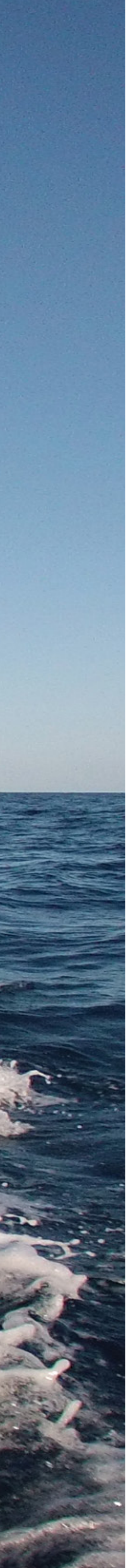
Yanwu Zhang

International Federation of Automatic Control Workshop on Navigation, Guidance, and Control of Underwater Vehicles, Porto, Portugal

Second Chinese Symposium on Deep Sea and Earth Sciences, Shanghai, China

Chinese Academy of Sciences Shenyang Institute of Automation, Shenyang, China

First Chinese Conference on Seafloor Observation, Shanghai, China



Mentorships

Nancy Barr, Thomas Hoover, Mike McCann, Kyra Schlining

Rhylae McClelland, high school student, Monterey Academy of Oceanographic Science (image selection, web content management systems, and long-range autonomous underwater vehicles)

James Barry

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

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

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

James Barry, Lonny Lundsten, Nancy Jacobsen Stout

Evelyn Byer, graduate student, Keck Graduate Institute (analysis of MBARI's deep-sea coral observations)

James G. Bellingham

Dongsik Chang, graduate summer intern, Georgia Institute of Technology (ocean currents prediction for navigation: tradespace between vehicle performance and ocean model accuracy)

M. Jordan Stanway, postdoctoral fellow (compact models for onboard planning)

Diane Wyse, graduate summer intern, Moss Landing Marine Laboratories (sensing, scattering, and surrogates: analysis of data from the laser in-situ scattering and transmissometry 100X sensor on the *Dorado* autonomous underwater vehicle)

James Birch, Christopher Scholin

Holly Bowers, postdoctoral fellow (using molecular methods to uncover cryptic species of *Pseudo-nitzschia* in Monterey Bay)

Peter Brewer

Anna Gallagher, undergraduate summer intern, Carleton College (measuring the concentration of CO_2 in the deep ocean: methods and detection limits using laser Raman spectroscopy)

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

François Cazenave, Andy Hamilton

Peter Corr-Barberis, undergraduate summer intern, University of California, Berkeley (improving the dynamics, efficiency, and recoverability of the power buoy system)

Francisco Chavez

Michael Fong, undergraduate summer intern, University of California, Berkeley (Wave Glider observations of pCO_2, pH, and upwelling dynamics in the Monterey Bay during the spring 2012 CANON experiment)

David Clague

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

Jason Coumans, Ph.D. student, McGill University (petrologic study of Taney Seamounts)

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

John Jamieson, Ph.D. student, University of Ottawa (age and distribution of sulfide deposits on the Endeavour Ridge)

Ryan Portner, postdoctoral fellow (origin, transport, and deposition of volcaniclastic sediments on seamounts)

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

David Clague, Julie Martin, Jennifer Paduan

Patricia Clark, undergraduate summer intern (lava flow morphologies along the Alarcón Rise)

Danelle Cline

Samantha Peterson, undergraduate summer intern, Florida Institute of Technology (the identification process: human and program effectiveness)

Judith Connor

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

Judith Connor, Susan von Thun

Geraldine Fauville, graduate summer intern, Sven Lovén Centre for Marine Sciences (MBARI diving into social media)

Kim Fulton-Bennett

Erin Loury, 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)

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

Hendrik Jan Ties Hoving, Bruce Robison

Alicia Bitondo, M.S. student, Moss Landing Marine Laboratories (cephalopods)

Ken Johnson

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

Yui Takeshita, Ph.D. student, Scripps Institution of Oceanography (chemical sensors on profiling floats)

Chad Kecy

Jaine Perotti, undergraduate summer intern, Florida Institute of Technology (software development for a low-voltage-load switching board)

William Kirkwood

Justin Tucker, graduate summer intern, University of California, Los Angeles (Shearwater: fluid dynamic considerations for development of a wing-in-ground-capable autonomous underwater vehicle)

Linda Kuhnz

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

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

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

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

Brandon Genco, undergraduate summer intern, Boston University (study on the abundance and population structure of the holothurian *Elpidia minutissima* at study site Station M)

Chris Lovera

Armando Alonso-Guillen, high school student, Pajaro Valley High School (effects of ocean acidification on filter feeding in Elkhorn Slough molluscs)

Aurelio Anaya, high school student, Pajaro Valley High School (effects of ocean acidification on filter feeding in Elkhorn Slough molluscs)

Erika Cancino, high school student, Pajaro Valley High School (effects of ocean acidification on filter feeding in Elkhorn Slough molluscs)

Alexis Rodriguez, high school student, Pajaro Valley High School (effects of ocean acidification on filter feeding in Elkhorn Slough molluscs)

George I. Matsumoto

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

Chantal Fry, high school student, Pajaro Valley High School (microcystin levels in Pinto Lake and neighboring bodies of water)

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

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

Margarita Rincon, high school student, Pajaro Valley High School (microcystin levels in Pinto Lake and neighboring bodies of water)

Adrian Rocha, high school student, Pajaro Valley High School (microcystin levels in Pinto Lake and neighboring bodies of water)

Alvaro Zamora, high school student, Pajaro Valley High School (microcystin levels in Pinto Lake and neighboring bodies of water)

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

Mike McCann

Francisco Lopez, graduate summer intern, University of Cadiz, Spain (Matlab stoqstoolbox for accessing in situ measurements)

Charles Paull

Grant Duffy, Ph.D. student, National Oceanography Centre (megafaunal benthic ecology of the submarine canyons of Southern California)

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

Esther Sumner, postdoctoral fellow (sedimentary processes in submarine canyons)

Kanna Rajan

Matthew Bernstein, M.S. student, Carnegie Mellon University (multi-robot exploration of the coastal ocean)

Lukas Chirpa, postdoctoral student, University of Huddersfield, United Kingdom (building domain models for automated planning)

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)

Jeremy Gottlieb, Ph.D. student, University of California, Santa Cruz (using the Oceanographic Decision Support System in concert with autonomous platforms)

Rishi Graham, postdoctoral fellow (distributed autonomy)

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

Bruce Robison

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

Steve Rock

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

Marcus Hammond, Ph.D. student, Stanford University (benthic mapping using AUVs)

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

Stephen Krukowski, Ph.D. student, Stanford University (optimized trajectories for terrain-relative navigation)

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

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

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

Rick Zhang, Ph.D. student, Stanford University (benthic mosaicking and navigation)

