MBARI

Monterey Bay Aquarium Research Institute

2013 ANNUAL REPORT


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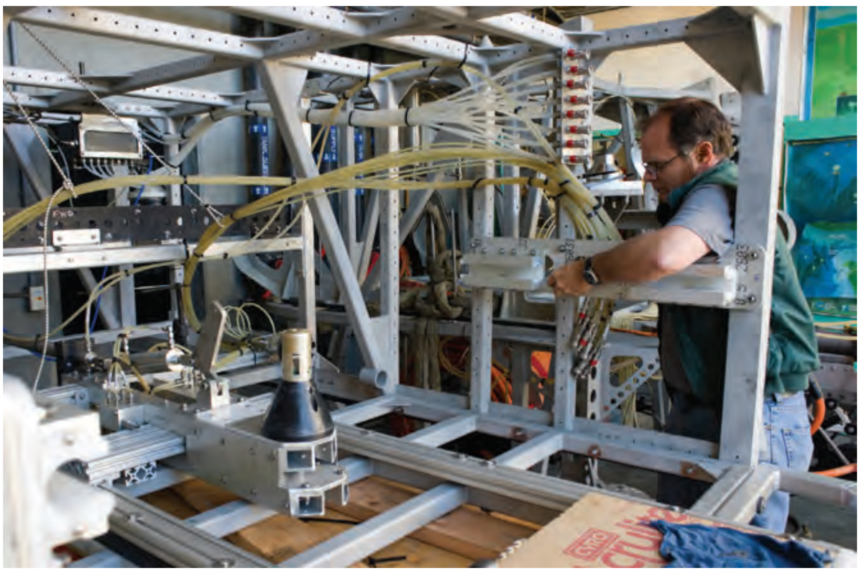
View From the Masthead

Investments in basic research frequently and unpredictably lead to new discoveries and a capacity for tackling problems that no one could have foreseen.

MBARI's emphasis on promoting engineering and science partnerships to realize new tools and techniques for exploring and studying the ocean have proven the truth of that statement time and again. Indeed, much of this year's report is a tribute to what stems from long-term investments in fundamental research and development programs.

Many of the sensors and platforms that we use routinely today, and that return such amazing images and insights into the structure and function of the ocean, took many years to develop and perfect, and most are still a work in progress. They are products of what we call "technology push/science pull". Technology push refers to engineering advancements that can unexpectedly open doors to new lines of inquiry. For example, this year we applied precision underwater navigation and acoustic sensor technologies to survey areas of seafloor that are designated as chemical weapon dump sites. Fundamental engineering advancements and marine operations capabilities made that work possible; scientists at MBARI never set out to undertake a search for long-discarded chemical weapons when our seafloor mapping system was first developed.

Likewise, scientific needs associated with solving a problem or answering a question—science pull—can catalyze engineering innovation. For instance, the desire to measure the rate at which animals consume oxygen under ambient ocean conditions stimulated a multi-year engineering effort that led to the realization of MBARI's midwater and benthic respirometry systems. These devices and their derivatives are now helping us understand basic parameters that govern the distribution and activities of animals that inhabit the deep sea, and how those animals may react to projected future ocean conditions. This synergy of engineering and science



Research Specialist Kim Reisenbichler helped develop the Midwater Respirometry System, which allows in situ experiments on the metabolism of midwater animals.

is something we strive to cultivate at MBARI. When it is combined with ready access to the sea it often pays unexpected dividends and takes us beyond our dreams.

The main stories we chose to focus on this year exemplify the push and pull of engineering and science. Many of the engineering projects are rooted in developments that started as simple concepts on a drawing board decades ago, unconnected to present day scientific inquiry, and some science projects were no more than pipedreams that until recently were viewed as promising but in all practicality far from being reality. A dogged determination to see these programs through has helped open our eyes to an ocean that is different from the one we knew only a few years ago. The value of new tools for observing and experimenting in the ocean is clear, but the long-term investment that was needed to achieve that capability is often easy to overlook. The development and application of remotely operated and autonomous underwater vehicles (ROVs, AUVs) are vivid examples of this truism.

MBARI has worked for decades to bring ROVs and AUVs, and the sampling systems and sensors they carry, to operational status. Their combined use to study an incredible diversity of ocean environments, and the plants and animals they hold, has led to an astounding number of revelations about life (and death) in the sea. With each new finding we are reminded of the complexity of ocean ecosystems, and how little we really know about the diversity and functions of organisms that occupy the largest habitat on Earth. Similarly, the ability to visualize the seafloor with ever-increasing resolution reminds us that our planet is a remarkably dynamic and still very mysterious place. It would be easy to imagine that this is the stuff of science fiction, but it is not. The reality of these findings has proven to be a powerful way to engage the public about both the marvels and importance of the oceans.

Another inescapable observation you will realize when thumbing through the following pages, is that we are living in an age of a rapidly changing ocean. That change is being driven in part by human activities. Attempting to understand the consequences of this change, let alone capturing a sense of what is "normal", given the vast expanse of the sea, presents a host of mindboggling challenges. The ocean is a source of air we breathe and food we eat, the basis of a multibillion-dollar global economy, and it is essential to maintaining the habitability of our planet. The implica-

The long-term investment in the institute's ships and autonomous underwater vehicles has paid off time and time again in new discoveries and the ability to conduct a wide range of experiments at sea.

tions of change are potentially so profound that we are compelled to make more measurements and undertake more experiments to better understand what the future holds and what it means to society. Ocean change is relevant to everyone, no matter how far you live from the shore.

In looking back on 2013, the success of basic research and development is evident. Some outcomes were anticipated, but many were not because they were only made possible by fundamental advancements made years ago—sometimes for reasons that had nothing to do with the sea. Looking to the future, the push and pull of engineering and science will continue to lead us in new directions as we seek to develop new tools and techniques for making basic observations, and for conducting controlled experiments to illuminate the trajectory of ocean ecosystems.

All of us at MBARI look forward to the unanticipated discoveries that the coming year will undoubtedly bring. We hope you do, too.

Chris Scholin
President and
Chief Executive Officer

Monterey Bay as a Window to the World

Time and again, MBARI scientists have made discoveries in Monterey Bay that shed light on marine life and processes elsewhere in the world ocean. The bay has been an excellent proving ground for experimentation and technology breakthroughs that may have broad application around the globe and perhaps on other planets.

A hidden world unveiled

Imagine going into your backyard—a place that is so familiar you would not expect to see anything new. But if you look closely, you might be surprised what lies hidden in the grass and under every rock. Monterey Bay is a lot like that proverbial backyard. It is one of the best-studied regions of the world ocean, yet each year we see species that are thought to be well characterized, but in truth are not, and encounter organisms that have never been described. Because the ocean, and especially the deep sea, is so vast and challenging to study, every observation and new discovery has implications for improving our understanding of the diversity of marine life and the complex interconnections that drive the cycling of matter throughout the ocean. Biologist Steve Haddock and his team are among those who are pushing back these boundaries, with a particular focus on gelatinous animals.

Gelatinous animals are largely made up of water, so they lose their shape and form if they are pulled up in a net. MBARI has worked for years to use remotely operated vehicles (ROVs) and other tools to enable the study of these animals in their natural habitat, the only way to see their true forms and functions (Figure 1). These transparent, soft-bodied animals include tiny, predatory arrow worms, colonial siphonophores, and umbrella-shaped medusae.

Figure 1: Studying live animals is key to figuring out which animal is which. Here, the exact same specimen of *Archeterokrohnia docrickettsae* is shown live, in seawater (left) and after chemical preservation. The remotely operated vehicle *Doc Ricketts* was used to collect the first live specimen of this 28-millimeter-long deep-sea arrow worm, which was then named for the vehicle.

Figure 2: In situ photographs of the siphonophores *Apolemia lanosa* (the wooly species), left, which is approximately two meters long, and *Apolemia rubriversa* (the red species), which is approximately 1.5 meters long.

The siphonophore genus *Apolemia* serves as a good example of a seemingly well-known group, but in fact it is one whose underlying diversity was greatly underestimated until recently. We know that these gelatinous animals, which can grow to more than 30 meters long, are important predators across the ocean. Worldwide, most specimens are called *Apolemia uvaria*—a catchall name. As Haddock and his collaborators looked closer, however, it became clear that there is a large unrecognized diversity of *Apolemia* species in Monterey Bay and elsewhere. The team recently described two of the most distinct and recognizable of these: *Apolemia lanosa* (the wooly species) and *A. rubriversa* (the red species) (Figure 2). These two species are different enough (one developing tree-like clusters along its body and the other with comb-like development along the length of its stem) that it is possible they do not even belong in the same genus, *Apolemia*. These two siphonophore groups are as distinctive from each other as fish-eating bald eagles are compared to the larger golden eagles that consume mammals. The habits and diets that distinguish the two *Apolemia* species remain a mystery. Recognizing differences in predator-prey interactions rather than lumping them together gives us a deeper understanding of ecosystem connections. This understanding, in turn, provides more insight into the implications of ecosystem change.

The delicate narcomedusa known as *Aegina* is another group whose diversity has been grossly underestimated. As tiny and cryptic as these jellies are, *Aegina* is still the second most common animal recorded in the MBARI video database. It is possible that nearly every four-tentacled jellyfish with a similar morphology has been assigned to this genus, and perhaps even identified as the same species—*Aegina citrea*. But by collecting specimens and closely examining their morphology and genetic makeup, the researchers ascertained that at least three undescribed groups are being lumped into a single category. Once more, what was thought to be a well-known, easily identifiable group of organisms is in fact something entirely different. How variations in the abundance of those different animals may relate to ocean conditions is not yet known. By sharing these findings with scientists from around the world, the team is helping to recognize if and how the relative abundance of these organisms is changing over time, to gain a better understanding of the role these animals play in structuring ocean ecosystems.

In addition to fine-tuning our current knowledge of marine life, MBARI researchers also frequently encounter undescribed animals. For example, the siphonophores *Lilyopsis fluoracantha* and *Resomia ornicephala*, along with "horned" comb jellies, were first found locally. Both these siphonophores exhibit fluorescence and in Monterey Bay, *Resomia* uses its fluorescent lures to attract its prey, krill. Those discoveries then led to the finding that the same animals also inhabit faraway seas, which in turn opened a door for others to help us gain a deeper understanding of these bizarre creatures.

These examples are potent reminders that there is much to be discovered in the oceans, even in well-studied "backyards" like Monterey Bay.

These gelatinous animals occupy a specific niche in the larger food web—their abundance and health impact both their predators and their prey. Ocean ecosystems, and especially the deep sea, are so interconnected, that every discovery enhances the global picture of diversity and ecosystem dynamics. The knowledge we are gaining locally is contributing to a clearer view of life in all corners of the sea.

Revealing the behaviors of enigmatic deep-sea animals

The behavior of deep-sea animals has long been a subject of mystery and speculation. In particular, the activities of animals in the dark waters far above the seafloor have been obscure. MBARI's program of regular ROV dives has made possible detailed observations of the behavior of these midwater animals. This information allows a much better understanding of the complex ecological interactions between species. It also provides an index of activity levels, which is necessary to quantify carbon and energy flux through the world ocean's vast midwater ecosystem.

In the last few years an unprecedented series of observations by the MBARI Midwater Ecology Group, led by Bruce Robison, have shaped this new field of study. As access to the deeper pelagic habitat has increased, the range of behavioral observations has expanded, from reproductive behavior, escape responses, and defensive behavior, to aggregation patterns, and predator tactics. These investigations encompass a range of species and topics and include the first-ever ethogram (the behavioral inventory of a species) of a deep-sea animal.

Until several years ago parental care was unknown among squids; it was assumed that adult females either glued their egg masses to the seafloor or released them to drift in midwater. But several ROV observations of *Gonatus onyx* revealed that the females of this squid species hold their developing eggs in their arms (Figure 3). They carry the eggs down into very deep water and brood them there, away from predators, for as long as nine months. Two more species have since been found to brood their eggs in a similar fashion and it now appears that this behavior may be widespread among deep-water squids.

In the dimly illuminated depths between about 200 and 800 meters, where shadows and shapes serve as important visual cues, a number of species including fishes, worms, and larvaceans change their shapes to deter predation. These animals respond to the presence of predators by

Figure 3: Two squids brooding their eggs as they swim along in the midwaters. Left, *Gonatus onyx*, and right *Bathyteuthis*. Both are about 75 centimeters long, not including their egg sacks.

Figure 4: The 11-centimeter *Lycodapus*, left, and the approximately 20-centimeter *Melanostigma*, right, have both been observed to curl up to deter their predators that would be looking for fish, but would not be attracted to a jelly-shaped object.

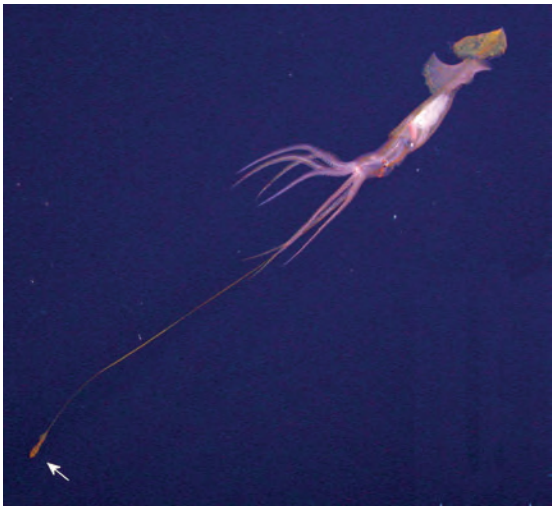


Figure 5: *Grimalditeuthis bonplandi* squid with one of its tentacles extended. The arrow points to a small "club" at the end of the tentacle that wiggles and appears to swim independently of the rest of the animal. This squid is estimated to be between 30 and 60 centimeters long from its fins to the tip of its arms.

curling their elongate bodies into circular shapes (Figure 4). The behavior is a case of protective mimicry in which the animals change their appearance to resemble jellies that are unpalatable to the predators.

Other animals practice aggressive mimicry—fishes, squids, and a variety of jellies use bioluminescent and fluorescent lures to attract prey close enough to be captured. A very recent discovery shows that the squid *Grimalditeuthis* attracts prey with highly flexible fins at the ends of its two long feeding tentacles. To attract prey, the fins "swim," creating the hydrodynamic signature of a fish in the water around the squid. When would-be predators strike at the fins, *Grimalditeuthis* grabs them with its eight arms (Figure 5).

The little siphonophore *Nanomia bijuga*, one of the principal predators of krill in Monterey Bay, typically positions itself in a J-shaped fishing posture with its tentacles splayed outward. When a krill contacts a tentacle, *Nanomia* begins swimming rapidly, contracts the tentacle, and draws the prey in until the siphonophore can grasp and maneuver the krill into one of its multiple stomachs. These tactics are well suited for feeding on prey that aggregate in patches.

Discovering a single behavior pattern in a deep-sea species is very exciting, but documenting a whole repertoire of behaviors in a single species is incredibly rare. A previous study by the MBARI midwater group described 59 behavioral components for the deep-living squid *Octopoteuthis* (Figure 6). The components separate into five categories: pigmentation, posture, locomotion, bioluminescence, and

Figure 6: *Octopotheuthis* squids, which are about 150 millimeters long, use color, posture, ink, and bioluminescence to communicate with their own and other species in the deep sea.

inking. The potential number of combinations of these components is enormous, but the study identified the patterns most commonly utilized and their potential applications. In the summer of 2013, that initial study was followed up with the use of archived video footage and real-time ROV dives to develop an ethogram for another squid, *Chiroteuthis*.

This new branch of research on the behavior patterns of deep-sea animals has great promise for expanding our understanding of how the largest ecosystem on Earth functions. It also has the potential to engage the public in deep-sea research as never before. For example, one form of outreach through which observations of behavior are shared with the scientific community and the public is the MBARI YouTube channel. MBARI staff recently produced and posted a two-minute distillation of more than an hour of ROV video showing a black-eyed squid, *Gonatus onyx*, struggling to subdue and eat a large owlfish, *Bathylagus milleri* (see page 40). The video quickly registered nearly a million viewings in the first week after posting.

Previewing life in the ocean of the future

Although the oceans have been considered vast and unchangeable throughout Earth's recent history, human activities, particularly fossil fuel emissions, are causing pervasive changes in ocean conditions far larger and more rapid than have occurred over the past 25 million years. The massive and increasing release of carbon dioxide to the atmosphere has well-known effects on the oceans, including acidification, warming, and reduced oxygen levels in deeper waters. Targeted experiments in Monterey Bay by Jim Barry and his Benthic Biology and Ecology Group are aimed at increasing understanding of the potential consequences of these anthropogenic changes for marine organisms and ecosystems.

Carbon dioxide is absorbed readily into the surface waters of the oceans, acidifying the seawater. Globally, more than one million tons of fossil fuel carbon dioxide are absorbed into the ocean surface every hour. Various scenarios for future emissions indicate that the acidity of ocean surface waters will increase by 150 to 200 percent by the end of this century. At the same time, the ocean is warming rapidly, with surface temperatures in some areas expected to increase by 3°C by 2100. That change will contribute significantly to increasing the Earth's heat content. Ocean warming, in turn, can lead to lower oxygen levels (deoxygenation) in deeper waters since the solubility of oxygen declines with increasing temperature. In addition, as surface waters warm they become more buoyant, potentially diminishing the normal wind-driven mixing of surface waters with deeper waters and thereby reducing the amount of oxygen that is mixed to mid-depths of the oceans.

How will marine organisms and ecosystems respond to this trio of major, simultaneous, and accelerating changes in ocean conditions? Will the direct impacts of ocean change on some organisms lead to cascading indirect effects and shifts in food webs? If a key group of organisms declines in number due to its sensitivity to ocean acidification, will its main predators suffer from low food levels, while its prey benefit from reduced predation? Such indirect consequences may disrupt ecosystems by reducing the efficiency of energy flow through predator-prey relationships. The massive scale and speed of changes in ocean conditions raise many questions concerning the future and function of marine ecosystems. These questions also touch on important social issues since humans are dependent on a myriad of natural benefits and services from the ocean, such as climate stabilization and food production.

Monterey Bay, with its well-developed oxygen minimum zone and upwelling of carbon-dioxide-rich waters, is an excellent natural laboratory to study the effects of the expected future ocean chemistry. In 2013, experimental studies of the sensitivity of local animals to ocean acidification and reduced oxygen levels spanned several species (Figures 7 and 8).

Hermit crabs are common, socially aggregating animals found in a wide variety of ocean habitats (Figure 9). Intertidal species have adapted to wide environmental fluctuations driven by tides, upwelling, and other factors, but those living in more stable conditions in the deep sea may have less capacity to survive changes in their habitat. A study of deep-sea hermit crabs showed that they are sensitive to ocean acidification, even though they inhabit oxygen-poor, more acidic waters in the oxygen-minimum layer off California. These small crabs wave their antennae to sense the environment, using chemosensory behavior to provide cues for finding food in the dark, cold waters. Upon exposure to more acidic waters, these crabs reduce their rate of antennae waving. This seemingly unimportant behavior was shown to be linked to the ability of the crab to sense and capture prey—animals in more acidic seawater had slower antennae movement, and also took longer to find food. In a food-poor environment, even a subtle change in feeding efficiency could lead to slower growth, less energy for reproduction, and perhaps reduced survival.

In a study of a commercially important, nearshore animal, juvenile abalone exposed for extended periods to more-acidic or less-oxygenated water, or both (as occurs naturally during upwelling events in which deep nutrient-rich waters

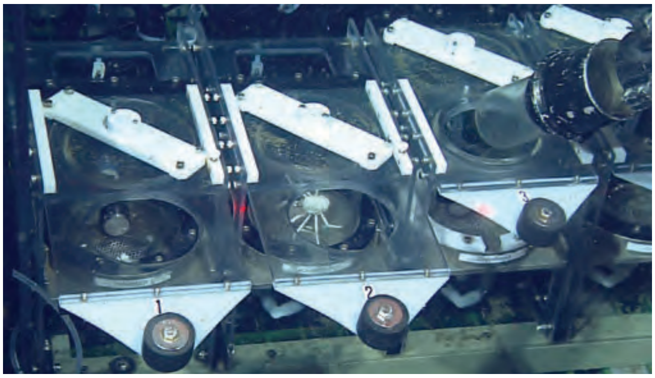


Figure 7: Galatheid crabs are loaded into the chambers of the Benthic Respirometer System to experimentally evaluate the effects of increased carbon dioxide on the animals.

Figure 8: Jim Barry examines several local species of galatheid crabs, or squat lobsters, which were collected at an experimental site 3,100 meters deep in Monterey Bay.

are forced up toward the surface) experienced reduced growth and survival. Thus, should the frequency and duration of upwelling events in Monterey Bay increase in the future—a possibility forecast in some climate change scenarios—then local abalone populations may be negatively impacted. Given realistic projections of conditions over the coming century, controlled experiments can help illuminate the potential consequences of a changing ocean.

Ideally, such experiments would measure the impact of ocean change on whole populations and intact marine communities, but this is often intractable. In contrast, studies of physiological or other performance measures of individual animals like those noted above are possible and informative, but provide only limited insights into the effects of ocean change beyond the level of select, individual organisms. In an effort to expand these experiments to include more species, the shallow-water Free Ocean Carbon Dioxide Enrichment (swFOCE) system was devised with the idea of enabling researchers to scale experiments from the level of individuals to multiple species. The swFOCE system is under development through a collaboration of scientists at MBARI, Hopkins Marine Station of Stanford University, and the Center for Ocean Solutions. The swFOCE system will allow investigators to regulate the acidity of seawater within partially open enclosures on the seafloor, to support experiments evaluating the impacts of ocean acidification on multispecies assemblages over relatively long time periods, and under conditions similar to the natural environment. This ability to conduct controlled experiments will help researchers to unravel the confounding effects of deoxygenation, warming, and acidification on biological communities in the ocean.