Leslie Rosenfeld

Jason Adelaars, graduate summer intern (geospatial analyses of atmospheric and oceanic parameters off the California coast)

Brian Schlining, Nancy Jacobsen Stout

Erica Curles, undergraduate summer intern, University of California, Santa Cruz (the Deep-Sea Guide: developing for the public versus an internal client)

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)

Josi Taylor

Emmelie Avila, high school student, Pajaro Valley High School (ocean acidification: effects on behavior of echinoderms)

Brian Navarro, high school student, Pajaro Valley High School (ocean acidification: effects on behavior of echinoderms)

Daisy Rocha, high school student, Pajaro Valley High School (ocean acidification: effects on behavior of echinoderms)

Paulina Serna, high school student, Pajaro Valley High School (ocean acidification: effects on behavior of echinoderms)

Robert Vrijenhoek

Audrey Djunaedi, undergraduate summer intern, University of Washington (dosage response of a zooplankton molecular detection system with true environmental background)

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

Alexandra Z. Worden

Valeria Jimenez, Ph.D. student, University of California, Santa Cruz (ecology of photosynthetic eukaryotes)

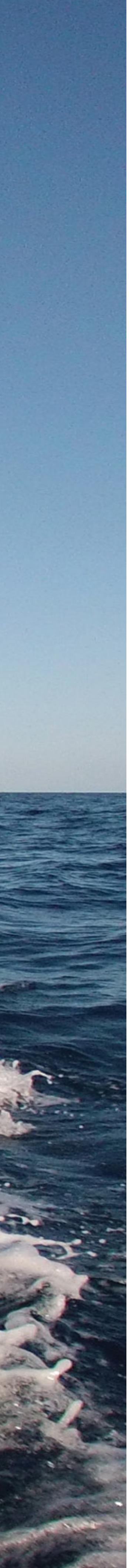
Adrian Jones, Ph.D. student, University of Southern California (mixotrophy)

Alexander Limardo, Ph.D. student, University of California, Santa Cruz (to be determined)

Darcy McRose, graduate student, Stanford University (the role of vitamins in regulating growth of marine algae)

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

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



2012 Publications

Audzijonyte, A., E.M. Krylova, H. Sahling, and **R.C. Vrijenhoek** (2012). Molecular taxonomy reveals broad trans-oceanic distributions and high species diversity of deep-sea clams (Bivalvia: Vesicomyidae: Pliocardiinae) in chemosynthetic environments. *Systematics and Biodiversity*, **10**: 403-415, doi: 10.1080/14772000.2012.744112.

Bjorkstedt, E.P., R. Goericke, S. McClatchie, E. Weber, W. Watson, N. Lo, W.T. Peterson, R.D. Brodeur, T. Auth, J. Fisher, C. Morgan, J. Peterson, J. Largier, S.J. Bograd, R. Durazo, G. Gaxiola-Castro, B. Lavaniegos, **F.P. Chavez**, C.A. Collins, B. Hannah, J. Field, K. Sakuma, W. Satterthwaite, M. O'Farrell, S. Hayes, J. Harding, W.J. Sydeman, S.A. Thompson, P. Warzybok, R. Bradley, J. Jahncke, R.T. Golightly, S.R. Schneider, R.M. Suryan, A.J. Gladics, C.A. Horton, S.Y. Kim, S.R. Melin, R.L. DeLong, and J. Abell (2012). State of the California Current 2011–2012: ecosystems respond to local forcing as La Niña wavers and wanes. *California Cooperative Oceanic Fisheries Investigations Reports*, **53**: 41-76.

Brewer, P.G. (2012). Book Review: "Ocean Acidification" Edited by J.-P. Gattuso and L. Hansson, Oxford University Press. *Limnology and Oceanography Bulletin*, **21**: 14-16.

Buck, K.R., N.N. Rabalais, J.M. Bernhard, and **J.P. Barry** (2012). Living assemblages from the 'dead zone' and naturally occurring hypoxic zones. In: *Anoxia: Evidence for Eukaryote Survival and Paleontological Strategies*, edited by A.V. Altenbach, J.M. Bernhard, and J. Seckbach. Springer Netherlands, pp. 343-352, doi: 10.1007/978-94-007-1896-8_18.

Buitenhuis, E.T., W.K.W. Li, D. Vaulot, M.W. Lomas, M. Landry, F. Partensky, D.M. Karl, O. Ulloa, L. Campbell, S. Jacquet, F. Lantoine, **F. Chavez**, D. Macias, M. Gosselin, and G.B. McManus (2012). Picophytoplankton biomass distribution in the global ocean. *Earth System Science Data Discussions*, **5**: 221-242, doi: 10.5194/essdd-5-221-2012.

Bush, S.L., **H.J.T. Hoving**, **C.L. Huffard**, **B.H. Robison**, and L.D. Zeidberg (2012). Brooding and sperm storage by the deep-sea squid *Bathyteuthis berryi* (Cephalopoda: Decapodiformes). *Journal of the Marine Biological Association of the United Kingdom*, **92**: 1629-1636, doi: 10.1017/S0025315411002165.

Caress, D.W., **D.A. Clague**, **J.B. Paduan**, **J.F. Martin**, B.M. Dreyer, W.W. Chadwick Jr., A. Denny, and D.S. Kelley (2012). Repeat bathymetric surveys at 1-metre resolution of lava flows erupted at Axial Seamount in April 2011. *Nature Geoscience*, **5**: 483-488, doi: 10.1038/ngeo1496.

Chavez, F.P. (2012). Climate change and marine ecosystems. *Proceedings of the National Academy of Sciences of the United States of America*, doi: 10.1073/pnas.1217112109.

Condon, R.H., C.M. Duarte, K.A. Pitt, K.L. Robinson, C.H. Lucas, K.R. Sutherland, H.W. Mianzan, M. Bogeberg, J.E. Purcell, M.B. Decker, S.-I. Uye, L.P. Madin, R.D. Brodeur, **S.H.D. Haddock**, A. Malej, G.D. Parry, E. Eriksen, J. Quiñones, M. Acha, M. Harvey, J.M. Arthur, and W.M. Graham (2012). Recurrent jellyfish blooms are a consequence of global oscillations. *Proceedings of the National Academy of Sciences of the United States of America*, doi: 10.1073/pnas.1210920110.

Condon, R.H., W.M. Graham, C.M. Duarte, K.A. Pitt, C.H. Lucas, **S.H.D. Haddock**, K.R. Sutherland, K.L. Robinson, M.N. Dawson, M.B. Decker, C.E. Mills, J.E. Purcell, A. Malej, H. Mianzan, S.-I. Uye, S. Gelcich, and L.P. Madin (2012). Questioning the rise of gelatinous zooplankton in the world's oceans. *BioScience*, **62**: 160-169, doi: 10.1525/bio.2012.62.2.9.

Curtis, B.A., G. Tanifuji, F. Burki, A. Gruber, M. Irimia, S. Maruyama, M.C. Arias, S.G. Ball, G.H. Gile, Y. Hirakawa, J.F. Hopkins, A. Kuo, S.A. Rensing, J. Schmutz, A. Symeonidi, M. Elias, J.M. Eveleigh, E.K. Herman, M.J. Klute, T. Nakayama, M. Obornik, A. Reyes-Prieto, E.V. Armbrust, S.J. Aves, R.G. Beiko, P. Coutinho, J.B. Dacks, D.G. Durnford, N.M. Fast, B.R. Green, C.J. Grisdale, F. Hempel, B. Henrissat, M.P. Höppner, K.-I. Ishida, E. Kim, L. Kořený, P.G. Kroth, Y. Liu, S.-B. Malik, U.G. Maier, **D. McRose**, T. Mock, J.A.D. Neilson, N.T. Onodera, A.M. Poole, E.J. Pritham, T.A. Richards, G. Rocap, S.W. Roy, C. Sarai, S. Schaack, S. Shirato, C.H. Slamovits, D.F. Spencer, S. Suzuki, **A.Z. Worden**, S. Zauner, K. Barry, C. Bell, A.K. Bharti, J.A. Crow, J. Grimwood, R. Kramer, E. Lindquist, S. Lucas, A. Salamov, G.I. McFadden, C.E. Lane, P.J. Keeling, M.W. Gray, I.V. Grigoriev, and J.M. Archibald (2012). Algal genomes reveal evolutionary mosaicism and the fate of nucleomorphs. *Nature*, **492**: 59-65, doi: 10.1038/nature11681.

Das, J., **J. Harvey**, **J. Ryan**, **F. Py**, **R. Graham**, **K. Rajan**, and G. Sukhatme (2012). Multi-stage Bayesian regression for adaptive sampling of marine phenomena. Robotics: Science and Systems *Workshop on Robotics for Environmental Monitoring*, Sydney, Australia.

Das, J., **F. Py**, **T. Maughan**, **T. O'Reilly**, **M. Messié**, **J. Ryan**, G.S. Sukhatme, and **K. Rajan** (2012). Coordinated sampling of dynamic oceanographic features with underwater vehicles and drifters.

International Journal of Robotics Research, **31**: 626-646, doi: 10.1177/0278364912440736.

Dektor, S., and **S.M. Rock** (2012). Improving robustness of terrain-relative navigation for AUVs in regions with flat terrain. *Proceedings of Oceanic Engineering Society/Institute of Electrical and Electronics Engineers Autonomous Underwater Vehicles 2012*, Southampton, UK. 1-7, doi: 10.1109/AUV.2012.6380751.

Demir-Hilton, E., D.A. Hutchins, K.J. Czymmek, and K.J. Coyne (2012). Description of *Viridilobus marinus* (gen. et sp. nov.), a new raphidophyte from Delaware's inland bays. *Journal of Phycology*, **48**: 1220-1231, doi: 10.1111/j.1529-8817.2012.01212.x.

Doney, S.C., M. Ruckelshaus, J.E. Duffy, **J.P. Barry**, F. Chan, C.A. English, H.M. Galindo, J.M. Grebmeier, A.B. Hollowed, N. Knowlton, J. Polovina, N.N. Rabalais, W.J. Sydeman, and L.D. Talley (2012). Climate change impacts on marine ecosystems. *Annual Review of Marine Science*, **4**: 11-37, doi: 10.1146/annurev-marine-041911-111611.

Drazen, J.C., D.M. Bailey, H.A. Ruhl, and **K.L. Smith Jr.** (2012). The role of carrion supply in the abundance of deep-water fish off California. *PloS One*, **7**: e49332, doi: 10.1371/journal.pone.0049332.

Edwards, K.J., C.G. Wheat, B.N. Orcutt, S. Hulme, K. Becker, **H. Jannasch**, A. Haddad, T. Pettigrew, W. Rhinehart, K. Grigar, W. Bach, **W. Kirkwood**, and A. Klaus (2012). Design and deployment of borehole observatories and experiments during IODP Expedition 336, Mid-Atlantic Ridge flank at North Pond. *Proceedings of the Integrated Ocean Drilling Program*, **336**: doi: 10.2204/iodp.proc.336.109.2012.

Fischer, E.V., K.R.M. Mackey, D.F. Cusack, L.R.G. DeSantis, L. Hartzell-Nichols, J.A. Lutz, J. Melbourne-Thomas, R. Meyer, D.A. Riveros-Iregui, C.J.B. Sorte, **J.R. Taylor**, S.A. White (2012). Is pre-tenure interdisciplinary research a career risk? *EOS*. **93**: 311-312.

Fisher, A.T., T. Tsuji, K. Petronotis, C.G. Wheat, K. Becker, J.F. Clark, J. Cowen, K. Edwards, **H. Jannasch**, and the IODP Expedition 327 and Atlantis Expedition AT18-07 Shipboard Parties (2012). IODP Expedition 327 and Atlantis Expedition AT 18-07: Observatories and experiments on the eastern flank of the Juan de Fuca Ridge. *Scientific Drilling Journal*, **13**: 4-11, doi: 10.2204/iodp.sd.13.01.2011.

Frolov, S., J. Paduan, M. Cook, and **J. Bellingham** (2012). Improved statistical prediction of surface currents based on historic HF-radar observations. *Ocean Dynamics*, **62**: 1111-1122, doi: 10.1007/s10236-012-0553-5.

Frolov, S., **J.P. Ryan**, and **F.P. Chavez** (2012). Predicting euphotic-depth-integrated chlorophyll-a from discrete depth and satellite-observable chlorophyll-a off central California. *Journal of Geophysical Research*, **117**: doi: 10.1029/2011JC007322.

García-Olaya, A., **F. Py**, J. Das, and **K. Rajan** (2012). An online utility-based approach for sampling dynamic ocean fields. *Institute of Electrical and Electronics Engineers Journal of Oceanic Engineering*, **37**: 185-203, doi: 10.1109/JOE.2012.2183934.

Gilly, W.F., J.M. Beman, S.Y. Litvin, and **B.H. Robison** (2012). Oceanographic and biological effects of shoaling of the oxygen minimum zone. *Annual Review of Marine Science*, **5**: 393-420, doi: 10.1146/annurev-marine-120710-100849.

Gomez, F., A. Montecinos, S. Hormazabal, L.A. Cubillos, M. Correa-Ramirez, and **F.P. Chavez** (2012). Impact of spring upwelling variability off southern-central Chile on common sardine (*Strangomera bentincki*) recruitment. *Fisheries Oceanography*, **21**: 405-414, doi: 10.1111/j.1365-2419.2012.00632.x.