Figure 9: Research has shown that deep-sea hermit crabs, such as these five-centimeter-long specimens on the seafloor, are sensitive to changes in ocean acidity.

From Elkhorn Slough to the Southern Ocean: Who's minding the water?

The vastness of the ocean presents a daunting challenge for scientists: How can we interpret trends in ocean ecosystems when the measurements we make are few and far between? In the open sea, most scientists have historically relied on ships to transport them perhaps no more than once a year to locations where they spend only a short time capturing a snapshot of ocean conditions that prevail below the sea surface. In the coastal zone, where conditions may change hourly, most sampling is done no more frequently than once a month. Far offshore, processes that drive ecosystem structure and function often work on a seasonal time scale. Closer to the coast, similar processes operate much more rapidly. The problems this presents lead to a singular conclusion that all ocean scientists agree on: the ocean is grossly undersampled!

Current records of fundamental ocean properties such as oxygen, pH, nutrients, or chlorophyll describe a range of ocean states. However, the sample-to-sample variability observed in ocean time series may not necessarily reflect actual trends at any given location and time because so few measurements are collected for extended periods and in rapid succession. Furthermore, the limited sampling provides little scientific insight into the processes that actually underlie the snapshot observations.

Figure 10: Sensors on this Land/Ocean Biochemical Observatory mooring in Elkhorn Slough record the daily transport of nitrate in and out of the wetland slough.

Developing new tools and techniques to overcome these challenges is a major driver of Ken Johnson's Chemical Sensor Group activities. Application of this approach in Elkhorn Slough, near MBARI in Central California, highlights some of the advances in understanding when sampling resolution is more closely matched to environmental processes. Opportunities for deploying analogous sensor suites in the vast expanse of the Southern Ocean provide another perspective on how we can address the fundamental problem of "being there".

Johnson and his group developed the Land/Ocean Biogeochemical Observatory (LOBO) mooring system to sample the nearshore ocean and tidal estuaries. These compact moorings (Figure 10) can be deployed from a small boat, yet are robust enough to survive in open coastal waters. The system was designed for making high-resolution observations in regions dominated by tides—places where fluctuations in key variables occur on an hourly basis. LOBO systems have been deployed for more than 10 years in Elkhorn Slough (Figure 11), and commercially produced LOBO systems are now used throughout the U.S.

Observations made in Elkhorn Slough using LOBO moorings show remarkably high levels of nitrate, a key nutrient for phytoplankton at the base of the food web. These high levels were already known from a monthly sampling program conducted by the Elkhorn Slough National Estuarine Research Reserve. But the hourly measurements from the LOBO moorings reveal the transport of nitrate into and out of the slough daily over years. This high-resolution record enables an understanding of what drives the variability of this important nutrient, and how that in turn affects other processes.

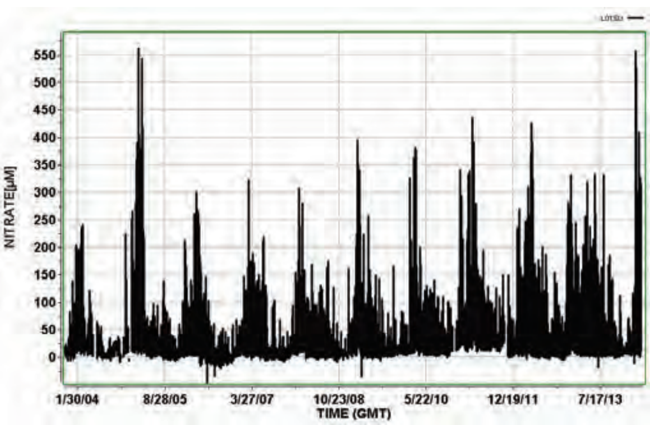


Figure 11: The concentration of nitrate measured at hourly intervals over 10 years on the LOBO L01 mooring in Elkhorn Slough shows the general increase in nitrate over time due to greater usage of fertilizers in agriculture, with modulations due to environmental variability such as high rainfall in 2004-2005.

In most coastal estuaries with high nitrate concentrations, algae grow on the surfaces of seagrasses, thriving on the nitrate; these algae are known as epiphytes. As the epiphytes grow, they block the sunlight that seagrasses need for photosynthesis, killing the seagrass. But in Elkhorn Slough, seagrass beds are currently expanding. How can this be? In the early 1980s seagrass in Elkhorn Slough had nearly disappeared. About the time that it reached its minimum extent, sea otters repopulated the slough after being absent for decades. As the sea otter population increased in the slough, so did the seagrass. Johnson and his collaborators showed that the increased sea otter population in relation to its prey—crabs and sea slugs—was the link to solving this mystery.

The process that gave rise to this outcome is termed "top-down control". A top-level predator such as the sea otter exerts strong population control on a prey species, which then has a ripple effect through lower levels of the food web. In this case, the otters were feasting on crabs that normally eat sea slugs. The sea slugs graze on epiphytic algae. With fewer crabs eating sea slugs, the sea slug population increased, resulting in fewer epiphytes and healthier seagrass. The entire ecosystem benefited from the recovery of a single, top predator. This striking finding was made possible in part by the high-resolution chemical records obtained using the LOBO moorings.

Extending high-resolution measurements on a much larger scale

Unlike the highly sampled Elkhorn Slough near Monterey Bay, large areas of the remote Southern Ocean may only be sampled once every few decades, if they are sampled at all. Yet the Southern Ocean plays an enormous role in global carbon and heat budgets. It accounts for half of the ocean's uptake of human-created carbon dioxide and more than 60 percent of the heat uptake by the ocean. Large changes in Southern Ocean circulation may already be occurring due to a changing climate and wind patterns. As atmospheric carbon dioxide enters the Southern Ocean, its waters are predicted to become corrosive to aragonite (a form of calcium carbonate) within the short span of 16 years. The rapidly changing chemistry of the Southern Ocean

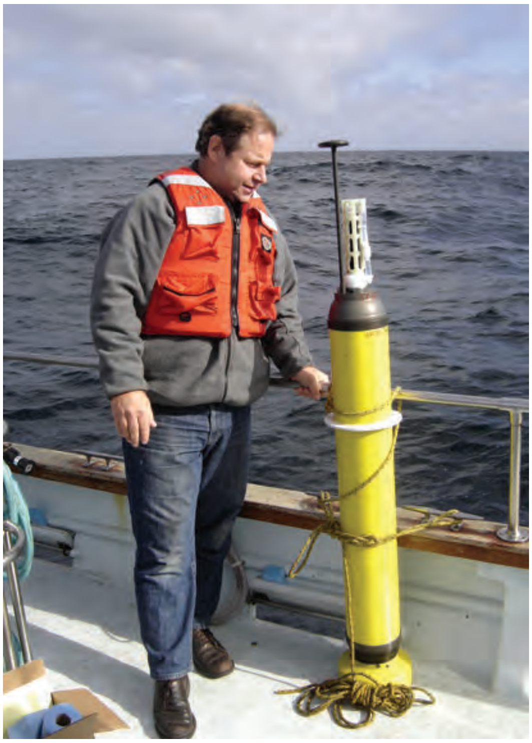


Figure 12: Senior Research Specialist Hans Jannasch prepares the launch of an Apex profiling float with chemical and biological sensors in Monterey Bay.

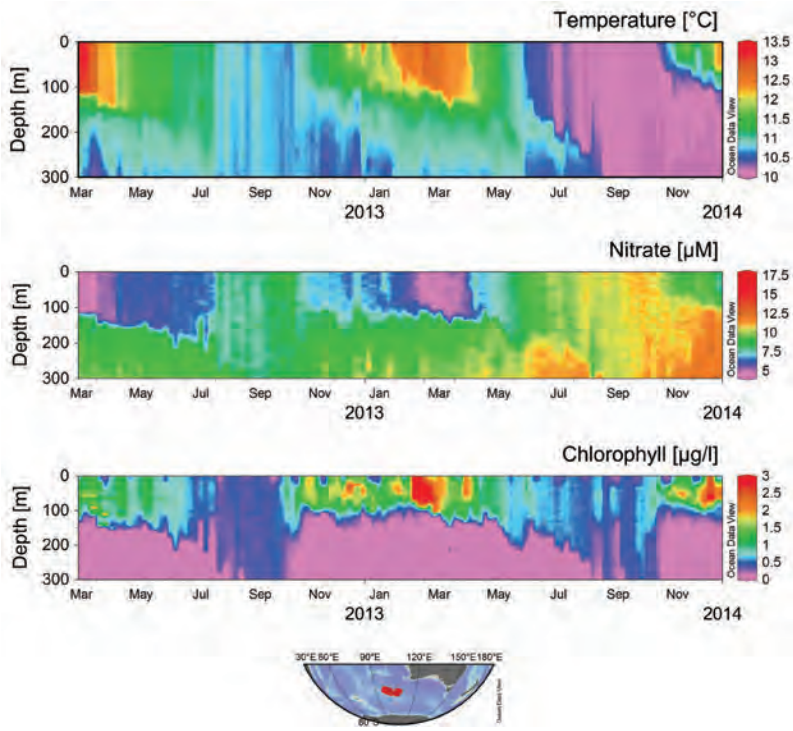


Figure 13: Time and depth sections of temperature, nitrate, and chlorophyll measured by a profiling float in the Indian sector of the Southern Ocean to the southwest of Australia, March 2012 through January 2014.

could have significant impacts on organisms that make shells of aragonite. The shift in the balance of predator and prey relationships that may result from this fundamental chemical change—in this case predators that consume animals with shells—could have profound consequences for ecosystem structure.

Tracking the trajectory of the Southern Ocean ecosystem presents a unique opportunity for learning how oceanic food webs will respond to a warmer and more acidic ocean, but even basic assessments of fundamental ocean properties in that region are very hard to come by due to the difficulty and expense of conducting shipboard expeditions. Autonomous sensors and systems that can operate for years without human intervention are the only practical tools that will enable sampling in such remote locations at time and space scales that avoid undersampling.

Johnson's group has focused on tackling this problem by integrating nitrate, oxygen, and bio-optical sensors onto profiling floats (Figure 12), autonomous platforms that can operate for years taking measurements throughout a broad swath of the upper ocean. Eight of these floats are currently deployed in the Southern Ocean, providing an unprecedented view of annual variability in biogeochemical cycles from the sea surface to 300 meters deep. These floats reveal the depletion of nitrate and an accumulation of chlorophyll each austral summer (Figure 13)—a result of phytoplankton growth and uptake of nitrate—direct measures of basic ocean metabolism.

In 2014, an additional 13 floats with pH sensors will be deployed to begin the first large-scale observations of variability and acidification of open waters of the Southern Ocean. Planning is under way for an international effort to expand this observing system across the entire Southern Ocean with hundreds of profiling floats. If these observations are sustained, scientists will have an unprecedented window into the consequences of a more corrosive ocean on shelled animals. In keeping with MBARI's vision to develop tools locally that can be applied globally, this effort to understand ocean change will play out far from the confines of Monterey Bay where these sensor systems were first devised and tested.

DNA probe technology goes live in the deep sea

Microorganisms are the most numerically abundant organisms in the ocean. Every drop of seawater contains thousands of individual cells representing a mind-boggling diversity of species that scientists are only beginning to comprehend. These organisms play an essential role in cycling inorganic and organic matter, but many details of how the microbes perform this vital function are not yet known. The advent of modern molecular biological methods for cataloging and analyzing organisms' genetic material, proteins, and lipids has revolutionized our understanding of these processes, and revealed a myriad of biochemical transformations that are essential for sustaining life in the ocean. Consequently, quantifying changes in microbial community structure and activity in response to variable ocean conditions is an active area of research, but also one that is fundamentally limited by the ability to monitor particular sites and make repeated measurements over time. Nowhere is this challenge greater than in the deep sea.

Microbial communities in the vast, cold, and dark ocean interior are thought to be relatively stable with little change over time. But microbes thrive in chemically rich environments such as cold seeps, hydrothermal vents, and subsurface rocks and sediments. Such extreme environments are thought to be a window to Earth's past, when early life first took hold and photosynthesis had not yet evolved. The fascination with cataloging the diversity of deep-sea microbes and the role they play in elemental cycling extends beyond the ocean; some scientists speculate that the first signs of extraterrestrial life encountered on other planets may be something akin to microbes found in extreme environments here on Earth.

Developing the means to autonomously acquire, preserve, and analyze samples from extreme environments is one way the National Aeronautics and Space Administration (NASA) has sought to learn about life on Earth and the challenges of looking for life on other planets. That interest sparked support from NASA's Astrobiology Science and Technology for Exploring Planets (ASTEP) program for a multi-year, multi-institutional project to modify MBARI's Environmental Sample Processor (ESP) for use in the deep sea. The ESP is a self-contained, autonomous, robotic laboratory. It concentrates particles from surrounding waters and then either preserves that material for later analysis, or immediately applies a variety of tests to detect genetic material of microbes present in the water.

Previously, in collaboration with researchers from the California Institute of Technology and Harvard University, the ESP team deployed a deep-sea version of the ESP (D-ESP) on the seafloor at methane vents, and in the caldera of an active submarine volcano. Those deployments lasted only days due to limited power. In 2013 the team left the D-ESP on the seafloor for over eight months—the longest time an instrument of this kind has ever been operated in the deep ocean (Figure 14).

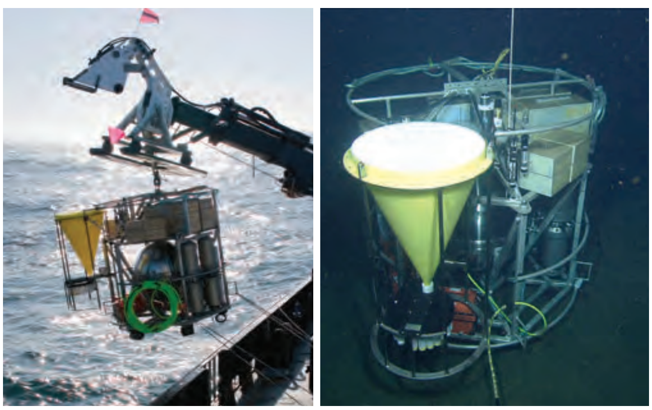


Figure 14: Left, the deep-sea Environmental Sample Processor is deployed from the R/V *Rachel Carson*. Right, the D-ESP on the seafloor at a depth of 900 meters. The titanium sphere that encloses the D-ESP is roughly one meter in diameter.

Figure 15: The Environmental Sample Processor was deployed on the Monterey Accelerated Research System cabled observatory, which provides a steady power and communications link to the node at the end of a 52-kilometer cable at a depth of 900 meters below the sea surface.

This ambitious experiment took advantage of the Monterey Accelerated Research System (MARS) cabled observatory in Monterey Bay that sits 900 meters below the sea surface, some 52 kilometers offshore (Figure 15). The cable provided power and communications to the instrument, allowing researchers to receive data in real time, 24 hours a day, for over eight months without going to sea. New algorithms were developed that allowed the team to select specific environmental conditions under which the D-ESP would automatically acquire and process a water sample. By setting different sample-collection thresholds over the six-month period, the team was able to collect material from a range of water masses passing over the MARS site. Results surprisingly showed that the microbial community was not static, but instead varied significantly over time. It also proved that highly sophisticated, automated laboratories like the D-ESP can operate successfully for extended periods in the ocean. This unique achievement opens up further opportunities for developing ESP technology, to enable new modes of observing microbes, and for conducting controlled experiments in the deep sea.

Phytoplankton need vitamins, too

Photosynthetic marine plankton account for about half the annual atmospheric carbon dioxide uptake in the world. This process, collectively referred to as primary production, is driven by a diverse array of microorganisms. The tremendous diversity of these organisms complicates the development of predictive models for the global carbon cycle. Many marine algae have never been grown in a laboratory. Even for those that can be cultured and subjected to experimentation, our understanding of the controls that govern their physiology is rudimentary. One of the basic, but poorly understood, controls is the role that vitamins play in modulating primary production.

Just as vitamins are essential for human growth, they are also an important factor in controlling phytoplankton growth and community composition in the sea. Vitamin B_1 is noteworthy in this regard—it plays a critical role in metabolic processes and is essential to all life, but it is particularly scarce in the ocean. Only a few types of phytoplankton are thought to synthesize it de novo (from scratch); most others are thought to depend on external supplies. When

Tracking harmful organisms using technology developed for the deep sea

The state of Washington is one of the nation's most productive areas for shellfish harvesting and aquaculture. Yet, as in many other areas, Washington's shellfish can become poisonous when certain types of harmful algae or bacteria become abundant in local waters. The challenge is to detect these harmful organisms while they are still at low levels, before they contaminate the shellfish harvest and pose a health hazard.

The need to detect minute numbers of particular organisms parallels one of the key requirements of MBARI's deep-sea ESP project. The D-ESP development centered on detecting microorganisms found at great depth in the ocean, but the core technology needed to make the necessary measurements is equally applicable to environments that are far less extreme and much easier to access. To evaluate this idea further, MBARI researchers worked in concert with the Center for Ocean Solutions, government agencies, shellfish growers, and native tribes in the Puget Sound area to test the ESP technology for detecting outbreaks of harmful organisms in shellfish-growing areas (Figure 16). Instruments were placed in two locations, and data from those devices were posted in real time on the Internet. The study proved the feasibility of real-time monitoring of shellfish growing areas using autonomous, robotic systems like the ESP.

Figure 16: MBARI Senior Research Technician Roman Marin III programs the Environmental Sample Processor at Taylor Shellfish Farms in Samish Bay, Washington.

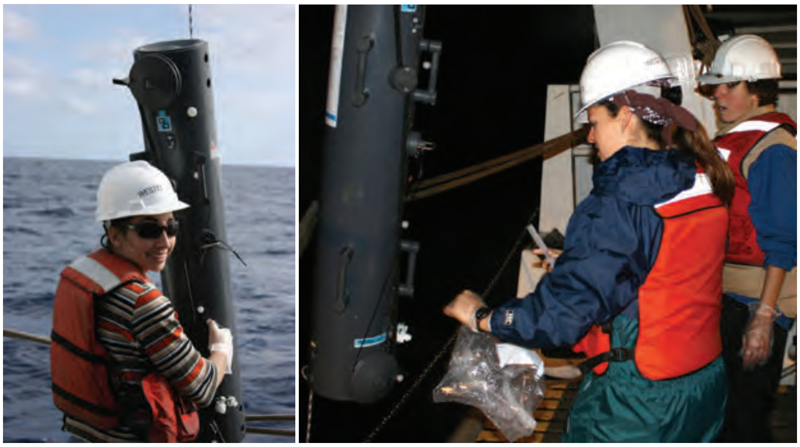


Figure 17: Trace-metal clean-sampling devices are used to target specific algal populations with as little impact to water chemistry as possible. At left, Microbiologist Alexandra Worden prepares to deploy the bottle from the back of the research vessel *Western Flyer*; at right, Graduate Research Assistants Melinda Simmons and Darcy McRose prepare for a launch at night during the same cruise.

Figure 18: Postdoctoral Fellows Jian Guo, left, and Susanne Wilken set up a laboratory experiment growing phytoplankton in seawater enriched with carbon dioxide to understand how the algae respond to changing climate and ocean conditions.

vitamin B_1 becomes limited it might be expected that the phytoplankton community would shift to the few species that can make it, while those that depend on a ready-made, external source would be reduced in number. Recent work by Microbiologist Alexandra Worden and her team proves that this view is too simplistic; phytoplankton are far more adept at overcoming vitamin deficiency than expected, and that finding is helping us understand how other marine organisms cope with vitamin deficiency, too (Figure 17 and 18). How is that possible? The answer lies in their DNA.

By comparing the entire complement of DNA sequences from various phytoplankton—a technique known as comparative genomics—Worden and her colleagues found something unexpected: sequences called riboswitches that enable a specialized type of gene control. Common gene control mechanisms often involve regulatory proteins. In contrast, riboswitches alter gene expression by interacting with particular metabolites directly; the binding affects expression. Riboswitches are thought to be the modern descendants of an ancient sensory and regulatory system.

Many bacteria have riboswitches that typically provide feedback control on genes involved in the biosynthesis or transport of a metabolite such as vitamin B_1. Worden's team discovered that the riboswitches found in algae were present in many lineages not known to utilize this form of gene control. Moreover, the new riboswitches appeared capable of sensing vitamin B_1, even though the genes they are associated with are not part of the classically known vitamin B_1 pathways (and in fact have no known function). Before this study, almost all reported vitamin-B_1-sensing riboswitches were associated with known genes belonging to the B_1 biosynthesis pathway.

This series of clues led the team to hypothesize that the algal riboswitches were affiliated with previously undescribed genes encoding proteins in the pathway for vitamin B_1 synthesis. Laboratory testing of a widespread alga, *Micromonas*, found from tropical to polar waters, showed that expression of those genes increased dramatically when B_1 was not available—that is, they were highly responsive to vitamin B_1 depletion. Further analysis of their evolutionary history showed that one of the genes is present not only in marine algae, but also in parasites, pathogens, and even in the most abundant heterotrophic marine bacterial group, SAR11.