González, J., I. Masmitjà, S. Gomáriz, E. Molino, J. del Río, A. Mànuel, J. Busquets, A. Guerrero, F. López, M. Carreras, D. Ribas, A. Carrera, C. Candela, P. Ridao, J. Sousa, P. Calado, J. Pinto, A. Sousa, R. Martins, D. Borrajo, A. Olaya, B. Garau, I. González, S. Torres, **K. Rajan**, **M. McCann**, and J. Gilabert (2012). AUV based multi-vehicle collaboration: Salinity studies in Mar Menor coastal lagoon. In: *Proceedings of the International Federation of Automatic Control Workshop on Navigation, Guidance and Control of Underwater Vehicles*, Porto, Portugal. 6 pp. doi: 10.3182/20120410-3-PT-4028.00048.

Gottlieb, J., **R. Graham**, **T. Maughan**, **F. Py**, G. Elkaim, and **K. Rajan** (2012). An experimental momentum-based front detection method for autonomous underwater vehicles. In: *Proceedings of the Institute of Electrical and Electronics Engineers International Conference on Robotics and Automation*, Saint Paul, Minnesota, USA. p. 5322-5327 doi: 10.1109/ICRA.2012.6225115.

Graham, R., **F. Py**, J. Das, D. Lucas, **T. Maughan**, and **K. Rajan** (2012). Exploring space-time tradeoffs in autonomous sampling for marine robotics. *13th International Symposium on Experimental Robotics*, Québec City, Canada. 15 pp.

Haines, S., V. Subramanian, E. Mayorga, D. Snowden, R. Ragsdale, **C. Rueda**, and M. Howard (2012). IOOS vocabulary and ontology strategy for observed properties. *Oceans 2012*, Hampton Road, Virginia. 1-9, doi: 10.1109/OCEANS.2012.6405083.

Hales, B., P.G. Strutton, M. Saraceno, R. Letelier, T. Takahashi, R. Feely, C. Sabine, and **F. Chavez** (2012). Satellite-based prediction of pCO_2 in coastal waters of the eastern North Pacific. *Progress in Oceanography*, **103**: 1-15, doi: 10.1016/j.pocean.2012.03.001.

Harvey, J.B.J., **J.P. Ryan**, **R. Marin III**, **C.M. Preston**, **N. Alvarado**, **C.A. Scholin**, and **R.C. Vrijenhoek** (2012). Robotic sampling, in situ monitoring and molecular detection of marine zooplankton. *Journal of Experimental Marine Biology and Ecology*, **413**: 60-70, doi: 10.1016/j.jembe.2011.11.022.

Harvey, J., **Y. Zhang**, and **J. Ryan** (2012). AUVs for ecological studies of marine plankton communities. *Sea Technology Magazine*. **53**: 51-54.

Helo, C., **D.A. Clague**, D.B. Dingwell, and J. Stix (2012). High and highly variable cooling rates during pyroclastic eruptions on Axial Seamount, Juan de Fuca Ridge. *Journal of Volcanology and Geothermal Research*, doi: 10.1016/j.jvolgeores.2012.12.004.

Hill, T.M., M. LaVigne, H.J. Spero, T. Guilderson, B. Gaylord, and **D. Clague** (2012). Variations in seawater Sr/Ca recorded in deep-sea bamboo corals. *Paleoceanography*, **27**: doi: 10.1029/2011PA002260.

Hobson, B.W., **J.G. Bellingham**, **B. Kieft**, **R. McEwen**, **M. Godin**, and **Y. Zhang** (2012). Tethys-class long range AUVs-extending the endurance of propeller-driven cruising AUVs from days to weeks. *Proceedings of Oceanic Engineering Society/Institute of Electrical and Electronics Engineers Autonomous Underwater Vehicles 2012*, Southampton, UK. 8 pp., doi: 10.1109/AUV.2012.6380735.

Holland, N.D., **L.A. Kuhnz**, and K.J. Osborn (2012). Morphology of a new deep-sea acorn worm (class Enteropneusta, phylum Hemichordata): a part-time demersal drifter with externalized ovaries. *Journal of Morphology*, **273**: 661-671, doi: 10.1002/jmor.20013.

Holland, N.D., K.J. Osborn, and **L.A. Kuhnz** (2012). A new deep-sea species of harrimaniid enteropneust (Hemichordata). *Proceedings of the Biological Society of Washington*, **125**: 228-240.

Houts, S.E., **S.M. Rock**, and **R. McEwen** (2012). Aggressive terrain following for motion-constrained AUVs. *Proceedings of Oceanic Engineering Society/Institute of Electrical and Electronics Engineers Autonomous Underwater Vehicles 2012*, Southampton, UK. 1-7, doi: 10.1109/AUV.2012.6380749.

Hoving, H.J.T. and **B.H. Robison** (2012). Vampire squid: detritivores in the oxygen minimum zone. *Proceedings of the Royal Society B*, **279**: 4559-4567, doi: 10.1098/rspb.2012.1357.

Hoving, H.J.T. and M. Vecchione (2012). Mating behaviour of a deep-sea squid revealed by in situ videography and the study of archived specimens. *Biological Bulletin*, **223**: 263-267.

Johnsen, S., T.M. Frank, **S.H.D. Haddock**, E.A. Widder, and C.G. Messing (2012). Light and vision in the deep-sea benthos: I. Bioluminescence at 500–1000 m depth in the Bahamian Islands. *Journal of Experimental Biology*, **215**: 3335-3343, doi: 10.1242/jeb.072009.

Jolliff, J.K., R.W. Gould Jr., B. Penta, W.J. Teague, S. DeRada, **F.P. Chavez**, and R.A. Arnone (2012). Water mass bio-optical properties in the Monterey Bay region: Fluorescence-based inference of shifts in phytoplankton photophysiology. *Journal of Geophyiscal Research: Oceans*, **117**: doi: 10.1029/2011JC007568.

Kahn, A.S., H.A. Ruhl, and **K.L. Smith** (2012). Temporal changes in deep-sea sponge populations are correlated to changes in surface climate and food supply. *Deep Sea Research I*, **70**: 36-41, doi: 10.1016/j.dsr.2012.08.001.

Kelley, D.S., S.M. Carbotte, **D.W. Caress**, **D.A. Clague**, J.R. Delaney, J.B. Gill, H. Hadaway, J.F. Holden, E.E.E. Hooft, J.P. Kellogg, M.D. Lilley, M. Stoermer, D. Toomey, R. Weekly, and W.S.D. Wilcock (2012). Endeavour segment of the Juan de Fuca ridge: one of the most remarkable places on Earth. *Oceanography*, **25**: 44-61, doi: 10.5670/oceanog.2012.03.

Kitts, C., P. Mahacek, T. Adamek, K. Rasal, V. Howard, S. Li, A. Badaoui, **W. Kirkwood**, G. Wheat, and S. Hulme (2012). Field operation of a robotic small waterplane area twin hull boat for shallow-water bathymetric characterization. *Journal of Field Robotics*, **29**: 924-938, doi: 10.1002/rob.21427.

Klapp, S.A., F. Enzmann, **P. Walz**, T. Huthwelker, J. Tuckermann, J.-O. Schwarz, T. Pape, **E.T. Peltzer**, R. Mokso, D. Wangner, F. Marone, M. Kersten, G. Bohrmann, W.F. Kuhs, M. Stampanoni, and **P.G. Brewer** (2012). Microstructure characteristics during hydrate formation and dissociation revealed by X-ray tomographic microscopy. *Geo-Marine Letters*, **32**: 555-562, doi: 10.1007/s00367-012-0276-0.

Kline, D.I., L. Teneva, K. Schneider, T. Miard, A. Chai, M. Marker, **K. Headley**, B. Opdyke, M. Nash, M. Valetich, J.K. Caves, B.D. Russell, S.D. Connell, **B.J. Kirkwood**, **P. Brewer**, **E. Peltzer**, J. Silverman, K. Caldeira, R.B. Dunbar, J.R. Koseff, S.G. Monismith, B.G. Mitchel, S. Dove, and O. Hoegh-Guldberg (2012). A short-term in situ CO_2 enrichment experiment on Heron Island (GBR). *Scientific Reports*, **2**: doi: 10.1038/srep00413.

Lee, W.L., H.M. Reiswig, W.C. Austin, and **L. Lundsten** (2012). An extraordinary new carnivorous sponge, *Chondrocladia lyra*, in the new subgenus *Symmetrocladia* (Demospongiae, Cladorhizidae), from off of northern California, USA. *Invertebrate Biology*, **131**: 259-284, doi: 10.1111/ivb.12001.

Levin, L.A., V.J. Orphan, G.W. Rouse, A.E. Rathburn, **W. Ussler III**, G.S. Cook, S.K. Goffredi, E.M. Perez, A. Waren, B.M. Grupe, G. Chadwick, and B. Strickrott (2012). A hydrothermal seep on the Costa Rica margin: middle ground in a continuum of reducing ecosystems. *Proceedings of the Royal Society B*, **279**: 2580-2588, doi: 10.1098/rspb.2012.0205.

Lin*, Y.-C., **T. Campbell**, C-C. Chung, G-C. Gong, K.-P. Chiang, and **A.Z. Worden** (2012). Distribution patterns and phylogeny of marine stramenopiles in the North Pacific Ocean. *Applied and Environmental Microbiology*, **78**: 3387-3399.

Lundsten, L., **S.B. Johnson**, G.M. Calliet, A.P. DeVogelaere, and **D.A. Clague** (2012). Morphological, molecular, and in situ behavioral observations of the rare deep-sea anglerfish *Chaunacops coloratus* (Garman, 1899), order Lophiiformes, in the eastern North Pacific. *Deep Sea Research I*, **68**: 46-53, doi: 10.1016/j.dsr.2012.05.012.

Mackey, K.R.M., C.E. Mioni, **J.P. Ryan**, and A. Paytan (2012). Phosphorus cycling in the red tide incubator region of Monterey Bay in response to upwelling. *Frontiers in Microbiology*, **3**: doi: 10.3389/fmicb.2012.00033.

Maier, K.L., A. Fildani, T.R. McHargue, **C.K. Paull**, S.A. Graham, and **D.W. Caress** (2012). Punctuated deep-water channel migration: High-resolution subsurface data from the Lucia Chica channel system, offshore California. *Journal of Sedimentary Research*, **82**: 1-8.

Maier, K.L., A. Fildani, **C.K. Paull**, T.R. McHargue, S.A. Graham, and **D.W. Caress** (2012). Deep-sea channel evolution and stratigraphic architecture from inception to abandonment from high-resolution autonomous underwater vehicle surveys offshore central California. *Sedimentology*, doi: 10.1111/j.1365-3091.2012.01371.x.

McGillivary, P., **K. Rajan**, J.B. de Sousa, F. Leroy, and R. Martins (2012). Integrating autonomous underwater vessels, surface vessels and aircraft as persistent surveillance components of ocean observing studies. *Proceedings of Oceanic Engineering Society/Institute of Electrical and Electronics Engineers Autonomous Underwater Vehicles* 2012, Southampton, U.K. 1-5, doi: 10.1109/AUV.2012.6380734.

Messié, M. and **F.P. Chavez** (2012). A global analysis of ENSO synchrony: The oceans' biological response to physical forcing. *Journal of Geophyiscal Research: Oceans*, **117**: doi: 10.1029/2012JC007938.

Moeseneder, M.M., **K.L. Smith Jr.**, H.A. Ruhl, D.O.B. Jones, U. Witte, and J.I. Prosser (2012). Temporal and depth-related differences in prokaryotic communities in abyssal sediments associated with particulate organic carbon flux. *Deep Sea Research I*, **70**: 26-35, doi: 10.1016/j.dsr.2012.07.010.

Monier, A., R.M. Welsh, C. Gentemann, G. Weinstock, E. Sodergren, E.V. Armbrust, J.A. Eisen, and **A.Z. Worden** (2012). Phosphate transporters in marine phytoplankton and their viruses: Cross-domain commonalities in viral-host gene exchanges. *Environmental Microbiology*, **14**: 162-176, doi: 10.1111/j.1462-2920.2011.02576.x.

Padial, J., M. Hammond, S. Augenstein, and **S.M. Rock** (2012). Tumbling target reconstruction and pose estimation through fusion of monocular vision and sparse-pattern range data. *Proceedings of Institute of Electrical and Electronics Engineers Conference on Multisensor Fusion and Integration for Intelligent Systems*, Hamburg, Germany. 419-425, doi: 10.1109/MFI.2012.6343026.

Patterson, J., J. Thomas, **L. Rosenfeld**, J. Newton, L. Hazard, **J. Scianna**, R. Kudela, E. Mayorga, C. Cohen, M. Cook, M. Otero, and **J. Adelaars** (2012). Addressing ocean and coastal issues at the West Coast scale through regional ocean observing system collaboration. *Oceans 2012*, Hampton Road, Virginia. 1-8, doi: 10.1109/OCEANS.2012.6404937.

Paull, C.K., **D.W. Caress**, **E. Lundsten**, **R. Gwiazda**, **K. Anderson**, M. McGann, J. Conrad, B. Edwards, and **E.J. Sumner** (2012). Anatomy of the La Jolla Submarine Canyon system; offshore southern California. *Marine Geology*, **335**: 16-34, doi: 10.1016/j.margeo.2012.10.003.