The team then analyzed all the known algal B_1 biosynthesis genes. One of the species investigated was *Emiliania huxleyi*, a coccolithophore that can form such massive blooms that they can be detected from space (Figure 19). It is also an organism that can be grown readily in the laboratory and is known to require vitamin B_1 for growth, making it an ideal model organism for experimentation. The team noticed that *E. huxleyi* contained all but one of the genes for B_1 biosynthesis. That one missing gene is responsible for synthesizing a precursor used during the B_1 biosynthesis process. Given the presence of the novel riboswitch-containing gene and an almost complete classical pathway, the team then tested whether *E. huxleyi* might actually be able to grow with

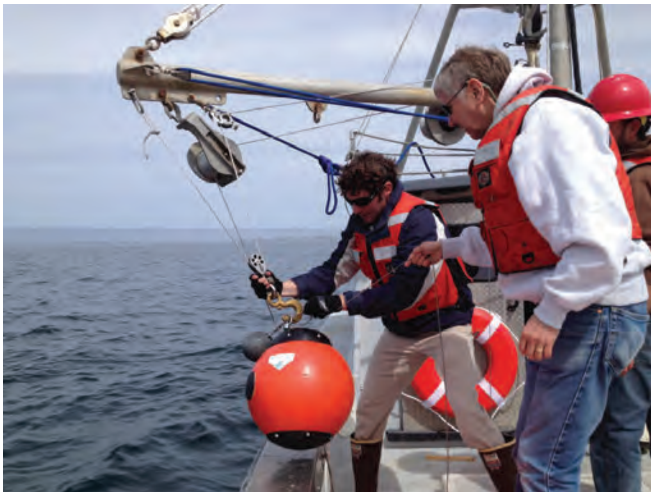
Figure 19: This electron micrograph of a single-cell of *Emiliania huxleyi* shows the calcite disks called coccoliths that enclose this phytoplankton. The scale bar is 1.56 microns long.

just the addition of the precursor compound, a compound which is much more stable in seawater than vitamin B_1. Indeed, *E. huxleyi* grew just as well with the precursor as it did when the vitamin itself was present. Thus, although *E. huxleyi* was long thought to be dependent on rare oceanic vitamin B_1, this is not the case.

This research changes the current understanding of the extent to which vitamin B_1 controls phytoplankton growth and community composition. It also reveals new aspects of gene regulation in several major eukaryotic lineages and potentially unrecognized components in vitamin B_1 biosynthesis. In addition to work to understand how these genes function, the team is also evaluating these genes as the basis of a sensory system to measure vitamin stress since vitamin B_1 levels are very difficult to quantify in the environment. Collectively, this body of work is helping to reshape our understanding of the controls governing a major portion of the global carbon cycle.

Sediment transport in submarine canyons

Submarine canyons are conduits through which sediment, eroded from the continents, moves from shallow waters into the deep sea. These canyons carry a substantial proportion of all the sediment transported onto the ocean floor. Over the last 14 years, efforts by MBARI and other groups working in Monterey Canyon have shown that these movements are primarily associated with relatively brief but intense events, punctuated by periods of little activity. Despite the extremely low slopes that occur within the canyon axes, these events can move large objects, such as



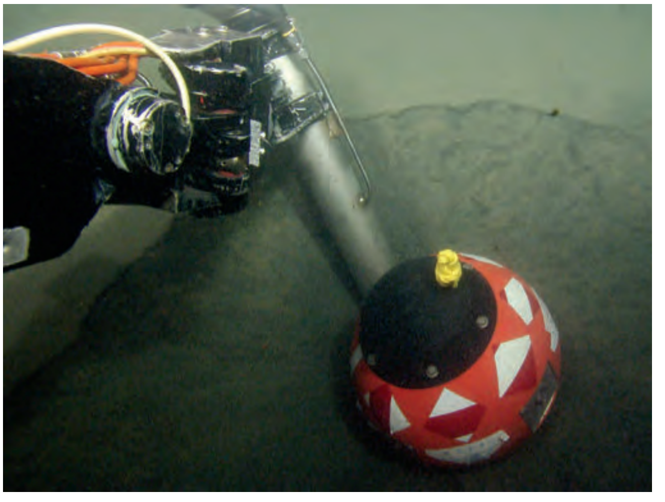


Figure 20: Above, Engineers Brian Kieft, left, and Bob Herlien deploy a benthic event detector (BED) instrument from the R/V *Paragon*. Below, video still image shows a BED deployed on the canyon floor in a depression intentionally dug using ROV *Ventana*.

boulders, downslope. At present such displacements are impossible to predict and detecting any movement is a significant challenge with existing tools and technology. Thus the phenomenon is poorly understood.

The existing model is that high-energy underwater avalanches of sediment, called turbidity currents, transport boulders over the bottom either in suspension or along with the sediment flowing along the seafloor, which is called “bedload”. However, previous measurements of devices deployed on the floor of Monterey Canyon suggest that large objects may be carried downslope within the seafloor as entire sections of the seafloor slump downslope. The key question is whether large objects are transported as bedload over the seafloor or whether they ride down-canyon on fluidized seafloor sediments. These two models imply two very different motions: in the former the object will rotate and bounce along the seafloor, whereas in the latter the object will slide down-canyon.

To differentiate between these mechanisms, an MBARI team led by Charlie Paull and Brian Kieft created a "smart boulder"—a motion-sensing instrument that can be placed within the sediment or on the canyon floor. This device, called a benthic event detector (BED), can record its motion as it moves down-canyon, providing detailed data on when an event occurred, how far and fast it moved, and the nature of its motion.

To build such a novel device, engineers first had to figure out how to retrieve these important data once the instrument has been moved and possibly buried. The answer lies in a tried and true technology: acoustics. Acoustic beacons are often used to locate objects, even when they are buried in a few meters of sediment. However, extracting and physically recovering an instrument that is fully buried in sediment is essentially impossible. Therefore, the BED design does not depend on physically recovering the instrument. Instead, the data recorded by the BED can be transmitted via an acoustic modem to a mobile receiver fitted on a surface craft or ROV.

Figure 21: Left, the BED electronic package. Right, software display of BED orientation data.

BEDs were first deployed in Monterey Canyon at 300-meter depths during the winter and spring of 2013 (Figure 20). The initial tests validated event detection and acoustic communication between the R/V *Paragon* and a BED, and also demonstrated that geolocation by acoustic ranging is sufficient to track the object should it move. The team also tethered an additional BED to the boat to test the ability to selectively address, configure, and communicate with multiple instruments on the seafloor, and software was improved to provide a more intuitive visualization of BED motion (Figure 21).

After repeated surveys to prove the seafloor BED was still in place and working, communication with the deployed system was suddenly lost. After a number of unsuccessful searches, the acoustic beacon was finally detected at a depth of 500 meters—200 meters deeper than before—and the BED had astoundingly travelled nearly nine kilometers down the canyon's axial channel (Figure 22). Information recovered using the acoustic modem revealed the exact time that the BED was swept down-canyon in a 50-minute-long sediment transport event. Less than one week after this information was obtained, the ROV *Ventana* searched for and recovered the instrument, which was half-buried in sediment. This incredible record is undergoing analysis but

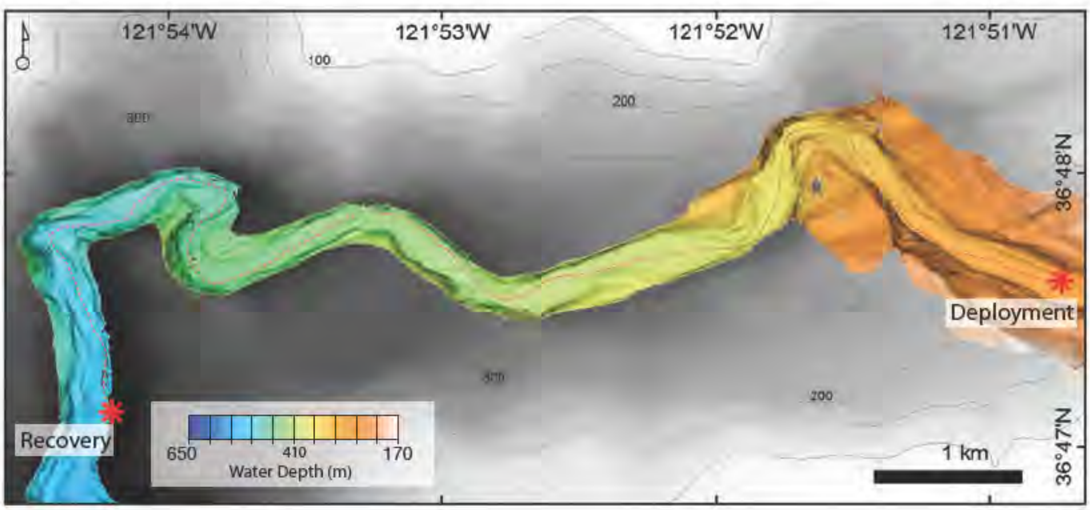


Figure 22: Map shows the deployment and recovery locations and the potential path recorded by the BED instrument in one 50-minute-long event in early June.

Adapting technology for new capabilities

Sometimes MBARI engineers create brand new technology to meet the needs of ocean scientists, but other times they start with an existing tool that can be adapted to meet those requirements. The Wave Glider is a good example of the latter. The Wave Glider is a small commercially available, autonomous vehicle that travels along the surface of the ocean, powered by wave energy for propulsion and solar energy for instrumentation. Several engineering efforts coordinated by Thom Maughan have added hardware and software to this platform that provides exciting new capabilities to several of the institute's research programs.

Figure 24: The Wave Glider communications hotspot and the radio relay antennas are designed for harsh ocean conditions. The vehicle's surface float is a little over two meters long.

One successful adaptation was the installation of a Wave Glider-based radio communications relay hotspot to receive and then retransmit data to shore from autonomous underwater vehicles (AUVs), simultaneously reducing the time AUVs spend on the surface and increasing the data volume that can be returned (Figure 24). The addition of an acoustic modem extended this data relay capability to subsea instrumentation and was used to locate and download data from the benthic event detectors.

A separate acoustic modem was deployed on a Wave Glider to test the ability of the long-range AUV to home in on a moving device, laying the groundwork for a future underwater docking system where the AUVs would be able to recharge batteries or send data back to shore. In 2013, a Wave Glider was deployed for two months for a Monterey Bay field program, as well as for a fish-tracking program in Portugal involving MBARI researchers. A receiver was attached to the Wave Glider in a demonstration of an opportunistic payload for tracking halibut and sharks tagged with acoustic beacons. By the end of the year, MBARI decided to purchase a Wave Glider to augment the institution's existing fleet of vehicles and instruments.

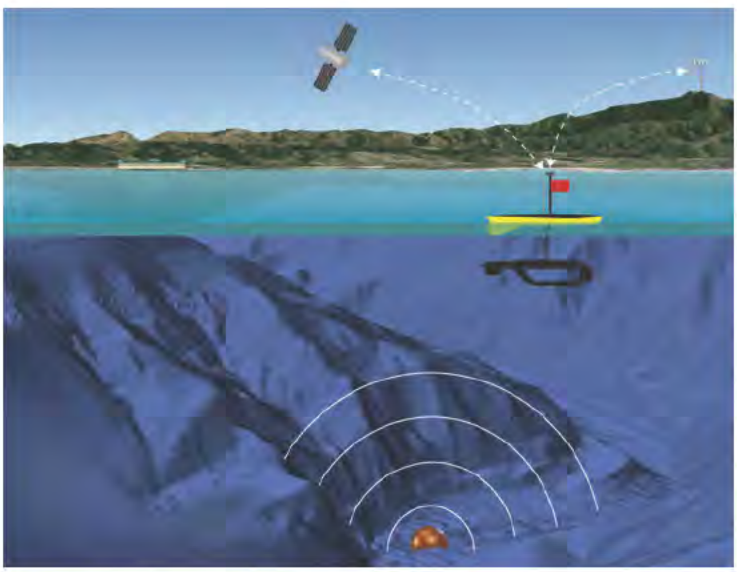


Figure 23: Illustration of the communications from the BED using a Wave Glider.

it is clear that the BED captured both rolling and sliding motions during the event.

After retrieving the data from the buried BED, *Ventana* was used to deploy a second BED back where the first one had originally been placed. This unit was recovered, unmoved, at its original site late in the year. The team also planted two spherical BEDs and two cubical concrete blocks with embedded acoustic beacons in the canyon floor in an experiment to determine whether the shape of the BED contributed to the rolling motion noticed in the data. This kind of experiment has never been done before; it sets a precedent for what could be done elsewhere to learn about canyon processes in other parts of the world.

Communicating with an array of BEDs over a long period can be time-consuming and costly when relying on ships, so the team has been working to offload some of the monitoring and data recovery to the Wave Glider (see sidebar). Initial steps were completed in early December when the Wave Glider was launched with a modified keel that held an acoustic modem (Figure 23). The Wave Glider successfully provided communications to land allowing users to query BEDs for events without having to leave shore. The instruments are undergoing several refinements in preparation for deploying an array of BEDs in 2015 as part of a large canyon-wide experiment.

Tracking complex phenomena in a dynamic ocean environment

Collecting biological, chemical, and physical data at sites in the deep ocean, and monitoring those sites for change over time, is a key thrust of MBARI's Strategic Plan. These observations provide critical information that not only can help us understand the health and biodiversity of the ocean at a given time, but also help quantify long-term alterations associated with important phenomena such as climate change. Icebergs are a surprising link in MBARI's quest to develop the capacity to make these kinds of measurements.

Atmospheric warming has been associated with retreating glaciers, the accelerating loss of ice shelves, and the increasing prevalence of icebergs in the Southern Ocean over the last decade. In previous work, MBARI Scientist Ken Smith and his team have proven that these icebergs are hotspots of chemical and biological enrichment that substantially affect the pelagic ecosystem of the Southern Ocean. Their studies of free-drifting icebergs in the northwest Weddell and Scotia Seas have shown that significant delivery of terrestrial material to surrounding waters is accompanied by enhancement of biological activity and carbon export. The research team hypothesized that the unique conditions created by free-drifting icebergs will increase primary production and sedimentation of organic carbon. These enriched conditions would increase the drawdown of carbon dioxide during photosynthesis, resulting in increased carbon sequestration in the Southern Ocean associated with the proliferation of free-drifting icebergs. A team of MBARI engineers and scientists are building on years of development of remotely operated and autonomous vehicles to tackle challenges of studying icebergs and their impact on their environment.

Understanding the complex interactions between the biological food web and the chemical and physical processes surrounding an iceberg requires many different measurements. Because icebergs often slough off large sections of ice, it is not safe for a ship to get very close, so previous observations have mostly been conducted from ships more than 400 meters away using small ROVs that sample near

Figure 25: A schematic of the interacting chemical, biological, and physical processes surrounding an iceberg being sampled by a ship, an autonomous underwater vehicle, a remotely operated vehicle, and a Lagrangian sediment trap.

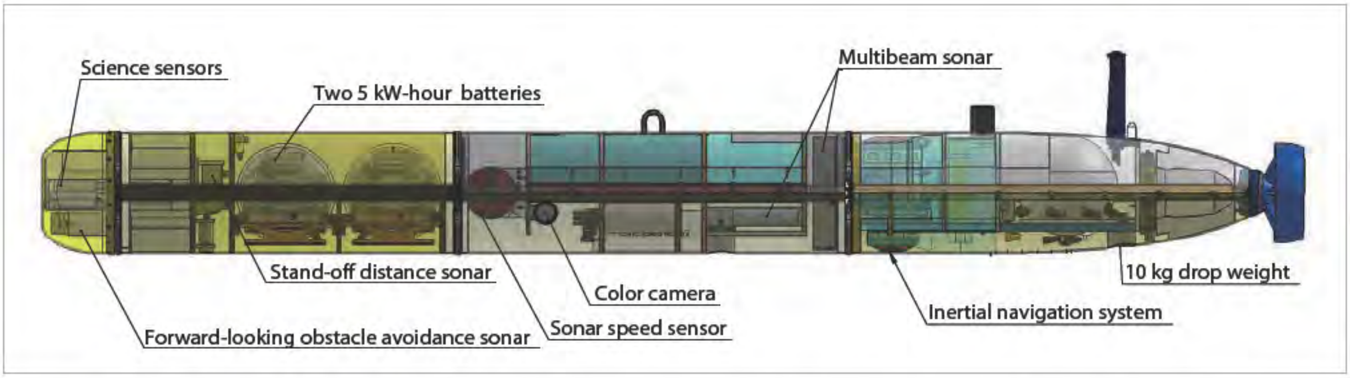


Figure 26: Schematic of the port-side view of the Iceberg AUV. All sonars and cameras on the vehicle can be pointed up, down, left, or right. The science sensors at the front of the vehicle measure conductivity, temperature, depth, dissolved oxygen, light intensity, and fluorescence.

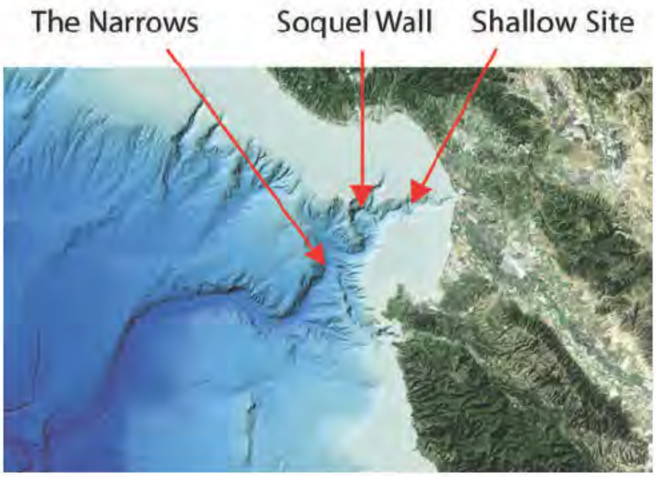


Figure 27: Test sites explored in Monterey Bay, California.

the iceberg's surface or Lagrangian sediment traps that drift under the iceberg (Figure 25). Smith is now working with Stanford University Professor Steve Rock, an MBARI adjunct researcher, to enhance existing AUV technology to enable data collection very close to icebergs. This delicate operation requires a new generation of precision navigation.

This new navigation system enables mapping of large areas of complex terrain, then returning to selected sites within that terrain to collect visual images, water samples, or take other measurements. A new vehicle and a new set of navigation and control algorithms are required to accomplish this task and enable safe operation within 200 meters of the iceberg. The new vehicle is based on MBARI's *Dorado*-class AUV (Figure 26) equipped with one suite of sensors

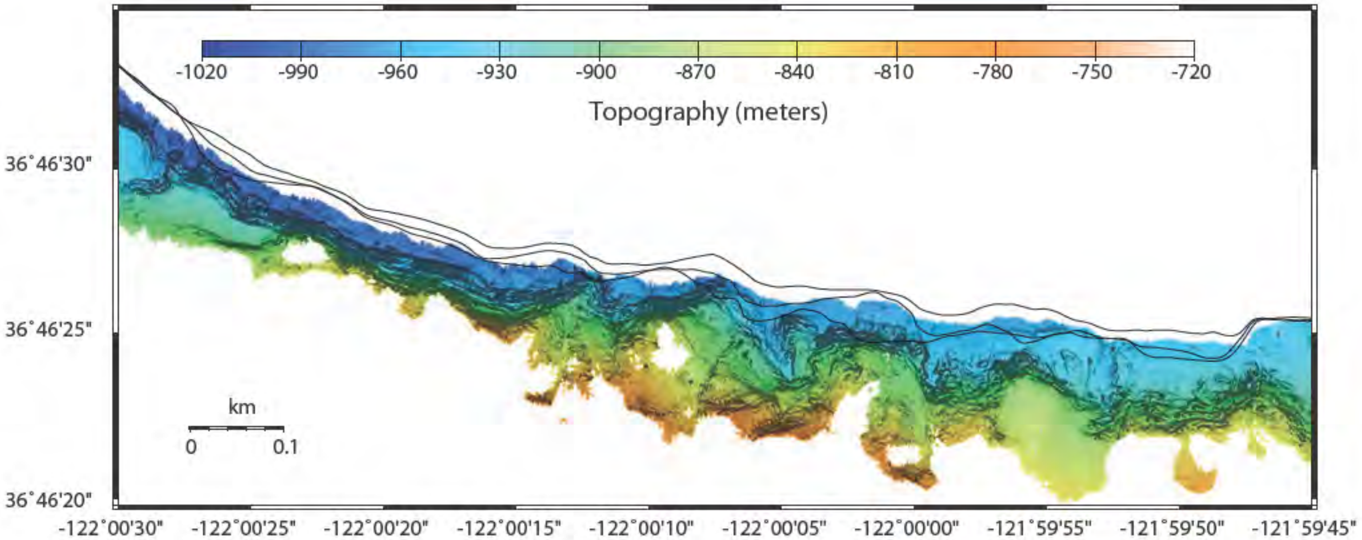


Figure 28: New sensors and navigation algorithms allowed the AUV to follow this section of wall in Soquel Canyon. Several overhangs above this sheer cliff make it difficult to map in detail solely with a traditional multibeam sonar aimed toward the seafloor. Black lines are AUV tracks at different depths.

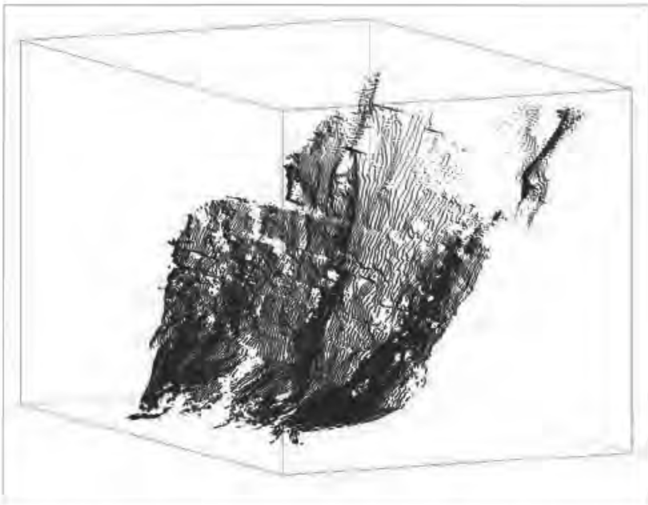


Figure 29: Section of the Soquel wall test site map made up of data points returned from the multibeam sonar system with the sonar oriented horizontally. Details of the side of the sheer cliff can be seen that are not visible in bathymetry collected with downward-facing sonar. The wall pictured here is about 180 meters tall; the sides of this box are each about 200 meters long.

to enable navigation with respect to the vertical walls of an iceberg (or of a deep canyon) and another suite of sensors to collect data to support the science goals. A new set of control algorithms will guide the AUV as it seeks an iceberg, locates its submerged surface, and then tracks that surface to collect mapping and other science data.

Tests of this new vehicle began in 2013 in Monterey Bay (Figure 27). A modified version of the mapping AUV was used for these trials, with modifications that included the new control and navigation algorithms as well as a side-looking mapping sonar. Steep and rugged canyon walls in Monterey Bay were selected as surrogates for the submerged section of an iceberg; the detailed maps of the terrain revealed precipitous canyon walls and features never before seen (Figures 28 and 29).

As with MBARI's Environmental Sample Processor, this project has received funding from NASA's ASTEP program in support of developing new technologies that will enable robotic exploration for evidence of life in extreme environments, such as deep space, and to advance these technologies by demonstrating them in Earth-based missions. The technologies being developed for the new AUV are specifically relevant to these NASA objectives. They support the mapping of bodies such as asteroids, and the robotic exploration of new worlds in deep space (for example, under the ice of Europa) where position- and orientation-sensing information is limited. The technology MBARI is now demonstrating in the deep canyons of Monterey Bay, and eventually in waters surrounding icebergs, may one day be applied to the extreme environments of deep space.

Zooplankton Biodiversity and Biooptics in the Deep Sea

Project lead/manager: Steven Haddock
Project team: Lynne Christianson, Warren Francis, Meghan Powers
Collaborators: William Browne, University of Miami, Florida; Robert Condon, Dauphin Island Sea Lab, Alabama; Casey Dunn and Stefan Siebert, Brown University, Providence, Rhode Island; 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

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

Midwater Ecology

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Rob Sherlock
Collaborators: Kat Bolstad, Auckland University of Technology, New Zealand; Stephanie Bush, Steven Haddock, George I. Matsumoto, and Ken Smith, MBARI; Jeffrey Drazen and Richard Young, University of Hawaii, Manoa; William Gilly, Hopkins Marine Station of Stanford University, Pacific Grove, California; Rudy Kloser, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; Karen Osborn, Smithsonian Institution, Washington, D.C.; Brad Seibel, University of Rhode Island, Kingston

Benthic Biology and Ecology

Project leads: James Barry, Craig Okuda
Project manager: James Barry
Project team: Kurt Buck, Taewon Kim, Chris Lovera, Eric Pane, Josi Taylor, Patrick Whaling

Novel Applications of Chemical Sensors

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

SURF Center (Sensors: Underwater Research of the Future)

Project lead: 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, 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; 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

Phytoplankton Ecology and Dynamics

Project lead: Alexandra Z. Worden
Project managers: Sebastian Sudek, Alexandra Z. Worden
Project team: Nilo Alvarado, Charles Bachy, Chang Jae Choi, Jian Guo, Valeria Jimenez, Alexander Limardo, Camille Poirier, Melinda Simmons, Lisa Sudek, Jeltje van Baren, Susanne Wilken, Amy Zimmerman
Collaborators: Craig Everroad, NASA Ames Research Center, Moffett Field, California; Stephen Giovannoni, Oregon State University, Corvallis; Patrick Keeling, University of British Columbia, Vancouver, Canada; Adam Monier, University of Laval, Quebec City, Canada; Thomas Richards, Natural History Museum, London, United Kingdom; Alyson Santoro, University of Maryland, Cambridge

Benthic Event Detectors

Project lead: Charles Paull
Project manager: Brian Kieft
Project team: Krystle Anderson, Larry Bird, Dale Graves, Bob Herlien, Denis Klimov, Eve Lundsten, Mike McCann, Alana Sherman, Esther Sumner

Wave Glider Feasibility Study

Project lead/manager: Thom Maughan
Project team: Paul Coenen, Brian Kieft

Distributed Autonomy

Project lead/manager: Kanna Rajan
Project team: Mark Chaffey, Tom O'Reilly, Frederic Py
Collaborators: Joao Sousa, University of Porto, Portugal

Iceberg AUV

Project leads: Brett Hobson, Steve Rock, Ken Smith
Project team: David Caress, Rich Henthorn, Eric Martin, Rob McEwen, Paul McGill, Hans Thomas
Collaborators: Marcus Hammond, Sarah Houts, Jose Padial, and David Stonestrom, Stanford University, California

Expeditions

Expeditionary missions bring together MBARI scientists, engineers, operations personnel, and communications staff to explore and experiment at sites far from Monterey Bay.

In 2013 ships from other institutions provided exceptional opportunities to utilize MBARI assets in collaborative projects based in Mexico and the Arctic. In addition, MBARI research vessels *Western Flyer* and *Rachel Carson* carried the ROV *Doc Ricketts* and the *D. Allan B.* mapping AUV to research sites north and south of Central California.

Mapping an ancient undersea meteor crater

About 65 million years ago, an asteroid or comet crashed into a shallow sea near what is now the Yucatán Peninsula of Mexico. The resulting firestorm and global dust cloud caused the extinction of many land plants and large animals, including most of the dinosaurs.

The ancient impact created a huge crater, over 160 kilometers across. Unfortunately for geologists, this crater is almost invisible today because it is buried under layers of debris hundreds of meters thick and almost a kilometer of marine sediments. Although fallout from the impact has been found in rocks around the world, surprisingly little research has been done on the rocks close to the impact site, in part because they are so deeply buried. All existing samples of impact deposits close to the crater have come from deep boreholes drilled on the Yucatán Peninsula.

MBARI's Charlie Paull had long suspected that rocks associated with the impact might be exposed along the Campeche Escarpment, a 600-kilometer-long underwater cliff just northwest of the Yucatán Peninsula (Figure 30). Nearly 4,000 meters tall, the Campeche Escarpment is one of the steepest and tallest underwater features on Earth. It is comparable to one wall of the Grand Canyon—except that it lies thousands of meters beneath the sea.

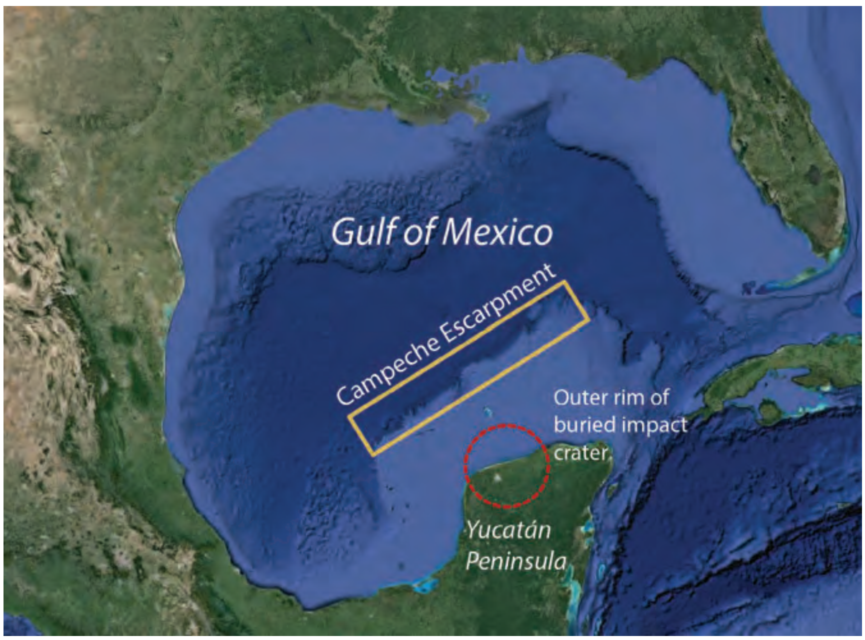


Figure 30: Google Earth map of the Campeche Escarpment in the Gulf of Mexico, near the Yucatán Peninsula. Red circle shows location of the buried impact crater.

The Campeche Escarpment is the edge of an ancient carbonate platform that ultimately owes its relief to accumulation of biogenic sediments in shallow tropical waters over millions of years. Whether the extreme steepness of the escarpment is attributable to reef growth along its edge or to erosion has long been an open question.

In March 2013, an international group of researchers led by Paull created the first detailed map of the Campeche Escarpment. The team included staff of the Schmidt Ocean Institute and researchers from the Universidad Nacional Autónoma de México and the Centro de Investigación Científica de Yucatán. The information to create the map was acquired using a state-of-the-art multibeam sonar system on the research vessel *Falkor*, a ship operated by the Schmidt Ocean Institute (Figure 31). The resulting images have recently been incorporated into Google Maps (maps.google.com) and Google Earth (earth.google.com) for viewing by researchers and the general public.

Figure 31: Postdoctoral Fellow Esther Sumner and Software Engineer David Caress process data aboard the R/V *Falkor*.

As in the walls of the Grand Canyon, sedimentary rock layers exposed on the face of the Campeche Escarpment provide a sequential record of the events that have occurred over millions of years. Based on the new maps, Paull believes that rocks formed before, during, and after the impact are all exposed along different parts of this underwater cliff (Figure 32).

Paull hopes to one day collect samples along the Campeche Escarpment. Only a couple of decades ago, the idea of performing large-scale geological surveys thousands of meters below the ocean surface, followed by targeted sampling missions, would have seemed a distant fantasy. Over the last eight years, however, such operations have become almost routine for MBARI geologists using a variety of underwater robots.

The newly created maps of the Campeche Escarpment could open a new chapter in research about one of the largest extinction events in Earth's history. Already researchers from MBARI and other institutions are using these maps to plan additional studies in this little-known area. Detailed analysis of the bathymetric data and eventual fieldwork on the escarpment will reveal fascinating new clues about what happened during the massive impact event that ended the age of the dinosaurs—clues that have been hidden beneath the waves for 65 million years.

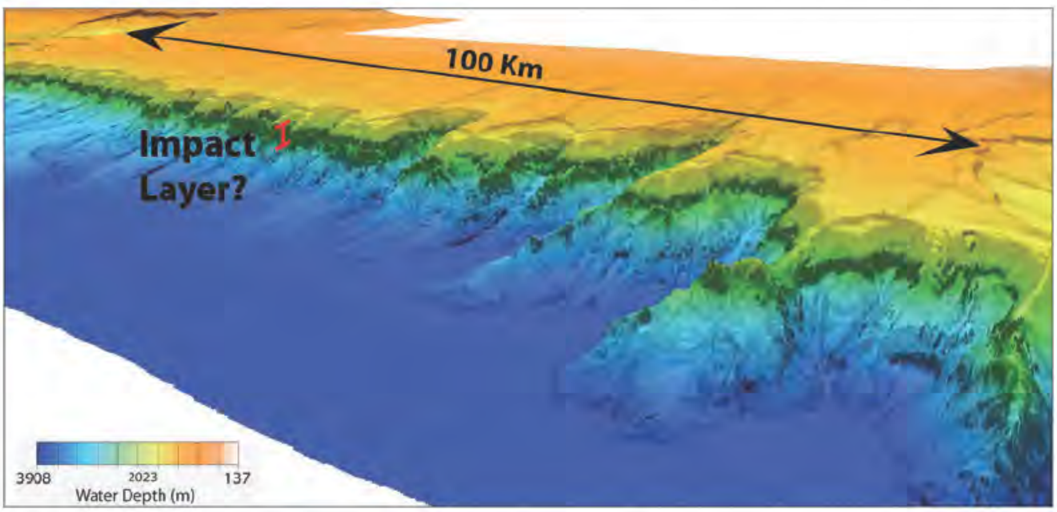


Figure 32: A perspective view of an approximately 100-kilometer segment along the face of the Campeche Escarpment. The top Cretaceous-Paleocene boundary is inferred to be associated with the zone labeled as "impact layer" below.

Exploration of the Arctic seafloor

The Arctic region is undergoing arguably the most dramatic thermal change of any place on Earth. Large temperature shifts in the region—continuing aftereffects of the end of the last Ice Age some 12,000 years ago—are causing flooding and decomposition of the permafrost and gas hydrates.

To learn more about the formation and thawing of permafrost and gas hydrate, with associated release of water and gas into the ocean, Charlie Paull led an expedition to the Beaufort Sea in the Arctic, in collaboration with the Geological Survey of Canada (GSC) and the Department of Fisheries and Oceanography in British Columbia. First, the Korean Polar Research Institute and the GSC conducted geophysical surveys to gain spatial information about the seafloor with a variety of sensors on the Korean icebreaker *Araon*. With some support from the Canadian government, Paull's team transported the MBARI mapping autonomous underwater vehicle (AUV) and a small remotely operated vehicle (ROV) north for a subsequent cruise in the same region aboard the Canadian Coast Guard icebreaker *Sir Wilfrid Laurier*.

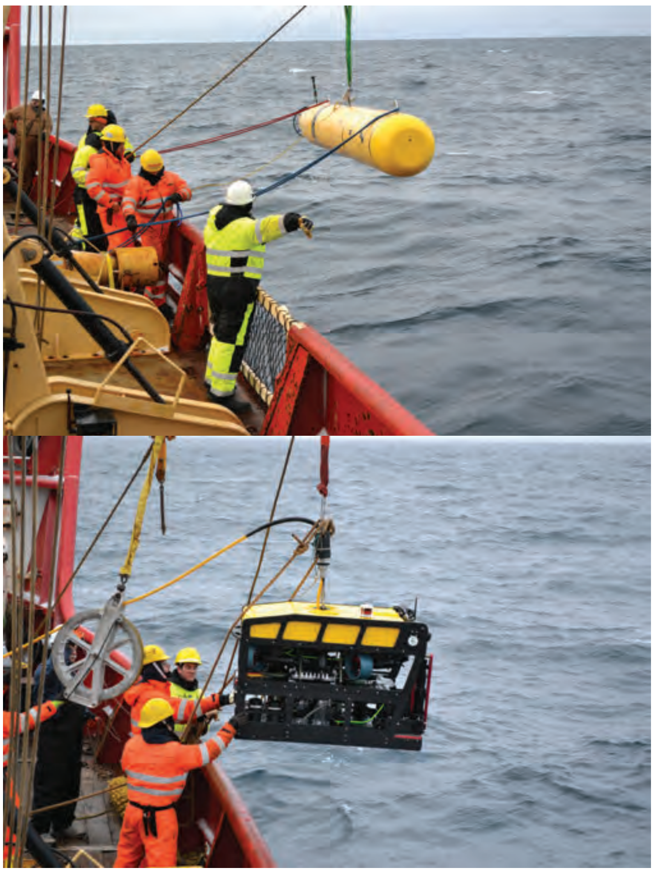


Figure 33: The AUV, above, and the mini ROV, below, are deployed from the icebreaker *Sir Wilfred Laurier*.

MBARI contributions to the program included AUV mapping surveys and ROV surveys down to depths of one kilometer, and analyses of pore waters collected from sediments cores. This was the first cruise on which MBARI's mapping AUV and the new mini ROV were used simultaneously (Figure 33). It was also the first deep-water AUV dives ever conducted in the western Arctic, and a rare deep-water Arctic ROV operation. The presence of large masses of rapidly moving sea ice in the study area presented a continuous challenge to operations as plans were adjusted hour-by-hour (Figure 34).

Extensive deposits of submerged permafrost and gas hydrates occur under the continental shelf of the Beaufort Sea, extending to the shelf edge. Flooding of relatively warm Arctic Ocean waters (-1.5°C) over the frigid subaerial tundra at the end of the last Ice Age have led to the exceptionally large temperature change. Previously the tundra had experienced -15°C or lower mean annual temperatures. The warming pulse produced by the rising Arctic Ocean waters during the deglaciation is still propagating into the subsurface, stimulating the decomposition of both terrestrial permafrost and gas hydrates at depth—freeing methane and freshwater in the process. The most pressing and unresolved issues are where that water and methane go, and what the movement of that material is doing to the morphology, stability, hydrology, and biology of the continental margin. The prospect that increased periods of ice-free conditions associated with global climate change may further dramatically alter this once-pristine environment make it urgent that the global community

Figure 34: A block of ice encroaches on an ROV dive.

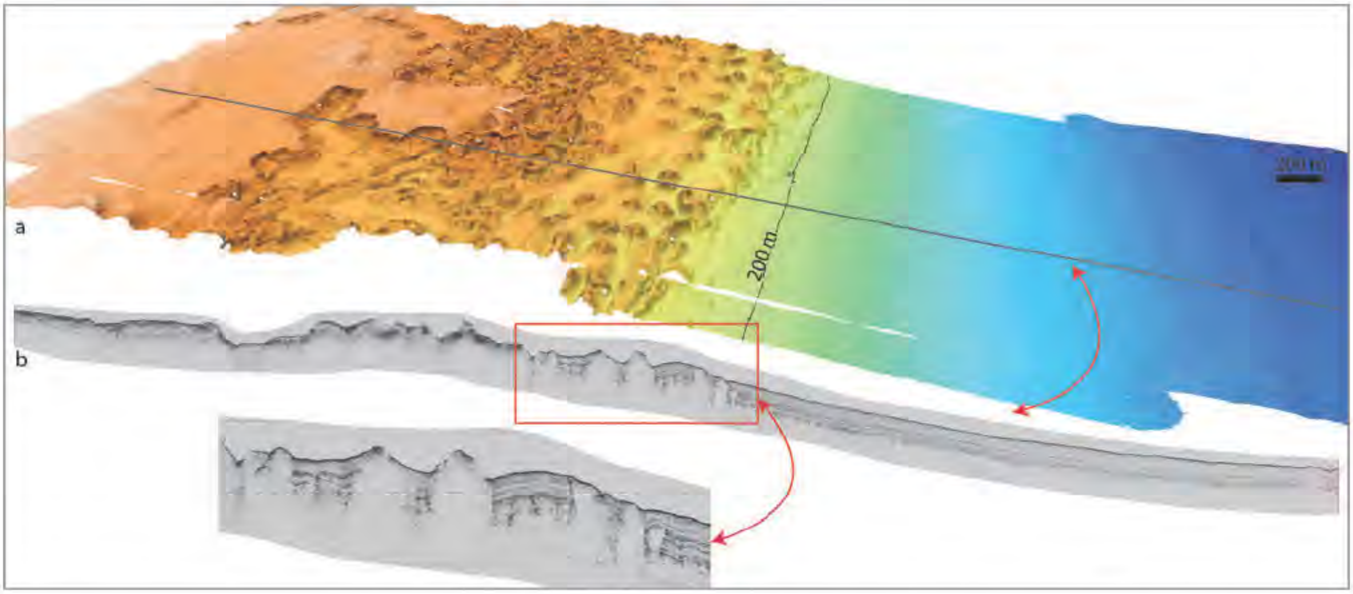


Figure 35: Top, complex surface morphology revealed in AUV surveys of the shelf edge and upper slope of the Beaufort Sea in the Canadian Arctic. Bottom, profile of the sediments beneath the seafloor surface crossing through several mounds.

document this change, including its unique geology and biological communities.

Some sections of the shelf edge and slope in the Beaufort Sea have been mapped using multibeam systems from ships on the sea surface. These regional maps showed the existence of numerous areas with distinctive seafloor features that are either uncommon elsewhere or unique to the Arctic environment. These include multiple and apparently young slide scars, mud volcanoes on the slope that are about one kilometer across, and numerous 10-meter-high, steep-sided mounds which occur near the shelf edge (Figure 35). The processes that created these mounds are still poorly understood but indicate a dynamic seafloor undergoing geologically rapid changes related to ice formation in the marine environment and active fluid flow from the subsurface.

Despite the limited exploration conducted in the area, the research team identified numerous sites in the Beaufort Sea that indicate active fluid venting. ROV observations revealed vigorous methane venting at various locations on the seafloor, and episodically from mud volcanoes. Discrete springs were also observed on the soles of landslide scars where shimmering waters flow out from the seafloor. Chemical analyses of the samples collected show that the source of the venting methane and emanating water is decomposing permafrost and/or gas hydrates. This large number of seafloor fluid-venting sites, and the variety in mode and frequency of fluid flow is remarkable and raises the question about how typical and widespread the observed processes are on the Arctic shelf.

Information gleaned from the AUV and ROV dives indicates that glacial moraine is present on the continental shelf, well outside of areas thought to represent the thickest past ice sheet. The ROV was used to sample pebbles and cobbles within fine-grained muds. In some cases the cobbles contain gouges that indicate that they were carried by glacial ice (Figure 36). Preliminary interpretations of these observations suggest that these sediments, which are widespread on the shelf edge and within landslide deposits down to at least one kilometer water depth, are glacial sediments. This was surprising since it has long been thought that, similar to Siberia and most of Alaska, the Beaufort Shelf was ice-free during glacial times. The expedition's findings call for a reconsideration of Arctic history, which has implications for the understanding of human evolution and how people came to inhabit North America. The work is also highly relevant to the push for oil and gas exploration and extraction, most notably in light of the unstable seafloor and other potential geological hazards in the area. This body of work is a great example of MBARI technology used in collaborative research, and how the results of exploration and discovery can have great import for policy makers.

Figure 36: Dale Graves, above, flies the mini ROV and uses its manipulator arm to sample rocks. Still image from video, below, shows a boulder and other rocks scattered on the seafloor that are characteristic of glacial till deposits.