Pfeil, B., A. Olsen, D.C.E. Bakker, S. Hankin, H. Koyuk, A. Kozyr, J. Malczyk, A. Manke, N. Metzl, C.L. Sabine, J. Akl, S.R. Alin, R.G.J. Bellerby, A. Borges, J. Boutin, P.J. Brown, W.-J. Cai, **F.P. Chavez**, A. Chen, C. Cosca, A.J. Fassbender, R.A. Feely, M. González-Dávila, C. Goyet, N. Hardman-Mountford, C. Heinze, M. Hood, M. Hoppema, C.W. Hunt, D. Hydes, M. Ishii, T. Johannessen, S.D. Jones, R.M. Key, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, A. Lenton, A. Lourantou, L. Merlivat, T. Midorikawa, L. Mintrop, C. Miyazaki, A. Murata, A. Nakadate, Y. Nakano, S. Nakaoka, Y. Nojiri, A.M. Omar, X.A. Padin, G.-H. Park, K. Paterson, F.F. Perez, D. Pierrot, A. Poisson, A.F. Ríos, J.M. Santana-Casiano, J. Salisbury, V.V.S.S. Sarma, R. Schlitzer, B. Schneider, U. Schuster, R. Sieger, I. Skjelvan, T. Steinhoff, T. Suzuki, T. Takahashi, K. Tedesco, M. Telszewski, H. Thomas, B. Tilbrook, J. Tjiputra, D. Vandemark, T. Veness, R. Wanninkhof, A.J. Watson, R. Weiss, C.S. Wong, and H. Yoshikawa-Inoue (2012). A uniform, quality controlled Surface Ocean CO_2 Atlas (SOCAT). *Earth System Science Data Discussions*, **5**: 735-780, doi: 10.5194/essdd-5-735-2012.

Pinto, J., J.B. de Sousa, **F. Py**, and **K. Rajan** (2012). Experiments with deliberative planning on autonomous underwater vehicles. Intelligent Robots and Systems *2012 Workshop on Robotics for Environmental Monitoring*, Vila Moura, Portugal.

Powers, M.L., **A.G. McDermott**, **N. Shaner**, and **S.H.D. Haddock** (2012). Expression and characterization of the calcium-activated photoprotein from the ctenophore *Bathocyroe fosteri*: Insights into light-sensitive photoproteins. *Biochemical and Biophysical Research Communications*, doi: 10.1016/j.bbrc.2012.12.026.

Py, F. and **K. Rajan** (2012). Towards distributed decision-making in situated agents. *Conference on Advances in Cognitive Systems*, Palo Alto, California.

Rago, T.A., **R. Michisaki**, B. Marinovic, and M. Blum* (2012). *Physical, nutrient, and biological measurements of coastal waters off Central California in March 2012*. Naval Postgraduate School. 63 pp.

Rajan, K., and **F. Py** (2012). T-REX: Partitioned inference for AUV mission control. In: *Further Advances in Unmanned Marine Vehicles*, edited by G.N. Roberts and R. Sutton. Institution of Engineering and Technology, pp. 171-199, doi: 10.1049/PBCE077E_ch9.

Rajan, K., **F. Py**, and J. Barreiro. Towards deliberative control in marine robotics. In: *Marine Robot Autonomy*, edited by M.L. Seto. Springer, pp. 91-175, doi: 10.1007/978-1-4614-5659-9_3.

Robidart*, J.C., **C.M. Preston**, R.W. Paerl, K.A. Turk, A.C. Mosier, C.A. Francis, **C.A. Scholin**, and J.P. Zehr (2012). Seasonal *Synechococcus* and *Thaumarchaeal* population dynamics examined with high resolution with remote in situ instrumentation. *The ISME Journal*, **6**: 513-523, doi: 10.1038/ismej.2011.127.

Rosenfeld, L., Y. Chao, and R. Signell (2012). IOOS modeling subsystem: vision and implementation strategy. *Final report of the Integrated Ocean Observing System Summit*, Herndon, Virginia.

Rubin, K.H., S.A. Soule, W.W. Chadwick Jr., D.J. Fornari, **D.A. Clague**, R.W. Embley, E.T. Baker, M.R. Perfit, **D.W. Caress**, and R.P. Dziak (2012). Volcanic eruptions in the deep sea. *Oceanography*, **25**: 142-157, doi: 10.5670/oceanog.2012.12.

Ryan, H.F., J.E. Conrad, **C.K. Paull**, and M. McGann (2012). Slip rate on the San Diego Trough Fault Zone, inner California Borderland, and the 1986 Oceanside earthquake swarm revisited. *Bulletin of the Seismological Society of America*, **102**: 2300-2312, doi: 10.1785/0120110317.

Sabine, C.L., S. Hankin, H. Koyuk, D.C.E. Bakker, B. Pfeil, A. Olsen, N. Metzl, A. Kozyr, A. Fassbender, A. Manke, J. Malczyk, J. Akl, S.R. Alin, R.G.J. Bellerby, A. Borges, J. Boutin, P.J. Brown, W.-J. Cai, **F.P. Chavez**, A. Chen, C. Cosca, R.A. Feely, M. González-Dávila, C. Goyet, N. Hardman-Mountford, C. Heinze, M. Hoppema, C.W. Hunt, D. Hydes, M. Ishii, T. Johannessen, R.M. Key, A. Körtzinger, P. Landschützer, S.K. Lauvset, N. Lefèvre, A. Lenton, A. Lourantou, L. Merlivat, T. Midorikawa, L. Mintrop, C. Miyazaki, A. Murata, A. Nakadate, Y. Nakano, S. Nakaoka, Y. Nojiri, A.M. Omar, X.A. Padin, G.-H. Park, K. Patterson, F.F. Perez, D. Pierrot, A. Poisson, A.F. Ríos, J. Salisbury, J.M. Santana-Casiano, V.V.S.S. Sarma, R. Schlitzer, B. Schneider, U. Schuster, R. Sieger, I. Skjelvan, T. Steinhoff, T. Suzuki, T. Takahashi, K. Tedesco, M. Telszewski, H. Thomas, B. Tilbrook, D. Vandemark, T. Veness, A.J. Watson, R. Weiss, C.S. Wong, and H. Yoshikawa-Inoue (2012). Surface Ocean CO_2 Atlas (SOCAT) gridded data products. *Earth System Science Data Discussions*, **5**: 781-804, doi: 10.5194/essdd-5-781-2012.

Salathé, R.M. and **R.C. Vrijenhoek** (2012). Temporal variation and lack of host specificity among bacterial endosymbionts of *Osedax* bone worms (Polychaeta: Siboglinidae). *BMC Evolutionary Biology*, **12**:, doi: 10.1186/1471-2148-12-189.

Schnitzler, C.E., K. Pang, **M.L. Powers**, A.M. Reitzel, J.F. Ryan, D. Simmons, T. Tada, M. Park, J. Gupta, S.Y. Brooks, R.W. Blakesley, S. Yokoyama, **S.H.D. Haddock**, M.Q. Martindale, and A.D. Baxevanis (2012). Genomic organization, evolution, and expression of photoprotein and opsin genes in *Mnemiopsis leidyi*: a new view of ctenophore photocytes. *BMC Biology*, **10**: doi: 10.1186/1741-7007-10-107.

Secor, S.M., **J.R. Taylor**, and M. Grosell (2012). Selected regulation of gastrointestinal acid-base secretion and tissue metabolism for the diamondback water snake and Burmese python. *Journal of Experimental Biology*, **215**: 185-196.