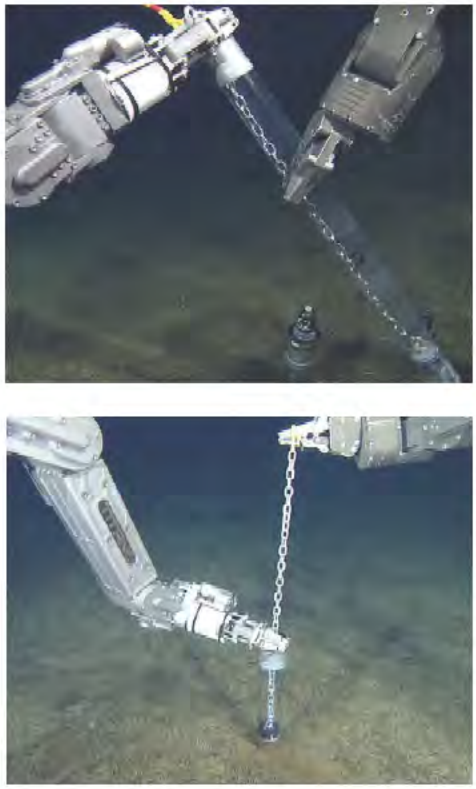


Figure 37: A new piston corer was used to address the long-standing challenge of obtaining core samples necessary to understand a volcano's eruptive history. The opportunity for MBARI's engineers, researchers, and marine operations personnel to work together over multiple years allowed the development of improved sediment sampling methods that made this work possible. The ROV pilots use both robotic arms to manipulate the corer. Right, a cross-section of a core shows the hydrothermal and glassy layers of the sediment (the scale along the left edge is in centimeters).

Pacific Northwest

MBARI's research vessel *Western Flyer* carried the ROV *Doc Ricketts* and a multidisciplinary group of scientists and collaborators on a seven-week trek to the waters off the coasts of Northern California, Oregon, and Washington. Three research teams explored and conducted experiments on gas hydrates, underwater volcanoes, the behavior of carbon dioxide in the deep sea, deep-sea animals, and processes associated with seafloor gas and oil venting and submarine canyons.

Undersea volcanoes hold many secrets

Working at the Juan de Fuca Ridge, Scientist Dave Clague and his team focused on questions about how and why submarine volcanoes erupt as compared to volcanoes on land. On land, scientific study of volcanoes is largely driven by the hazards posed to life and property or the prospect of geothermal power development. Studies of terrestrial volcanoes commonly begin with determining the frequency and style of past eruptions, in hope of predicting future eruptions and understanding what factors control their severity. Submarine volcanoes are subjected to different physical conditions, in particular by being under high pressure and immersed in water. These fundamental differences offer insight into the roles of different factors in controlling eruptive behavior. For example: How often and why do undersea calderas collapse during the growth of volcanoes? How common or rare are explosive eruptions at depth, under high pressure? Are explosive eruptions driven by steam explosivity or by release of deeper magmatic gases? What controls the style of lava flows produced by submarine eruptions?

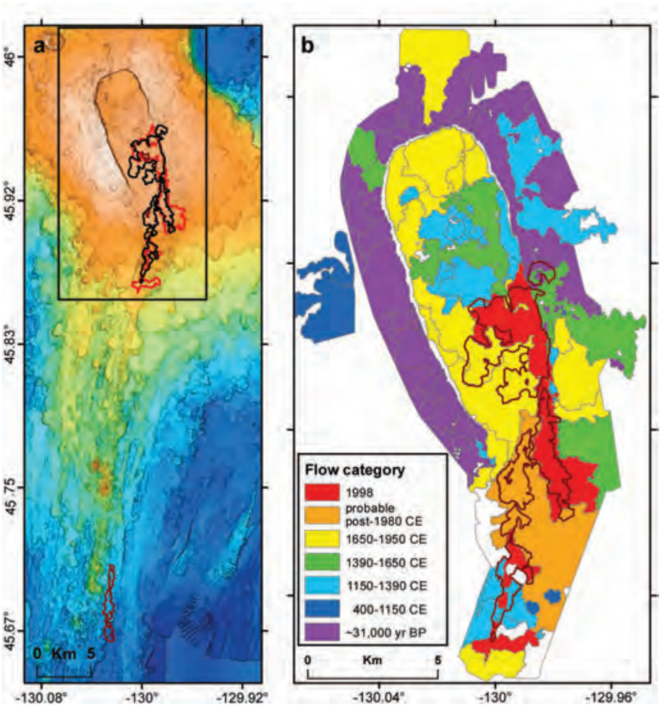


Figure 38: a) Map of Axial Seamount's summit and south rift zone, with high-resolution MBARI AUV bathymetry data superimposed on lower-resolution ship-based data. The 1998 lava flows are outlined in red and the 2011 flows are outlined in black. The box indicates the summit area shown in panel b. b) Detailed geologic map of the summit caldera and flanks, showing distribution and radiocarbon ages of older lava flows, created by combining AUV mapping with ROV observations and samples. The 2011 flow is shown as the brown outline overlapping the older flows.

Figure 39: Deckhand Jason Jordan operates the winch from the upper deck of the R/V *Western Flyer* for evening seafloor sampling. Heavy metal cores with wax-filled steel buds on the end are dropped to the seafloor. Upon impact with the submarine volcano, the cores chip off small bits of volcanic glass which stick to the wax. Laboratory analyses of these bits of glass provide clues to the age of the lava flow.

The Juan de Fuca Ridge is a good place to address such questions, as it is one of the most active segments of the global ridge system, with six known eruptions since the mid-1980s. Two eruptions, in 1998 and 2011, occurred at Axial Seamount, located midway along the ridge. The National Science Foundation's Ocean Observatories Initiative (OOI) built a cabled observatory at Axial, in part to monitor volcanic and hydrothermal activity. MBARI mapped the summit of Axial with the AUV in the years before and a few months after the 2011 eruption, allowing Clague's team to calculate the extent and volume of that eruption. With the entire summit region mapped at one-meter horizontal resolution, the eruptive history of Axial Seamount was revealed in unprecedented detail. The researchers used the AUV maps and ROV dives to determine where different lava flows came in contact, then sampled the flows and the sediment on them to determine the chemical compositions and relative ages of the flows.

One of the long-standing challenges associated with this work is obtaining samples of the thick volcanic sediments on the caldera rims. MBARI engineers, researchers, and marine operations personnel have worked together over multiple years to refine sediment-sampling methods using push cores, vibracores, and piston cores—methods that make it possible to understand the layering, or stratigraphy (Figure 37). The cores contain layers of volcanic material interspersed with layers containing animal shells that can be carbon-dated. This technique allows the team to estimate the ages of underlying flows, of explosive eruptions, of periods of intense hydrothermal activity, or of periods of quiet.

Combining information obtained from the surveys and samples led to construction of the most detailed geologic map ever made of a submarine volcano (Figure 38). The analysis indicates that the recent 13-year frequency between eruptions at Axial Seamount has been virtually unchanged for the last 800 years. Clague predicts that the next eruption will most likely occur around 2024. The erupted lavas have changed systematically through time in terms of their compositions and eruption styles. The older, hotter, and more primitive lavas erupted more violently and generated abundant glass debris that was deposited on the rims of the caldera. More recent eruptions have been less primitive, with relatively little glass debris, producing more extensive fluid flows that advanced several kilometers from their eruptive fissures (Figure 39).

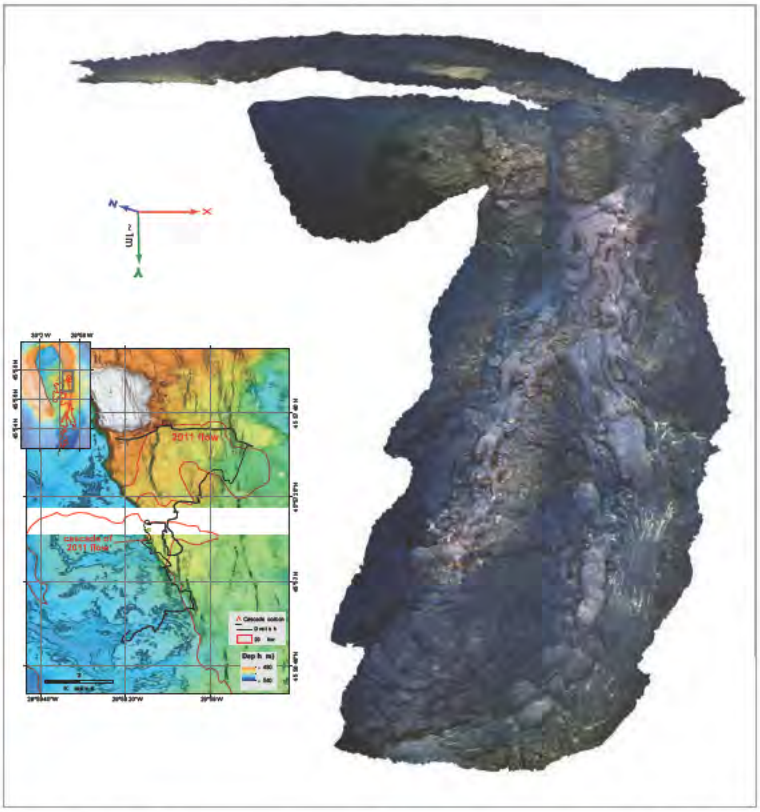


Figure 40: A three-dimensional mosaic of 2011 lava flows cascading over the 10-meter tall eastern caldera wall. Map shows location of lava flow.

The eruptive fissures for the 2011 lava flows near the summit were wide and deep. Molten lava had extruded, ponded, breached, and overflowed (Figure 40), and some drained back down, leaving behind gaping fissures. Pillars grew as water trapped beneath the advancing flow escaped through chilled margins that coalesced into hollow vertical tubes as the flow inflated. The voluminous flows formed large, complex channel systems that distributed lava far from the fissures. When the eruption finally ended, the solid lava crusts that formed the roofs of the channels collapsed, leaving behind pillars and arches of lava (Figure 41).

Comparing the mapping data collected before and after the 2011 eruption led to the discovery of another new flow that had erupted between the surveys, located deep on the south rift zone (Figure 38a). Two ROV dives in 2013 were spent exploring and sampling that flow and revealed a long, steep ridge of pillow lavas. The presence of hydrothermal bacterial mats indicated the flow was recent.

Axial Seamount has been and will continue to be an amazing natural laboratory for studying submarine volcanic activity. These geologic studies will be the foundation for understanding future mid-ocean ridge eruptions.

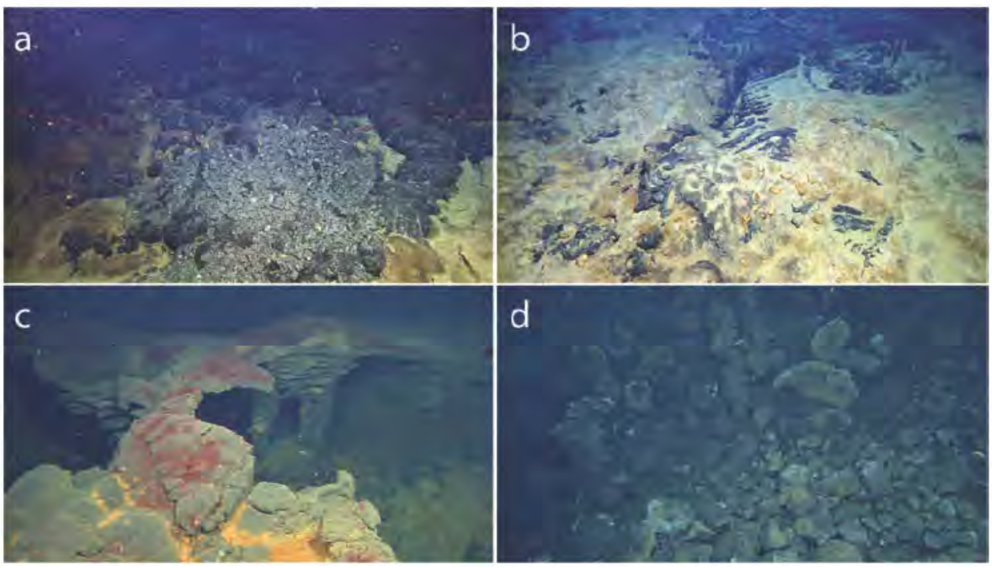


Figure 41: Still images from ROV video at Axial Seamount. a) Pillowed margin of the 2011 lava flow on top of sediment; including some pillows that exploded to form coarse angular crystalline debris. b) Sheet flow margin that has burrowed under the pre-existing sediment, causing disruption of the sediment. c) Lava pillars and arches formed along a deep channel that distributed lava downslope away from the fissure. The arches here are heavily stained by hydrothermal iron-oxide deposits. d) Broken pillows exposed in the near-vertical margin of the 2011 pillow ridge, with angular pillow talus formed during the eruption at the base.

Natural oil and gas vents in the ocean depths

It is not possible to directly simulate an oil spill, but it is evident that the environmental impact, cost, and complexities of a large spill are significant. Given the rapid rate at which oil can rise and spread, response efforts are logically directed at containment and there is little time for scientific observation. Natural hydrocardon seeps provide an opportunity to apply MBARI tools and techniques to study the chemical and physical behavior of small quantities of oil as they move from the seafloor to overlying water. These experiments provide a foundation for understanding how to respond to oil spills in the future.

Figure 42: Summer Intern Wilson Sauthoff controls the ROV's main science camera while the laser Raman spectrometer takes a reading prior to the collection of an oil sample from the seafloor. The spectra can be seen as a green line against a black background on the monitor at the top right; the various peaks in the graph indicate the presence of different gases.

One such seafloor site where gas and oil are released naturally is off Northern California, near Eel Canyon, offshore of Eureka. The gas vents were first discovered a few years ago by scientists from the University of New Hampshire and the National Oceanographic and Atmospheric Administration (NOAA). The natural seeps appeared as large plumes rising from the seafloor in their sonar display. A team from MBARI later mapped these sites in very high resolution with AUV *D. Allan B.* Further exploration by MBARI scientists using the high-resolution AUV maps revealed oil seeps in addition to the expected natural gas vents (Figure 42).

Peter Brewer and his team studied this region by capturing material coming out of the seafloor sediments naturally near Eel Canyon at 1,600-meters depth. They collected about 200 milliliters of oil from the upper few centimeters of sediments in a glass-walled core tube and, using MBARI's ROV *Doc Ricketts*, carefully flew the sample upwards while observing it as the temperature and pressure changed. Surprisingly the oil evolved large quantities of gas during its transit to the surface in spite of the very long time it had to equilibrate with the sediment pore waters (Figure 43). The research team used MBARI's laser Raman spectrometer to make in situ measurements of the gas; the oil itself is so highly fluorescent that direct Raman measurements of the oil were not possible. The chemical signals recorded showed that large quantities of methane, and lesser amounts of carbon dioxide and other gases were released (Figure 44). The quantity of dissolved gas makes the oil far more buoyant and thus it rises to the surface more quickly than expected.

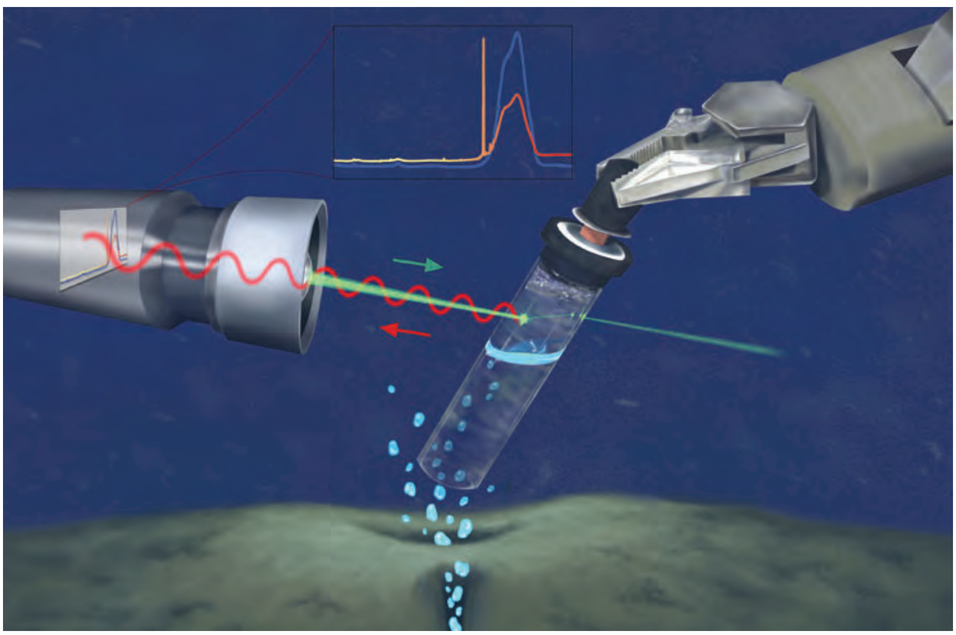


Figure 43: Conceptual illustration of the laser Raman spectrometer measuring the gas headspace above oil collected from the seafloor sediments and contained in a glass tube. The blue bubbles and the layer in the tube represent the oil that emanated from the seafloor (the oil fluoresces blue in the lights from the ROV). The ROV pilots held the tube of oil in one robotic arm and positioned the laser Raman spectrometer with the other robotic arm as the vehicle was brought toward the surface so the team could measure the gases that separated from the oil sample.

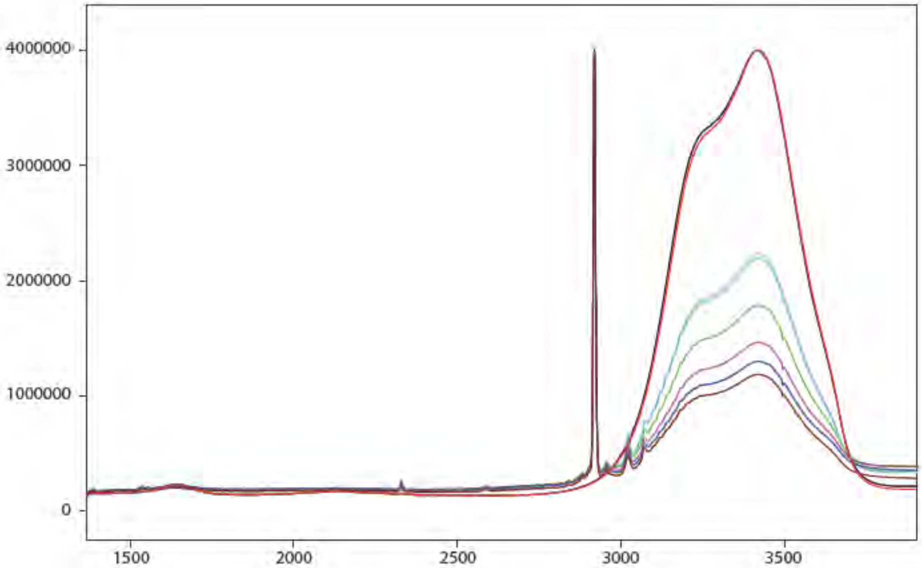


Figure 44: Laser Raman analysis of the gas headspace above a small volume of oil collected from the seafloor. The oil was contained in a glass tube for observation and laser Raman measurements as the ROV ascended from 1,750 meters to 200 meters. The sharply pointed peak in the center of this graph indicates a significant presence of methane. The smaller peaks to the right of the methane peak indicate other hydrocarbons were also present in this natural oil sample. The black and red lines are Raman spectra of seawater at 1,750 meters and 200 meters.

This work can be applied towards improving our understanding of the chemical and physical consequences associated with deep-sea oil spills, such as what occurred at the Deepwater Horizon platform in the Gulf of Mexico. That 2010 oil spill led to the realization that our fundamental knowledge of ocean physics and the chemistry and biology of oil-perturbed systems is inadequate, particularly when the oil is released from a deep source. The gas evolution detected in Brewer's experiment was similar to what was observed during the spill in the Gulf of Mexico.

This experiment exemplifies MBARI's goal of conducting controlled in situ experiments—and development of state-of-the-art tools—to contribute to our understanding of ocean processes, and the societal impact of human perturbations.

Southern California

Similar to the research sites to the north, Southern California offers MBARI scientists several sites of interest that complement those found locally. The low-oxygen waters off of Santa Monica portend the future of other ocean basins as a result of ocean warming. The R/V *Rachel Carson* was used to conduct seafloor mapping in advance of subsequent ROV dives from the R/V *Western Flyer*.

Microbial life in the future ocean

What will the future ocean look like under climate change? The warming of the ocean may shift microbial life, fundamentally altering processes that govern the cycling of matter and energy on a global scale. The 2013 expedition to Southern California, where the waters are warmer and contain less oxygen, provided Peter Brewer and MBARI Adjunct Victoria Orphan from the California Institute of Technology a chance to evaluate potential outcomes of a changing ocean.

The combination of oxygen concentration and temperature is one of the more powerful environmental controls that govern marine life. Ocean warming by just 2°C (a conservative estimate for the future) considerably reduces the solubility of oxygen in seawater. Since many areas of the U.S. West Coast already have zones at depth characterized by low oxygen, such change would lead to the expansion of "dead zones" in the near future. The lowest oxygen water in Monterey Bay exemplifies this situation; a slight warming will put these waters at risk of reaching a tipping point where the current community of organisms is replaced by something entirely different. What governs the oxidizing capacity of the ocean and buffers against the emergence of toxic hydrogen sulfide? How fast may the ocean go from one condition to another?

To examine these questions Brewer's team investigated conditions in the Santa Monica Basin, offshore of Los Angeles, where oxygen levels are naturally lower than those typically found in Monterey Bay. This region provides a realistic approximation for what Monterey Bay could experience in the future under slightly warmer conditions. Where oxygen levels drop to very low levels, higher forms of marine life are conspicuously absent—only microbes and occasional communities of clams that survive by harboring symbiotic bacteria thrive. With a 2°C warming and even less oxygen, microbes should increasingly respire chemical compounds leading to the emergence of toxic sulfide. Brewer and Orphan worked to test the chemistry-microbe linkages in the Santa Monica Basin. Their surveys showed relatively few areas characterized by cold seeps with accumulations of sulfidic clams and associated organisms. Instead, a disturbingly dreary view of empty seafloor showed the methane mounds were covered with a thick bacterial mat and little else (Figure 45). This finding resembles what can happen when a tipping point of oxygen and temperature is reached: the biological community shifts from one regime to another.