Shulman, I., B. Penta, M.A. Moline, **S.H.D. Haddock**, S. Anderson, M.J. Oliver, and P. Sakalaukus (2012). Can vertical migrations of dinoflagellates explain observed bioluminescence patterns during an upwelling event in Monterey Bay, California? *Journal of Geophysical Research*, **117**: c01016, doi: 10.1029/2011JC007480.

Sumner, E.J., P.J. Talling, L.A. Amy, R.B. Wynn, C.J. Stevenson, and M. Frenz (2012). Facies architecture of individual basin-plain turbidites: Comparison with existing models and implications for flow processes. *Sedimentology*, **59**: 1850-1887, doi: 10.1111/j.1365-3091.2012.01329.x.

Talling, P.J., G. Malgesini, **E.J. Sumner**, L.A. Amy, F. Felletti, G. Blakbourn, C. Nutt, C. Wilcox, I.C. Harding, and S. Akbari (2012). Planform geometry, stacking pattern, and extrabasinal origin of low strength and intermediate strength cohesive debris flow deposits in the Marnoso-arenacea Formation, Italy. *Geosphere*, **8**: 1207-1230, doi: 10.1130/GES00734.1.

Talling, P.J., D.G. Masson, **E.J. Sumner**, and G. Malgesini (2012). Subaqueous sediment density flows: Depositional processes and deposit types. *Sedimentology*, **59**: 1937-2003, doi: 10.1111/j.1365-3091.2012.01353.x.

Vernet, M., **K.L. Smith Jr.**, A.O. Cefarelli, J.J. Helly, R.S. Kaufmann, H. Lin, D.G. Long, A.E. Murray, **B.H. Robison**, H.A. Ruhl, T.J. Shaw, **A.D. Sherman**, J. Sprintall, G.R. Stephenson Jr., K.M. Stuart, and B.S. Twining (2012). Islands of ice: Influence of free-drifting Antarctic icebergs on pelagic marine ecosystems. *Oceanography*, **25**: 38-39, doi: 10.5670/oceanog.2012.72.

Vrijenhoek, R.C. (2012). Fitness loss and genetic rescue in stream-dwelling topminnows. In: *Conservation and the Genetics of Populations, 2nd Edition*, Wiley-Blackwell, pp. 313.

Vrijenhoek, R.C. (2012). On the instability and evolutionary age of deep-sea chemosynthetic communities. *Deep Sea Research II*, doi: 10.1016/j.dsr2.2012.12.004.

Vrijenhoek, R.C. and R.S. Waples (2012). Popular misconceptions. *Molecular Ecology*, **21**: 4155-4156, doi: 10.1111/j.1365-294X.2012.05658.x.

Weiss-Penzias, P.S., C. Ortiz Jr., R.P. Acosta, W. Heim, **J.P. Ryan**, D. Fernandez, J.L. Collett Jr., and A.R. Flegal (2012). Total and monomethyl mercury in fog water from the Central California coast. *Geophysical Research Letters*, **39**: L03804, doi: 10.1029/2011GL050324.

Wheat, C.G., K.J. Edwards, T. Pettigrew, **H.W. Jannasch**, K. Becker, E.E. Davis, H. Villinger, and W. Bach (2012). CORK-lite: bringing legacy boreholes back to life. *Scientific Drilling Journal*, **14**: 39-43, doi: 10.2204/iodp.sd.14.05.2012.

Worden, A.Z., J. Janouskovek, **D. McRose**, A. Engman, R.M. Welsh, S. Malfatti, S.G. Tringe, and P.J. Keeling (2012). Global distribution of a wild alga revealed by targeted metagenomics. *Current Biology*, **22**: R675-R677, doi: 10.1016/j.cub.2012.07.054.

Xu, J.P., **J.P. Barry**, and **C.K. Paull** (2012). Small-scale turbidity currents in a big submarine canyon. *Geology*, **41**: 143-146, doi: 10.1130/G33727.1.

Zhang, H., and M.P. Hare (2012). Identifying and reducing AFLP genotyping error: an example of tradeoffs when comparing population structure in broadcast spawning versus brooding oysters. *Heredity*, **108**: 616-625, doi: 10.1038/hdy.2011.132.

Zhang, X., **W.J. Kirkwood**, **P.M. Walz**, **E.T. Peltzer**, and **P.G. Brewer** (2012). A review of advances in deep-ocean Raman spectroscopy. *Applied Spectroscopy*, **66**: 237-249, doi: 10.1366/11-06539.

Zhang, Y., **J.G. Bellingham**, **M.A. Godin**, and **J.P. Ryan** (2012). Using an autonomous underwater vehicle to track the thermocline based on peak-gradient detection. *Institute of Electrical and Electronics Engineers Journal of Oceanic Engineering*, **37**: 544-553, doi: 10.1109/JOE.2012.2192340.

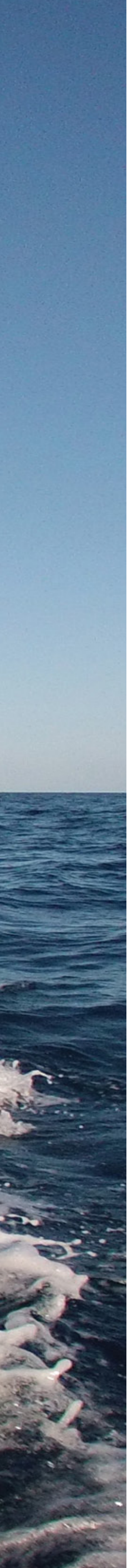
Zhang, Y., **M.A. Godin**, **J.G. Bellingham**, and **J.P. Ryan** (2012). Using an autonomous underwater vehicle to track a coastal upwelling front. *Institute of Electrical and Electronics Engineers Journal of Oceanic Engineering*, **37**: 338-347, doi: 10.1109/JOE.2012.2197272.

Zhang, Y., **J.P. Ryan**, **J.G. Bellingham**, **J.B.J. Harvey**, and **R.S. McEwen** (2012). Autonomous detection and sampling of water types and fronts in a coastal upwelling system by an autonomous underwater vehicle. *Limnology and Oceanography: Methods*, **10**: 934-951, doi: 10.4319/lom.2012.10.934.

Zhu, Z., **T.W. Kim**, and J.C. Choe (2012). Is female preference for large sexual ornaments due to the bias to escape predation risk? *BMC Evolutionary Biology*, **12**: doi: 10.1186/1471-2148-12-33.