The tipping point for the deep waters of Monterey Bay is far closer than most people realize. Typical deep-water oxygen-minimum levels at 650-meters depth today are at a point where it would only take a warming of about .5°C to shift into a dead zone analogous to what is now found in the Santa Monica Basin. A warming of this magnitude has already occurred elsewhere in the global surface ocean and this warming is slowly being transmitted to depth by ocean circulation. Further experiments to evaluate the role microbes play in driving these tipping points in the deep sea will be conducted at MBARI's cabled observatory. The power and communications infrastructure available at MBARI's Monterey Accelerated Research System (MARS) cabled observatory in Monterey Bay makes it an ideal setting to conduct further experiments to evaluate the role microbes play in structuring marine ecosystems.

As Brewer and his team continue to develop and test these basic theories, they are gaining the attention of governmental bodies such as the Intergovernmental Panel on Climate Change. The clear connections between fundamental chemical alterations that are occurring in the ocean now, and the associated impacts on marine life as revealed by observation and experimentation, forewarn of significant changes in marine ecosystems that may be inevitable.

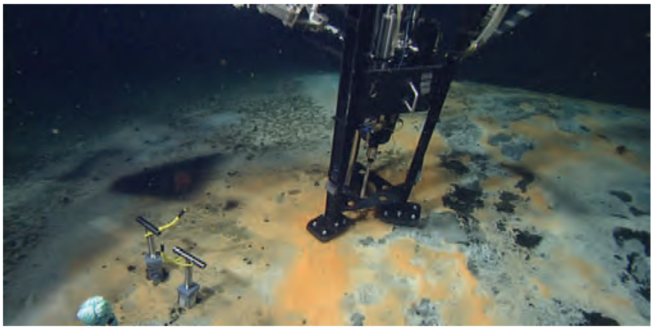


Figure 45: A probe is inserted into the seafloor to learn about the chemistry of the waters within the sediment underlying an orange bacterial mat at the summit of a methane hydrate mound in the Santa Monica basin.

Revisiting an old ocean dumping ground

Usually MBARI scientists study natural phenomena in the ocean, but their tools and techniques can also be used to identify and address human impacts and hazards. For example, after World Wars I and II, and through much of the Cold War, ocean dumping of chemical weapons was a fairly common practice. Large quantities of chemical munitions were disposed of in the waters off Japan, and in the Baltic and Adriatic Seas. Today these sites are still not well known, surveyed, or recorded on nautical charts.

In the United States between 1946 and 1974, the Navy recorded more than 300 instances of moving weapons to ocean disposal sites. Ocean dumping effectively ceased in 1972 with the establishment of the London Convention, but this agreement established no monitoring, mapping, or reporting requirements. Many records relating to the disposal of chemical munitions in U.S. waters are now missing or lost.

Recent navigational charts of the West Coast of the U.S. show seven locations off the coast of California labeled as "Chemical Munitions Dumping Area, Disused" that together cover some 12,000 square kilometers of seafloor. However only one such chemical munitions site is officially documented and no record exists for any chemical munitions being disposed of at other locations, thus creating confusion and uncertainty about potential risks to fishing trawlers working in these areas. Fishermen in several countries have been inadvertently exposed to chemical munitions when barrels or shells become entangled with their gear and brought onto the deck of their ship.

The ocean area directly to the west of Monterey Bay appears to be well populated with alleged "chemical munitions disposal sites" (Figure 46). Records show that a Liberty Ship and a barge containing large quantities of chemical munitions were disposed of in 1958 in the large box at upper left of this image. No chemical munitions records exist for the other sites, although some radioactive and chemical waste material records have survived. Consequently, the confusion of what lies on the seafloor appears to be a result of poor record keeping as well as miscommunication since the wording on navigational charts is generic and has changed over time.

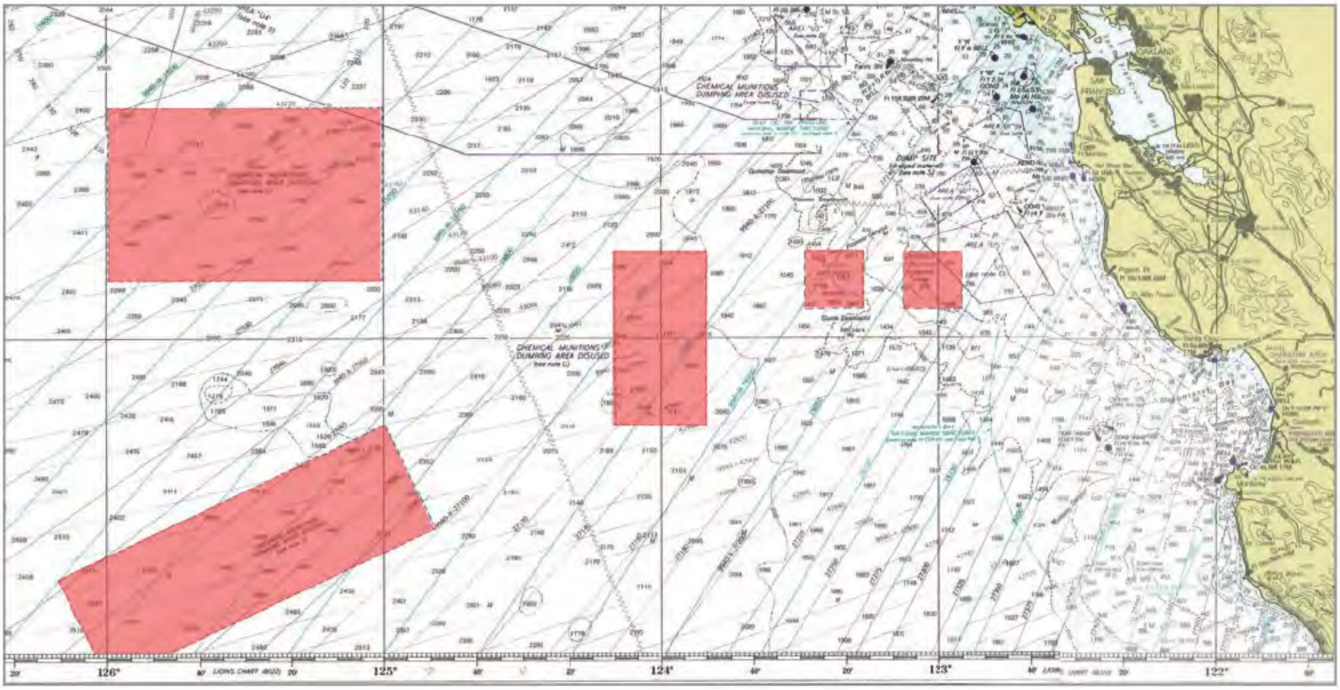


Figure 46: Pink rectangles on this navigation chart indicate areas designated as munitions dump sites off the coast of San Francisco and Monterey Bay.

In March 2013 Peter Brewer and his team used the MBARI mapping AUV to survey a corner of the designated chemical munitions dump site in the Santa Cruz Basin in Southern California. MBARI's newly established AUV survey techniques make it is possible to efficiently and precisely survey large swaths of seafloor. The AUV's sidescan sonar was used to image the debris field in preparation for inspection of targets using an ROV. The region is covered with soft sediment and the overlying water is very low in oxygen. The surveys revealed some 754 objects inside and outside the designated boundaries of the dump site. Subsequent ROV dives to investigate the targets identified items ranging from empty steel barrels to miscellaneous debris (Figure 47). There was no obvious evidence of chemical weapons material. Almost all of the targets were covered in dense and colorful assemblages of invertebrates: sponges, anemones, and crabs. Where barrels were sufficiently open for full visual inspection, the interior surfaces appeared to have become fully anoxic and were covered in white and yellow bacterial mat.

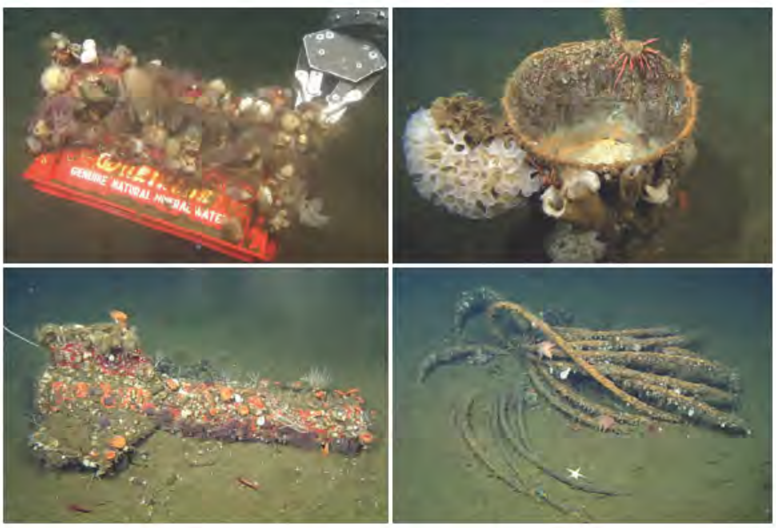


Figure 47: Debris found in the designated munitions dump areas included, clockwise from top left, an old package of bottled mineral water, a now-empty steel barrel, rope, and a target drone.

In addition to the anthropogenic debris, the team found that one of the targets identified in the AUV survey was a large, intact skeleton of a whale. Brewer noted this location so that colleague Bob Vrijenhoek's group could revisit the site during the next leg of the expedition (see sidebar).

According to Brewer, it is time to redraw the lines—errors in designating large areas as "chemical munitions sites" should be addressed and the naming revised. The material observed at this site appeared to be unpleasant—rusted barrels—but not acutely harmful. No direct evidence of munitions, chemical or conventional, was found.

Toward predicting harmful algal blooms

The photosynthetic activity of microscopic algae in the ocean produces living matter and oxygen that support much of life on Earth. However, not all algal blooms are beneficial; some are detrimental to humans and wildlife. Such outbreaks are known as harmful algal blooms (HABs). Some HABs give rise to toxic substances or irritants that enter the food web, the seafood supply, or the air we breathe, while others can lead to depletion of oxygen in seawater as bacteria degrade a dying bloom. HABs pose significant threats to fisheries, aquaculture, human health, recreation, tourism, and the economic vitality of coastal communities worldwide.

The global occurrence of HABs is increasing, thus motivating research programs to understand the nature and causes of these events as one step toward predicting and mitigating their impacts. Researchers are closely examining two regions along the California coast that are known

Unexpected finds

Molecular Ecologist Robert Vrijenhoek and his group took advantage of serendipitous discoveries of a sunken whale carcass and hydrocarbon seeps found during Peter Brewer's expedition south of the Santa Cruz Basin. The whale carcass hosted a chemosynthetic clam species that is new to science. Other organisms collected from the seeps provide the first genetic evidence of direct connections between populations of animals inhabiting hydrocarbon seeps in the Gulf of California and Monterey Bay. By connecting the dots between the Gulf of California and the Oregon-Washington margin, the Southern California discoveries enable genetic studies of historical population size and dispersal among chemosynthetic communities along the western American margin.

A depression found in the Santa Monica Basin corresponds with a known seafloor fracture zone in this area. Further exploration of this cleft with MBARI's ROV revealed a nearly vertical wall (Figure 48) with exposed layers of sediments alternately containing fossilized snails, clams, and serpulid worms (Figure 49). Vrijenhoek hypothesizes that these alternating communities were buried by sediment cascading from higher ground. Determining the timing of these events can provide a more detailed picture of seismic activities in this unstable region during the past 10,000 years—something of great interest to geologists as well as policy makers. Such unexpected finds illustrate how fundamental research and development activities often yield unanticipated discoveries of immense value.

Figure 48: Photomosaic of "Fossil Cleft" on the Santa Monica Mound. The cleft exposed alternating layers of sediments containing serpulid tubeworms and vesicomyid clams. The ages of these layers have yet to be determined. Living *Ectenagena elongata* clams occupying the surface rely on hydrogen sulfide emissions to feed their endosymbiotic bacteria.

Figure 49: Fossil community from the Santa Monica Mound. A diverse collection of invertebrates typically associated with chemosynthesis includes paired tubes from serpulid worms, snails, vesicomyid clams, and various limpets. The ages of these fossils are under investigation.

Figure 50: Focal harmful algal bloom study regions along the California coast. Right, the tiny diatom *Pseudo-nitzschia australis*, which produces a toxin that is harmful to marine life and humans. Scale bar is 20 micrometers.

HAB "hotspots", Monterey Bay and San Pedro Bay (Figure 50), with the aim of uncovering the conditions that lead to HAB outbreaks. This collaborative project is funded by the National Oceanic and Atmospheric Administration (NOAA) and includes researchers from NOAA, NASA, the University of Southern California, Moss Landing Marine Laboratories, the University of California at Santa Cruz, and MBARI.

During 2013, the team mounted field experiments in San Pedro Bay in the spring and in Monterey Bay in the fall. In each case, MBARI contributed a scientific, technological, and operational framework that enabled effective observation of HAB populations and the ecological processes driving their variability. To establish sustained observing presence specifically targeting HAB species and toxins, MBARI deployed two Environmental Sample Processors (ESPs) on moorings in each bay. Real-time analysis of environmental data by the ESPs was used to trigger sample collection when conditions indicated that a feature of interest was present, such as a bloom patch or changing ocean conditions. The detection of HAB species at these points (Figure 51) illustrates the environmental variability that often accompanies the emergence of particular species.

MBARI deployed two long-range AUVs to provide a larger, integrated ocean observing system that could reveal the relationships between changes in the environment and increased abundance of toxin-producing algae. These vehicles allow for extended observations and high-resolution sensing in space and time, permitting detailed examination of the variable environment within which the ESPs were operating (Figure 52).

The research vessel *Rachel Carson* added another dimension to this study by serving as a collaborative hub. Carrying scientists and engineers, the ship supported extensive sampling, onboard experiments, deployments of drifters that define ocean circulation patterns, and operation of the *Dorado* AUV (Figure 53). The *Dorado's* gulper water-sampling system, and adaptive sampling algorithms, were used to surgically sample bloom patches (Figure 52). The samples then underwent microscopic and molecular examination to reveal the composition and variability of the microalgal community overall, and the HAB community within it.

Collaborators contributed additional ships, gliders, and moorings for these studies. The extensive participation of researchers and their observing tools is a hallmark of this project, but it also leads to a torrential flow of information as the field work unfolds. Coordinating the various sensors and platforms, and making the data available and managing them during and after intensive field campaigns is challenging. To address this problem, MBARI engineers devised the Oceanographic Decision Support System (ODSS) and the Spatial Temporal Oceanographic Query System (STOQS) (Figure 54). These web-based tools allow all project participants, whether at sea or onshore, to participate in the experiment and get the most out of the instruments at their disposal. These kinds of technological advancements will continue. For example, the next generation of ESP will place molecular detection capabilities into the hull of the long-range AUV, greatly expanding capabilities for autonomous exploration and interrogation of microscopic life in the complex ocean environment (see page 43). Continuing development of ODSS and STOQS will direct information flow into effective experimental decision-making and collaborative research, carrying data from origination to dissemination.

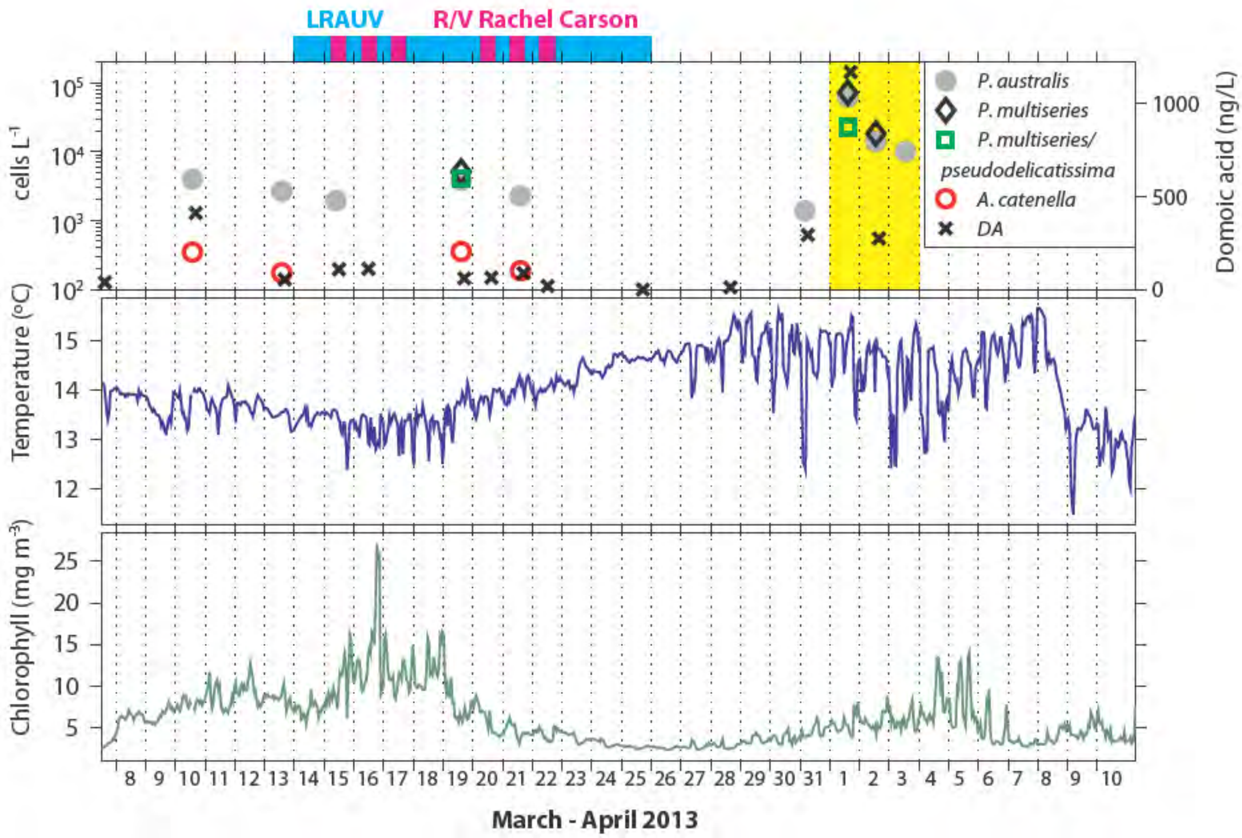


Figure 51: Harmful algal bloom (HAB) species and toxin relative to environmental variability; all observations were collocated on an Environmental Sample Processor (ESP) in San Pedro Bay during spring 2013. DA represents the toxin domoic acid, which causes amnesic shellfish poisoning and marine life mortality. The period highlighted in yellow identifies increased HAB and toxin signals associated with a moderate environmental change (cooling trend) and increase in chlorophyll concentrations. During the periods indicated at the top, the long-range AUVs *Tethys* and *Daphne* provided continuous high-resolution observations of the environment around the ESPs, and the R/V *Rachel Carson* conducted a series of day cruises.

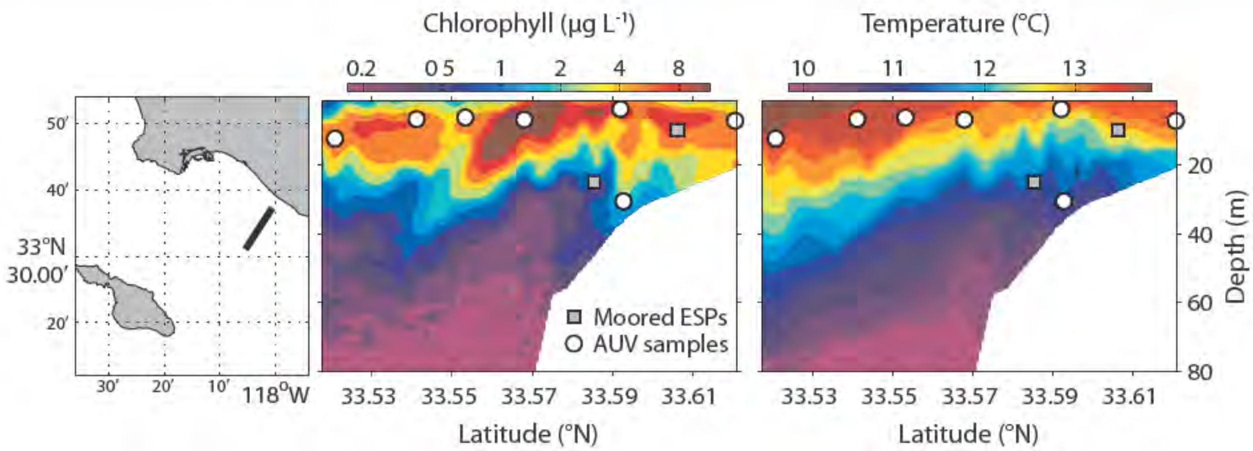


Figure 52: Vertical sections of temperature and chlorophyll concentrations (representing algal abundance) across the San Pedro shelf and adjacent channel, from the *Dorado* AUV, 17 March 2013. The location of the section is shown in the map at left. White circles show where *Dorado* autonomously triggered water-sample acquisition. Gray squares mark the locations of the moored ESPs.

Figure 53: Working from the deck of the research vessel *Rachel Carson*, Senior Research Specialist John Ryan launches a drifter to study the circulation in San Pedro Bay. The drifter's surface float, which has a GPS that sends its geographic position to shore, is attached to a subsurface drogue that drifts with the ocean currents.

Continental Margins and Submarine Canyon Processes

Project lead: Charles Paull

Project manager: Roberto Gwiazda

Project team: Krystle Anderson, David Caress, Dale Graves, Eve Lundsten, Esther Sumner, Hans Thomas

Collaborators: Phil Barnes, National Institute of Water and Atmospheric Research, New Zealand; Scott Dallimore and Michael Riedel, Geological Survey of Canada, British Columbia; Brian Edwards, Tom Lorenson, Mary McGann, and Jingping Xu, U.S. Geological Survey, Menlo Park, California; Juan Carlos Herguera, Center for Scientific Research and Higher Education at Ensenada, Baja California, Mexico; Char-Shine Liu, National Taiwan University; Dan Parsons, University of Hull, United Kingdom; Peter Talling, National Oceanography Centre, Southampton, United Kingdom

Seafloor Mapping and MB-System

Project lead/manager: David Caress

Project team: Krystle Anderson, David Clague, Doug Conlin, Eve Lundsten, Eric Martin, Julie Martin, Jenny Paduan, Charles Paull, Hans Thomas, Duane Thompson

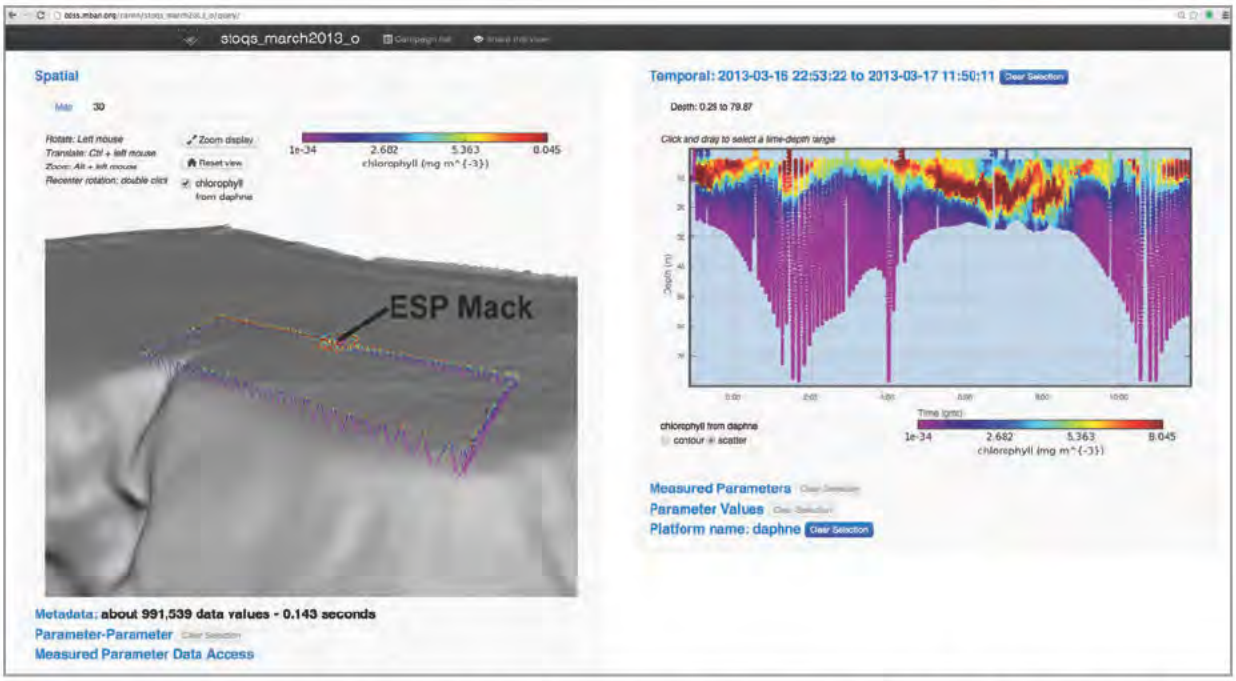


Figure 54: Visualization and analysis of the large data sets from this experiment in the ODSS/STOQs interface. Here, a three-dimensional view of chlorophyll concentrations described by a long-range AUV survey that passed by both ESPs deployed in San Pedro Bay. The AUV also conducted high-resolution cylindrical mapping around one of the ESPs.

Collaborators: Dale Chayes, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York; Christian Ferreira, University of Bremen, Germany

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: David Caress, François Cazenave, Linda Kuhnz, Julie Martin
Collaborators: Juan Carlos Braga, University of Granada, Granada, Spain; Paterno Castillo and Edward Winterer, Scripps Institution of Oceanography, La Jolla, California; Brian Cousens, Carleton University, Ottawa, Canada; Brian Dreyer, James Gill, and Don Potts, University of California, Santa Cruz; Fred Frey, Massachusetts Institute of Technology, Cambridge; Paul Fullagar, University of North Carolina, Chapel Hill; 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; Tom Guilderson, Lawrence Livermore National Laboratory, Livermore, California; James Hein and Mary McGann, 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; Shichun Huang, Harvard University, Cambridge, Massachusetts; John Jamieson and Tom Kwasnitschka, GEOMAR, Kiel, Germany; Christopher Kelley and John Smith, University of Hawaii, Honolulu; Deborah Kelley, University of Washington, Seattle; Anthony Koppers, Oregon State University, Corvallis; Craig McClain, University of North Carolina, Durham; Michael Perfit, University of Florida, Gainesville; Ryan Portner, Brown University, Providence; Willem Renema, Leiden University, The Netherlands; David Sherrod, U.S. Geological Survey, Vancouver, Washington; John Stix, McGill University, Montreal, Canada; Dorsey Wanless, Woods Hole Oceanographic Institution, Woods Hole, Massachusetts; Jody Webster, University of Sydney, Australia; Guangping Xu, Colorado State University, Fort Collins

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter G. Brewer, William Kirkwood
Project manager: Edward T. Peltzer
Project team: David Caress, Hans Thomas, Peter Walz
Collaborators: Colin Ingram, Andor Technology, Belfast, Northern Ireland; Samantha Joye, University of Georgia, Athens; Victoria Orphan, California Institute of Technology, Pasadena

Molecular Ecology and Evolution of Marine and Aquatic Organisms

Project lead: Robert C. Vrijenhoek
Project manager: Shannon Johnson
Project team: Julio Harvey, Mike McCann, John Ryan, Kristine Walz, Haibin Zhang, Yanwu Zhang
Collaborators: Asta Audzijonyte, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; David Clague, Danelle Cline, and Charles Paull, MBARI; Jennifer Fisher and William Peterson, Northwest Fisheries Science Center, Newport, Oregon; Shana Goffredi, Occidental College, Los Angeles, California; 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; Steven Morgan, University of California, Davis; Karen Osborn, Smithsonian Institution, Washington, D.C.; Heiko Sahling, University of Bremen, Germany; Tom Schultz and Cindy Van Dover, Duke Marine Laboratory, Beaufort, North Carolina; Verena Tunnicliffe, University of Victoria, Canada; Anders Warén, Swedish National Museum, Stockholm; Yong-Jin Won, Ewha Womans University, Seoul, South Korea; Brock Woodson, University of Georgia, Athens

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

Project leads: James Birch, John Ryan, Chris Scholin
Project manager: John Ryan
Project team: Nilo Alvarado, James Bellingham, Holly Bowers, Francisco Chavez, Elif Demir-Hilton, Brett Hobson, Scott Jensen, Brian Kieft, Denis Klimov, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, Jordan Stanway, Yanwu Zhang
Collaborators: David Caron and Burt Jones, University of Southern California, Los Angeles; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Meredith Howard, Southern California Coastal Water Research Project, Costa Mesa; Raphael Kudela, University of California, Santa Cruz; G. Jason Smith, Moss Landing Marine Laboratories, California

Weird and Wonderful

Media reports on ocean ecosystems are dominated by gloom and doom stories of declining ocean health, so stories that tell of the vibrancy and adaptations of marine animals could not be more welcome.

Anchovies attract spectacle of seabirds and mammals

In the late summer and early fall of 2013, Monterey Bay was invaded by an unusually large number of humpback whales. Some 300 animals frolicked, foraged, and put on spectacular displays. From their offices facing the sea in Moss Landing, MBARI employees and visitors witnessed these activities firsthand for days on end. Soon it became clear that the whales had been attracted to the bay by large populations of one of their favorite foods—anchovies. In fact, a multitude of other anchovy predators—from seabirds to sea lions and elephant seals—were benefiting as well.

It has been long known that small pelagic fish like anchovies and sardines have gone through boom and bust periods in California. The upwelling process off the coast of California, in which deeper nutrient-rich water is brought to the surface, enhancing phytoplankton growth, creates optimal conditions for the growth of small pelagic fish. This abundance of small fish feeds a wide diversity of larger predators, and can account for over 20 percent of the annual global fish catch even though that bounty occupies less than one percent of total ocean area. The small pelagic fish depend on upwelling for their nutrition—an infusion of nutrients brought by winds and the Earth's rotation that fuels an explosive growth of phytoplankton. When upwelling is strong, the algae and the fish that feed on them are spread out over large areas, but when upwelling is weak, they are concentrated next to the coast. When the small fish are concentrated, their predators can more easily harvest the food they need for growth and survival, and people can more easily witness the feeding frenzy from shore.

Figure 55: Whales were a common sight in Monterey Bay during field operations in the summer and fall, such as the launch of the long-range AUV, in the foreground.

The anchovies showed up with a bang in Monterey Bay during summer of 2013. The sea surface temperature and primary productivity in Monterey Bay were near average. However, a persistent high-pressure system in the atmosphere took hold from summer into winter. The location of the high-pressure system resulted in a continuous but weak upwelling pattern, ideal for concentrating phytoplankton and small pelagic fish close to shore. The concentration of fish attracted every predator up the food chain—sea birds, sea lions, and whales. The display also created a tourist boom as people came to see this natural wonder.

A case of mistaken identity

MBARI engineers were using tracking software to monitor the path of the long-range autonomous underwater vehicle (LRAUV) last fall, when the vehicle seemed to veer a bit off course. The team thought maybe it had become briefly entangled in kelp. When the vehicle was recovered after two weeks at sea, the team found large scrapes on its side, suggesting that perhaps the vehicle had come in contact with a boat propeller. But then they found the telltale evidence—several large shark teeth were embedded in the side of the vehicle. Instrumentation Technician Thomas Hoover measured the width of the bite marks on the vehicle, which were probably created by a 12- to 15-foot-long white shark. The aluminum shell and carbon-fiber fairing of the vehicle were badly gouged, but the vehicle completed its mission, running several more days after the attack—a testament to the design skills of MBARI's engineers.

Figure 56: Thomas Hoover indicates the width of the bite marks on the LRAUV (top). Center, Jim Bellingham, lead of the LRAUV team, holds one of the shark's teeth that was embedded in the LRAUV. Bottom, a close-up of a shark tooth pulled from the vehicle's outer shell. White sharks have rows of serrated teeth behind their main set, ready to replace any that break off.

A fatal encounter in the deep

This remarkable image acquired using MBARI's ROV *Doc Ricketts* reveals a struggle for survival never before seen by human observers. Owlfish, which are about 16 centimeters long, typically drift slowly in the darkness, waiting for a dim shadow or a flash of bioluminescence to reveal their prey. In contrast, the black-eyed squid, *Gonatus onyx*, is an active predator, searching through the midwater for fishes or shrimps to capture. When a squid finds a target, it shoots out its two long feeding tentacles, each tipped with suckers and claw-like hooks to snag the prey. Then it reels in the fish and envelopes it with its eight arms, using its sharp beak to sever the fish's spinal cord. The owlfish has a very quick escape response and with a flick of its tail it can dart out of the reach of a striking squid. The fish is also covered with large, shaggy scales that can easily be shed. When a squid's tentacles hit, the fish shrugs off two or three big scales at the point of contact and speeds off into the darkness. But if the squid is quick enough and its aim is true, it has a chance to kill and eat the fish. In this case the squid captured the owlfish and successfully carved its beak through the muscles surrounding the fish's backbone. A video of this deep-sea encounter was posted on the MBARI YouTube channel, garnering a million viewers in just a few weeks, showing the potential to engage the public in deep-sea research and highlight the importance of the oceans in sustaining the habitability of our planet.

Figure 57: A deep-sea squid tackles its prey, an owlfish.

Rock on the move

As the ROV traversed slowly over a stark muddy seafloor almost 200 meters deep, researchers noted occasional rocks covered in sponges and bryozoans—animals that settle on hard surfaces. Sudden movement caught their eyes as one of the rocks appeared to be walking. It turned out to be an extreme example of what many "masking" or "decorator" crabs do. With plenty of fishes and octopus around to prey on them, this type of camouflage can be very effective. Short, stiff hairs cover the outer shell creating a sort of "Velcro-like" surface. The crab actively attaches sessile animals to itself in an effort to appear as cryptic as possible. Another advantage is that the attached bryozoans may secrete a chemical that repels predators. The attached animals benefit in this relationship as well, as they are provided a much-needed habitat. Unlike most other crabs, this one does not molt continually once it reaches adulthood, which means it does not have to start over again with new camouflage every few months. MBARI scientists think this is the species *Loxorhynchus crispatus*, but they can't see enough of the crab to verify the identification

Figure 58: Decorator crab, whose carapace is about 10 centimeters long, practices an extreme form of camouflage by attaching animals to its back to hide from predators.

On the Horizon

The coming year will bring a prestigious ocean technology competition to MBARI, while in-house efforts will include significant enhancements to AUV capabilities. Major expeditions will also provide several scientists with opportunities to revisit sites of recent discoveries and experiments.

Distant field missions in 2014

In 2014, both the R/V *Western Flyer* and R/V *Rachel Carson* will travel to the north and south carrying MBARI's remotely operated vehicles (ROVs) and autonomous underwater vehicles (AUVs) to areas of significant interest to MBARI researchers (Figure 59).

Southern California

MBARI's multidisciplinary team, will again venture to Southern California to reiterate the successful harmful algal bloom experiment of 2013 (see page 33.) The R/V *Rachel Carson*, as well as multiple vehicles and diverse sensors, will be deployed off Los Angeles to answer targeted questions about harmful algal blooms and demonstrate another coordinated, collaborative field program. Molecular Ecologist Bob Vrijenhoek will examine and sample hydrocarbon seeps in the Santa Barbara Basin, Santa Monica Trough, and San Diego Trough during the R/V *Western Flyer* cruise. His research group is exploring the hypothesis that cold seeps and whale falls act as stepping stones for the dispersal of chemosynthetic animals along the California margin.

Using the R/V *Rachel Carson* and the mapping AUV, *D. Allan B.*, Chemist Peter Brewer will revisit the Santa Cruz Basin and continue his surveys to identify material in areas of alleged chemical munitions disposal near the Channel

Figure 59: Research topics at specific sites located to the north (left) and to the south (right) of Central California for planned MBARI investigations in 2014. Not pictured is the site in the Beaufort Sea in the Arctic, where Charlie Paull will return to study methane venting (see page 24).

Islands. After careful review of those AUV-based bathymetric maps, Brewer will return for a closer look with the ROV *Doc Ricketts* from the R/V *Western Flyer*.

Heading North

With a goal to map and sample all the historic lava flows on the Juan de Fuca and Gorda Ridges, Volcanologist Dave Clague will return to Axial Seamount and Gorda Ridge using the mapping AUV off the R/V *Rachel Carson*, followed by ROV sampling of key targets from the R/V *Western Flyer*. Chemist Peter Brewer will return to the Eel River Basin to delve further into his study of the behavior of oil and gas venting from the seafloor. Bob Vrijenhoek will take advantage of the R/V *Rachel Carson's* transit north to stop in Bodega Bay and use the AUV with gulper samplers to collect larvae of shallow-water invertebrates for his research on molecular ecology. Building on his 2013 work, Charlie Paull will return to the Arctic to study methane venting.

Automating video transects in the midwater

The Midwater Time Series program currently relies on ROVs to do quantitative video transects. Researchers are aiming to automate that process by modifying existing autonomous underwater vehicles. Such transects require the vehicle to move slowly enough such that each small animal can be seen on the video being recorded. Testing in 2013 proved that a *Dorado*-class AUV can be controlled at speeds as low as one knot with the addition of mid-body and duct-control planes (Figure 60). A survey of currently available video cameras revealed the potential to increase both image quality and frame rate of video capture, which offers the prospect of increasing the speed at which midwater time-series transects are conducted. This may result in more animal observations on the video, because animals might be less likely to avoid a stealthy AUV than the slower, more obtrusive ROVs. The team will complete camera and lighting design evaluations, and design, build, and field-test a new midwater AUV imaging module in 2014.

Towards the world's first mobile ecogenomic sensor

Molecular analytical techniques, like those used to detect and quantify sequences of DNA, are commonly used in the ocean sciences. These methods provide a powerful and sensitive means for identifying specific organisms and assessing their activities. However, such work generally requires returning samples to a sophisticated laboratory for specialized handling. Researchers envisioned "ecogenomic sensors" as devices that would automate many of these kinds of tests, allowing for direct use of molecular analyses in the ocean without any human intervention. When this idea first came forward, artist renderings showed moored devices embedded in a larger ocean observing system. Scientists and engineers at MBARI gave life to that notion through refinement and application of the first- and second-generation Environmental Sample Processor (ESP; see page 12). The ESP is a relatively large device (roughly the size of a 50-gallon drum) and is not easily fitted to small, mobile platforms, yet it has been successfully deployed in coastal, open-ocean, and deep-sea settings, validating the ecogenomic sensor concept.

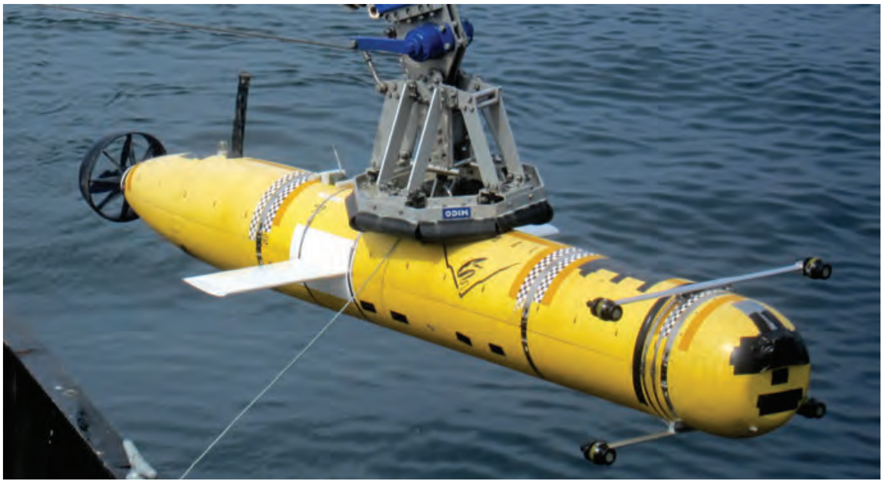


Figure 60. *Dorado* CTD AUV configured for low-speed stability testing. Additions to the standard AUV configuration in this image are four LED lights mounted on light bars on the bow and mid-body wings.

With support from the National Science Foundation and the Gordon and Betty Moore Foundation, MBARI is addressing these size limitations by devising a third-generation ESP specifically designed to fit in the long-range AUV (LRAUV). Development of this instrument presents a significant engineering challenge. Compared to its predecessor, the instrument must be reduced to about one tenth of its current size, made substantially lighter, allow for a greater variety of sample processing and analytical methodologies, and consume

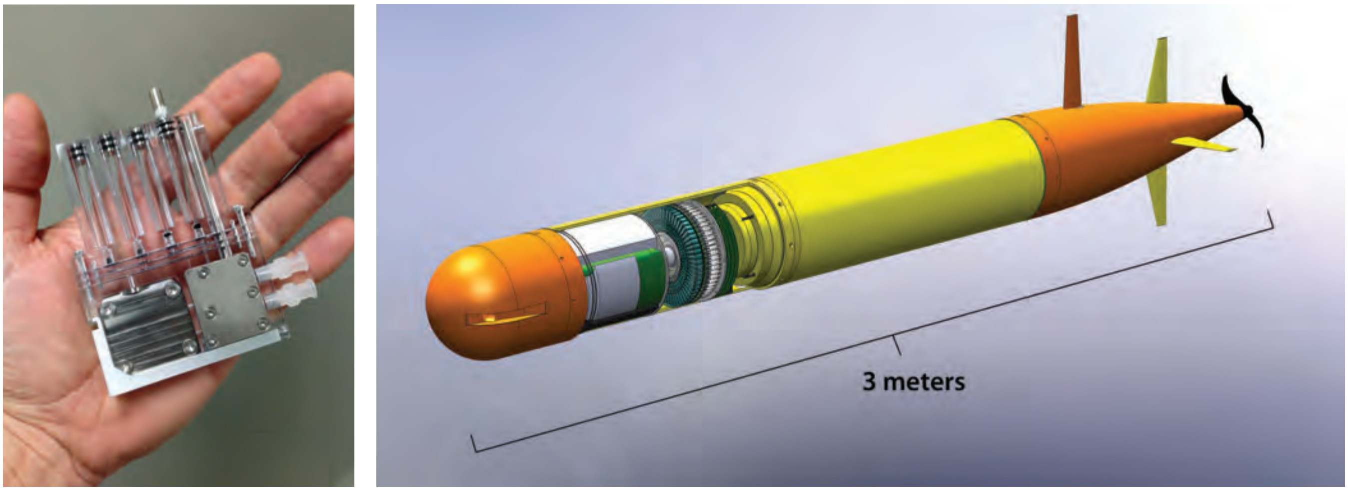


Figure 61: The third-generation ESP is designed around a single-use cartridge that contains filters for concentrating particles or dissolved substances, and the necessary reagents for processing that material for subsequent analysis (left). The cartridges fit onto a circular valve assembly that is fitted into a forward space of the LRAUV (right). The resulting vehicle will be nearly three meters in length, and will have the capacity to collect 60 samples while ranging freely in the ocean to 300 meters depth.

only a fraction of the power (Figure 61). When integrated with the LRAUV, researchers will be able to track features in the water column and selectively collect and analyze microbes while traveling over extended distances and periods of time. This first mobile ecogenomic sensor will be deployed in late 2014 in collaboration with partners at the University of Hawaii, Arizona State University, NOAA, and the University of Maine.