Bold indicates authors who were employed at MBARI in 2012

*Resident at MBARI in 2012



MBARI Officers and Board of Directors

Officers

Julie Packard, Chair
Executive Director
Monterey Bay Aquarium

Franklin (Lynn) M. Orr, Jr., Ph.D., Vice-Chair
Director, Precourt Institute for Energy
Stanford University

Christopher Scholin, Ph.D., President and Chief Executive Officer
Monterey Bay Aquarium Research Institute

C. Michael Pinto, Chief Financial Officer
Monterey Bay Aquarium Research Institute

Barbara P. Wright, Secretary
Partner, Finch Montgomery Wright LLP

Patricia Duran, Assistant Secretary
Monterey Bay Aquarium Research Institute

Board of Directors

Julie Packard, Chair
Executive Director, Monterey Bay Aquarium

Franklin (Lynn) M. Orr, Jr., Ph.D., Vice-Chair
Director, Precourt Institute for Energy
Stanford University

Christopher Scholin, Ph.D., President and Chief Executive Officer
Monterey Bay Aquarium Research Institute

Barbara P. Wright, Secretary
Partner, Finch Montgomery Wright LLP

Joseph P. Allen, Ph.D.
Principal, Argotyche, Inc.

Joel S. Birnbaum, Ph.D.
Senior Vice-President, Research and Development
Director, HP Laboratories (Retired)
Hewlett-Packard Company

Nancy Burnett
The David and Lucile Packard Foundation

Curtis Collins, Ph.D.
Professor Emeritus, Department of Oceanography
Naval Postgraduate School

Bruce C. Gilman, P.E.
President and Chief Executive Officer (Retired)
Sonsub, Incorporated

Eric O. Hartwig, Ph.D.
Associate Director of Research (Retired)
Naval Research Laboratory

G. Ross Heath, Ph.D.
Dean Emeritus, College of Ocean and Fishery Sciences
Professor Emeritus, School of Oceanography
University of Washington

Dean O. Morton
Executive Vice President
Chief Operating Officer and Director (Retired)
Hewlett-Packard Company

Norman Pace, Ph.D.
Distinguished Professor
Department of Molecular, Cellular, and Developmental Biology
University of Colorado

Karl Pister, Ph.D.
Chancellor Emeritus, University of California, Santa Cruz
Dean and Roy W. Carlson Professor of Engineering Emeritus
University of California, Berkeley

George N. Somero, Ph.D.
Associate Director
David and Lucile Packard Professor of Marine Sciences
Hopkins Marine Station
Stanford University

Robert C. Spindel, Ph.D.
Director Emeritus
Professor Emeritus, Electrical Engineering
Applied Physics Laboratory
University of Washington

Directors Emeritus

Walter Munk, Ph.D.
Frank Roberts

Credits

Project manager: Nancy Barr
Project team: Judith Connor, Patricia Duran, Mariah Salisbury, Chris Scholin
Graphic design: Wired In Design

On the cover: Researchers George Matsumoto and Meghan Powers and ROV Pilot Randy Prickett during a "blue-water" dive in which they are attached to a safety line. The divers were surprised to find animals that are usually seen during ROV dives at great depths in Monterey Bay occurred at shallower depths in the Gulf of California. See story page 17. *Photo by Steve Haddock*. Insets: Left, the R/V *Western Flyer* in the Gulf of California in a photo taken from a camera attached to a kite. *Camera rigged by Steve Haddock*. Center, the R/V *Zephyr* hosted the AUV mapping program in the Gulf of California. *Photo by Teresa Cardoza*. Right, divers organize their sampling gear as they begin a blue-water dive. *Photo by Steve Haddock*.

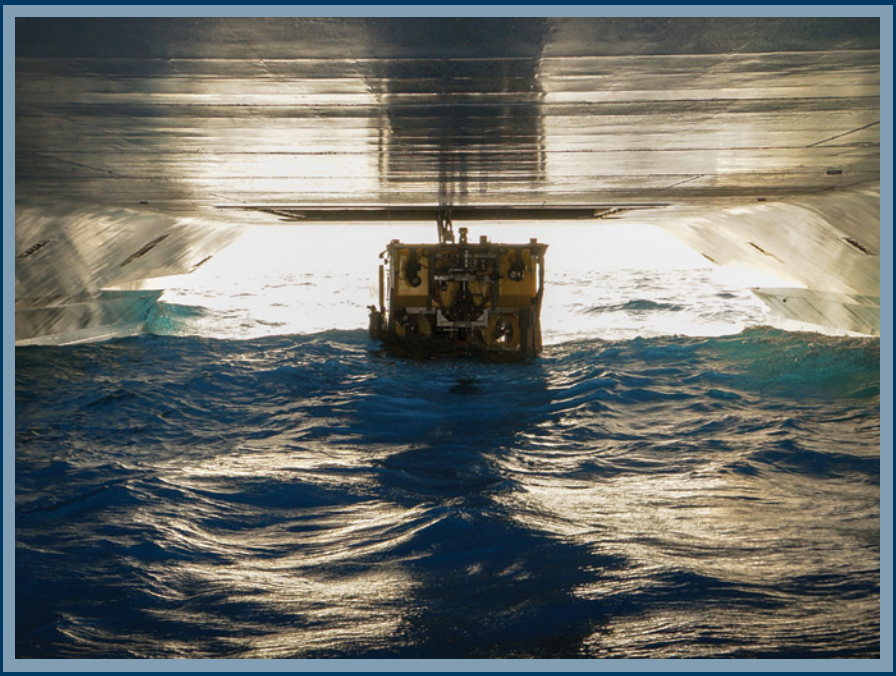
Back cover: Remotely operated vehicle *Doc Ricketts* is brought back up from a dive through the twin hulls of the R/V *Western Flyer*. *Photo by Andrew McKee*.

Inside back cover: Remotely operated vehicle *Ventana* is launched from the research vessel *Rachel Carson* for the first time after years of operating from the research vessel *Point Lobos*. The crew's safety vests were among the many items of equipment transferred from the old ship to the new. *Photo by Todd Walsh*.

Image credits (by page number): 3, 36, 37 (both on left), 38 (both), 39, 41 (left), 51, 52, 53, 55: Todd Walsh; 5: Illustration by Amadeo Bachar; 7 (top): Mike McCann; 8 (right), 50: Carola Buchner; 13: Sarah Mae Nelson; 15: Nancy Barr; 20 (top left): David Caress; 21 (right): Andrew McKee; 26: Mosaic by Lonny Lundsten; 28 (top): Dale Graves; 32 (bottom): Scott Belding; 34: Hans Thomas; 37 (right): Courtesy of Linda Lear Center for Special Collections & Archives, Connecticut College. 40 (top): Karl Jensen; 47 (left): Thomas Hoover; 47 (both on right): Rob Sherlock. Other than the diving images on the cover, all underwater images were taken with cameras on MBARI's robotic vehicles.

This report is available online at: http://www.mbari.org/news/publications/pubs.html. The 2012 Independent Auditors' Report is available online: http://www.mbari.org/about/financial/financial.html.

Printed on recycled paper made from 100 percent post-consumer waste, with hybrid UV inks.
Printed by a certified Bay Area Green Business.



M B A R I

Monterey Bay Aquarium Research Institute

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