The XPRIZE competition is coming to MBARI

MBARI will serve as host to one stage of an international technology competition in 2014. The Wendy Schmidt Ocean Health XPRIZE offers a $2 million prize to the team that creates the best pH sensor technology that will affordably, accurately, and efficiently measure ocean chemistry from its shallowest waters to its deepest depths. Such technology is key to improving the understanding of how carbon dioxide emissions are affecting ocean acidification.

Founded in 1995, the non-profit XPRIZE organization aims to solve grand challenges by creating and managing large-scale, high-profile, incentivized prize competitions that stimulate investment in research and development worth far more than the prize itself. The organization motivates and inspires innovators from all disciplines to leverage their intellectual and financial capital for the benefit of humanity.

The Ocean Health competition will take place in several stages and at several locations throughout 2014. MBARI will host participants who will bring their pH sensors for evaluation under controlled laboratory conditions by an independent team appointed by the XPRIZE staff. The entire competition is sure to raise awareness of the potential threats ocean acidification may bring, and will help catalyze the development and production of new sensors that are needed to understand this global phenomenon.

Behind the Scenes: Building on Each Other's Strengths

The founding of MBARI 26 years ago was an outgrowth of the Monterey Bay Aquarium. From the beginning we have maintained a special connection with our sister institution and have worked together on various programs.

The two organizations have separate staff, budgets, and missions but both recognize the importance of ocean research and conservation. The aquarium's commitment to engage visitors through memorable exhibitions and programs and MBARI's goal of disseminating MBARI research to the public are complementary. This special partnership was reinvigorated in 2013 with a host of collaborative efforts.

Through its exhibits and programs, the aquarium has the opportunity to share MBARI's research with nearly two million visitors a year. The aquarium's website and social media channels provide additional distribution avenues for MBARI's stunning high-definition video to various audiences. In turn, MBARI's research and technology developments provide compelling content and reliable information for the aquarium.

The communications groups of both institutions work together on news releases, coordinate video production, and share images and interesting stories on their social media sites as well as on their own websites.

Husbandry research and development, leading to the successful display of species never seen in an aquarium before, are core aquarium goals. Developing groundbreaking live exhibits with compelling animals enriches the guest experience. The new *Tentacles* exhibit—focusing on fascinating cephalopod species—has been enhanced through the use of MBARI video and photographs. MBARI ship days were allocated to aquarium staff, providing access to the deep ocean for collecting unusual animals that contributed to the success of the exhibit. We have also joined together to sponsor a

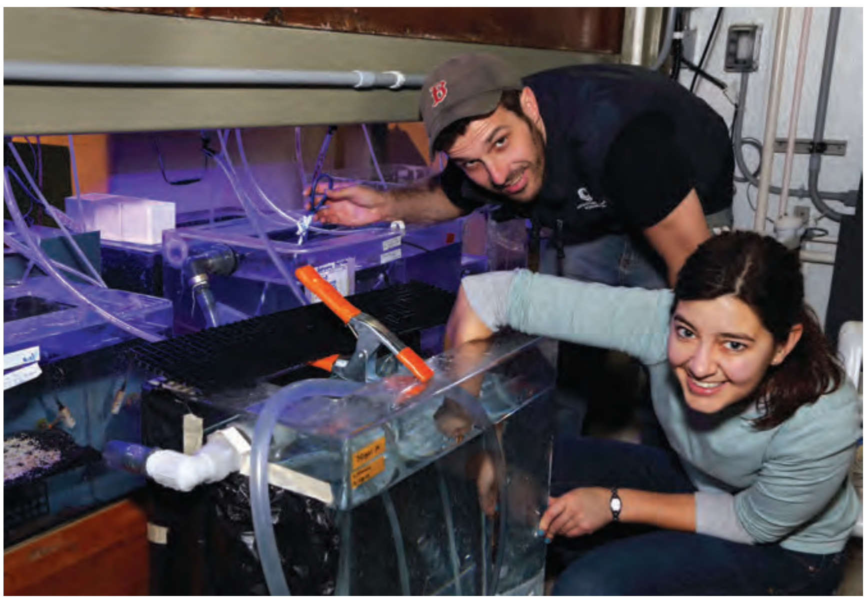


Figure 62: MBARI Postdoctoral Fellow Stephanie Bush and Monterey Bay Aquarium Aquarist Chris Payne, move recently hatched squid from one tank to another in preparation for the *Tentacles* exhibit.

Figure 63: The new *Tentacles* exhibit will include video of the football-sized *Vampyroteuthis infernalis*, left, and a *Chiroteuthis calyx*, similar to this one which is about 40 centimeters long. See page 7 for photo of an *Octopoteuthis*.

postdoctoral fellowship for a cephalopod expert who has been charged with collections, husbandry, and content review for this exciting exhibit (Figure 62).

Over the course of 2013, the aquarium team gathered several midwater cephalopods as part of this ongoing project. Of note, several *Octopoteuthis,* six *Vampyroteuthis,* and a few *Chiroteuthis* (Figure 63) have all been housed in either MBARI's cold room or in holding systems at the aquarium. These specimens have allowed the aquarium to begin tailoring husbandry techniques and infrastructure for a group of species that has never before been publicly displayed. In addition to the *Tentacles* exhibit, the aquarium has started work on an extensive revision of its exhibit highlighting MBARI research missions.

Since 1989, a microwave link has provided a live two-way feed between the aquarium and MBARI research vessels. This link is the nucleus for the aquarium's *Mysteries of the Deep* auditorium program which has been running twice a day for years. Research technicians in MBARI's video lab have been enthusiastic and instrumental in aquarium projects, including updating hundreds of image and information files on the *Mysteries of the Deep* software system, and hosting that program weekly (Figure 64). The auditorium program generates public interest in MBARI's work and mission by sharing content about MBARI research with thousands of aquarium visitors and provides a positive and innovative guest experience. MBARI has installed a similar software program into our Pacific Forum, as well as investing in a portable system, both of which have been very useful for outreach efforts.

Figure 64: Senior Research Technician Kyra Schlining shares her knowledge and experience with the audience at the aquarium's *Mysteries of the Deep* program.

MBARI staff also provided content to the aquarium's volunteer guide program with lectures and hands-on activities. For those dedicated guides who have contributed 3,000 volunteer hours, a personalized guided tour of MBARI is provided. We also work together on education programs, such as teacher training and the Watsonville Area Teens Conserving Habitats (WATCH) program, which gives local, underserved high school students an opportunity to conduct hands-on research. Several MBARI staff members have given many hours to mentor these budding scientists (Figure 65).

In 2013, cameras that bring deep-sea images back to shore generated great interest from the aquarium staff and visitors. One MBARI camera is on the Monterey Accelerated Research System (MARS) cabled observatory at a depth of 900 meters, sending back video of animals that congregate on the seafloor. The other camera project was a collab-

Figure 65: Senior Research Technician Chris Lovera serves as a mentor to several Pajaro Valley High School students as they learn about environmental research. Here, Lovera and high school junior Marcos Perez check a crab trap.

Aquarium-MBARI Projects (AMP)

Project leads: Sue Lisin, George Matsumoto
Project manager: George Matsumoto
Project team: Nancy Barr, Stephanie Bush, Judith Connor, Craig Dawe, Kim Fulton-Bennett, Jared Figurski, Eric Fitzgerald, Kevin Gomes, Dale Graves, Hendrik Jan Ties Hoving, Christine Huffard, Linda Kuhnz, Lonny Lundsten, Thom Maughan, Craig Okuda, Bruce Robison, Kyra Schlining, Nancy Jacobsen Stout, Susan von Thun
Monterey Bay Aquarium team: Hank Armstrong, Rita Bell, Alicia Bitondo, Lisa Borok, Christy Chamberlain, Mike Chamberlain, Paul Clarkson, Jim Covell, Jeff Doyle, Andrew Fischer, Randy Hamilton, Humberto Kam, Tommy Knowles, Koen Liem, Kenneth Maguire, Andrea McCann, Enrique Melgoza, Eric Nardone, Raul Nava, Chris Payne, George Peterson, Ken Peterson, Sonya Sankaran, Margaret Spring, Scott Stratton, Kim Swan, Jaci Tomulonis, Cynthia Vernon, Patrick Webster, Mary Whaley

Figure 66: The first functional prototype of the "SharkCafeCam", includes the video camera, battery with solar-energy harvesting, depth sensor, accelerometer, magnetometer, and temperature and light sensors.

orative effort between the aquarium and MBARI staff to develop small, robust video cameras (Figure 66) to attach to great white sharks for a glimpse of shark activities in the mid-Pacific where they are known to congregate. The collaborators are planning to fasten a camera to the back of a great white shark, wait several months, then use a novel animal-behavior-detection algorithm to trigger eight hours of camera-recording. The video will be retrieved from the tags when they pop off later in the year after the white sharks have migrated back to the coast of California.

The synergistic relationship between these two complementary institutions benefits research, aquarium attendance, and general public awareness and understanding of ocean issues, and further promotes the care and conservation of ocean resources.

Project Summaries

Augmented Reality Applications

Project leads: Douglas Au, Kevin Gomes, Tom O'Reilly
Project manager: Douglas Au

Several augmented reality technologies were investigated. These applications superimpose computer-generated imagery transparently on top of the real world in real time, and could enhance ship-board operations during field work. A wearable head-mounted display was obtained and tested. A gesture-based user-input system was obtained and tested.

This wearable heads-up display was tested for augmented reality applications.

Autonomous Underwater Vehicle (AUV) Infrastructure Support

Project leads: David Caress, John Ryan
Project manager: John Ryan
Project team: Mike McCann
Collaborators: Danelle Cline and Thom Maughan, MBARI

Improvements and upgrades were made to the mapping AUV data systems. Development of the Spatial Temporal Oceanographic Query System (STOQS) enabled effective integration of AUV data with a variety of data from other platforms, all managed using an intuitive graphical interface. Standard processing of large data sets from long-range AUVs was established for analysis in STOQS. Methods were developed for more effective and rapid processing of holographic image data acquired onboard the *Dorado* AUV.

Central and Northern California Ocean Observing System (CeNCOOS)

Project lead/manager: Leslie Rosenfeld
Project team: Fred Bahr, Aric Bickel, Francisco Chavez, Jennifer Patterson, Janine Scianna, Chris Wahl
Collaborators: 18 principal investigators from 14 institutions

CeNCOOS data processing, and data, product, and web services, were ported from a single computer at MBARI to an in-house virtual server, allowing for expandability and reduction in downtime. A new webpage (http://www.cencoos.org/sections/conditions/shore/)provides access to ocean data from all CeNCOOS-supported shore stations. The CeNCOOS team initiated a revamp of its website using a content management system to provide a better user experience and to allow for easier upkeep. Significant progress was made in implementing the revised CeNCOOS data management and communication strategy which centers on an integrated online data portal, which incorporates both point source data (from shore stations and moorings) and gridded data (from models and satellite imagery). The team also developed an ocean-acidification payload for the Wave Glider, conducted near-continuous Spray glider measurements of temperature, salinity, fluorescence, currents, and acoustic backscatter from the surface, adopted vision and mission statements, and made significant progress toward a new strategic plan.

Controlled, Agile, and Novel Observing Network (CANON)

Project leads: James G. Bellingham, Francisco Chavez, Chris Scholin, Ken Smith, Alexandra Z. Worden
Project manager: Francisco Chavez
Project team: Larry Bird, Danelle Cline, Duane Edgington, Kevin Gomes, Thom Maughan, Mike McCann, Monique Messié, Reiko Michisaki, Chris Wahl

The CANON project continued the development of systems that can elucidate important processes in the ocean at a resolution needed for predictions of how ecosystems will vary in the future. The focal areas have been in the integration and deployment of autonomous systems, such as the long-range AUV and the Environmental Sample Processor, and the intelligent collection of discrete samples. This effort has been supported by an Oceanographic Decision Support System (ODSS) and associated data-analysis package (STOQS). These developments were exercised in two field campaigns, one in Southern California to study the ecology of harmful algal blooms (see page 33) and a larger, second multiple-vehicle experiment in the fall off the Central California coast.

Core Conductivity-Temperature-Depth (CTD) Data

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

Support continued on the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. Development on the user interface for real-time ROV data display continued with several improvements. Validation work has indicated that the best way forward may include dual dissolved-oxygen sensors rather than a combination of optode and sensor.

Core Mooring Data

Project lead: John Ryan
Project manager: Mike McCann
Project team: Fred Bahr, Francisco Chavez, Rich Schramm

The mooring data directory structure, in place since 1988, was revamped with a new file system layout. The new layout aligns with the institute's policy of managing file permissions at the top level of each file-system share.

Core Navigation

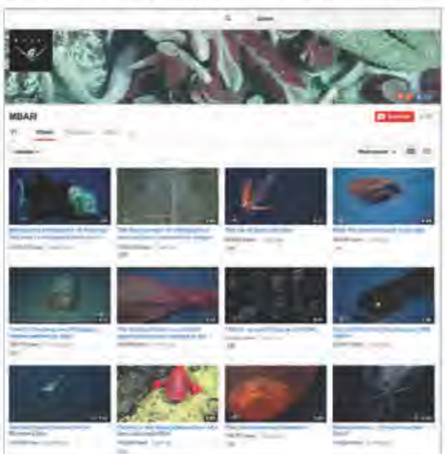
Project lead/manager: David Caress
Project team: Knute Brekke, Mike Burczynski, Ben Erwin, Linda Kuhnz, Eric Martin, Mike McCann, D.J. Osborne, Randy Prickett, Bryan Schaefer, Rich Schramm, Mark Talkovic

Efforts in 2013 included the operation and maintenance of ROV and ship navigation hardware, maintenance and development of software for automated processing and archiving of ship and ROV navigation, editing of ROV navigation data, and monitoring of data quality. Processing and archiving kept up with navigation data collection and integration into the Video Annotation and Reference System database.

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 2013, video lab staff annotated over 600 hours of ROV video, bringing the current number of individual observations to over 4.3 million. The system was updated with new high-definition frame-capturing code that replaces obsolete components and provides a flexible framework for incorporating new images and video streams from a variety of observation platforms, such as AUVs, flyaway ROVs, the Benthic Rover, and time-lapse cameras. Significant improvements were implemented for the Deep-Sea Guide, a companion web application, including enhancements to the program's infrastructure as well as the quality of visual images and supplementary data.



The MBARI video lab team maintains our popular YouTube channel, where highlights and results from the institute's research and development projects are illustrated using visually compelling images from our extensive video archives.

Cytometer Technology for Autonomous Platforms

Project leads: James G. Bellingham, Denis Klimov, Tom O'Reilly
Project manager: Tom O'Reilly
Project team: Francisco Chavez, Alexandra Z. Worden

Diversity and interactions among marine microbial populations are key to the geochemical cycles that maintain Earth's biosphere, and of great interest to MBARI scientists. This feasibility study is evaluating cell-characterization technologies that could be integrated with autonomous mobile platforms, potentially lowering costs and dramatically expanding the spatial and temporal range of these measurements. This study focuses on techniques that characterize individual cells. In 2013 the team concentrated on a literature search of available technologies, discussions with potential science users, instrument developers, and manufacturers. The team developed a matrix of existing oceanographic cytometers, their characteristics and capabilities, which will help to guide further investigation. The team met with experts to gain insight into cytometer design, capabilities, and integration issues. A commercial cytometer was integrated with the pumped profiler aboard the R/V *Rachel Carson* during the fall CANON cruise; data appear interesting and promising, and analysis is under way.

Development of a Coastal Profiling Float

Project leads: Ken Johnson, Gene Massion
Project manager: Gene Massion
Project team: Wayne Radochonski
Collaborators: Stephen Riser and Dana Swift, University of Washington, Seattle

The proof-of-concept prototype was tested in the MBARI test tank. The tank allowed for economical tests of the risky elements, primarily the buoyancy engine and control system, as part of a relatively complete, functional profiler designed only for shallow water use in the test tank. This testing went well, leading to the preliminary design for the seagoing coastal profiling float based on the lessons learned from the prototype. A design review was followed by fabrication and lab testing.

The coastal profiling float is lowered into the MBARI test tank.

Education And Research: Testing Hypotheses (EARTH)

Project lead/manager: George Matsumoto
Project team: Kevin Gomes, John Ryan
Collaborators: Robert Bidigare, Barbara Bruno, Jim Foley, David Karl, and Shimi Rii, Center for Microbial Oceanography: Research and Education, Honolulu, Hawaii; Ann Close and Stephanie Schroeder, Center for Dark Energy Biosphere Investigations, Los Angeles, California

The 2013 EARTH teacher workshop was held on the island of Oahu, Hawaii. Lessons covered MBARI's multidisciplinary CANON project and the STOQS data management software. Teachers left with a data activity they could use in their classrooms. Two satellite workshops were hosted in Texas and Alabama by previous EARTH participants.

Teachers in Manteo, North Carolina, at a satellite session to learn about the EARTH program and its website from one of the educators who participated in a previous EARTH workshop.

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.

This project synthesizes MBARI high-resolution AUV mapping data, lava flow elements, isotopic compositions, 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 in 1993, and between 1982 and 1991), North Cleft (eruption in 1986), and Axial (eruptions in 1998 and 2011). At Axial Volcano lavas have switched back and forth from lower-temperature crystal-free lavas to higher-temperature crystal-rich lavas several times 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: Aric Bickel, Jennifer Patterson, Janine Scianna
Collaborators: Clarissa Anderson and Raphael Kudela, University of California, Santa Cruz

A system was completed to automatically ingest data from UCSC gliders, which were deployed during the September CANON experiment. Full-resolution data from the recovered gliders were also generated from this experiment. Progress was made toward implementing a statistical harmful algal bloom (HAB) model. A year's worth of satellite surface temperature and chlorophyll data were retrieved. Cloud-free images were created for use in generating forecasts of potential HAB events.

Integrated MBARI Time-Series Program

Project leads: Francisco Chavez, Bruce Robison, Ken Smith
Project manager: Ken Smith
Project team: Kevin Gomes, Brett Hobson, Alana Sherman

Data for three independent time-series projects are being collected at MBARI: the Monterey Bay Time-Series project, the Midwater Time-Series project, and the Pelagic-Benthic Coupling project. An integrated program is proposed to occupy two time-series stations in the future. One station will be representative of Monterey Bay in the vicinity of the M-1 mooring and the existing "Midwater #1" study site, while "Station M" will represent the offshore region of the California Current. Existing data sets from each of the time-series over 24 years are being merged. Sensors and platforms are being identified to carry out time-series measurements at both stations over the next five to 10 years in concert with projected MBARI technology.

Investigations of Imaging for Midwater Autonomous Platforms (i2MAP)

Project leads: Mark Chaffey, Kim Reisenbichler
Project manager: Kim Reisenbichler
Project team: François Cazenave, Dave French, Richard Henthorn, Hendrik Jan Ties Hoving, Eric Martin, Rob McEwen, Bruce Robison, Rob Sherlock, Hans Thomas, Todd Walsh

The team's efforts primarily focused on *Dorado* testing to determine if the AUV can maintain stability while operating at speeds as low as one knot, the speed at which ROV-based midwater transects are currently conducted. The goal is to determine if Midwater Time Series video transects can be automated and transferred from an ROV to AUV. The AUV was fitted with prototype LED light arms mounted on the bow and then tested at various speeds with and without mid-body wings and duct-mounted control planes (See page 42).

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 at MBARI needed to be migrated to supported foundations (new hardware or virtual machines, current operating systems, database engines, etc.) In 2013, the entire mooring data processing chain was moved from old HP-UX servers to more recent Linux machines and the data storage was moved to our new file storage appliance. In addition, our focus turned towards retiring SQL Server 2000 and upgrading MBARI's internal and external web servers, but software compatibility issues between the application software dependencies and the newest operating system platforms slowed efforts.

Long-Range AUV: Testing and Initial Operations

Project leads: James G. Bellingham, Brett Hobson
Project manager: Brett Hobson
Project team: François Cazenave, Mark Chaffey, Jon Erikson, Kevin Gomes, Thomas Hoover, Brian Kieft, Denis Klimov, Rob McEwen, Ed Mellinger, Craig Okuda, Yanwu Zhang

The LRAUV project transitioned to multi-LRAUV field programs, improving reliability, integrating new sensors, and beginning the build of four new vehicles. Engineering efforts were initially dominated by the challenges associated with coordinating two vehicles at sea. Using two vehicles, cumulative time at sea now is on the order of 6,000 hours, allowing the development of a statistical understanding of failures. Attention focused on improving the operator interface, addressing subsystem and control problems (battery management, thruster controller, radio antenna, vertical plan control, etc.), and integrating new sensors and communications systems. One of the new vehicles, *Makai*, is already advanced in construction, and will be operated by MBARI staff. Three more LRAUVs have been funded by the National Science Foundation, and will be operated by University of Hawaii.

LRAUV Verification Imager Feasibility Study

Project lead: James G. Bellingham
Project manager: Mark Chaffey
Project team: Brett Hobson

The installation of an inexpensive consumer camera on the *Tethys* long-range AUV has provided tantalizing images of the surrounding environment. These images form a data set that is not captured by other vehicle sensors. This project has been determining the feasibility of improving the AUV's ability to capture large quantities of images under all lighting conditions by designing an enhanced imaging system that leverages recent improvements in compact, high-resolution consumer cameras and high-efficiency LED lighting. Numerous cameras have been evaluated and four candidates have been selected for optical analysis and laboratory testing.

This image of *Chrysaora fuscescens* was taken with a consumer camera mounted on the *Tethys* long-range autonomous underwater vehicle.

MBARI External Website Upgrade

Project leads: Nancy Barr, Kevin Gomes
Project manager: Nancy Barr
Project team: Judith Connor, Kim Fulton-Bennett, Annette Gough, George Matsumoto, Reiko Michisaki, Todd Ruston, Nancy Jacobsen Stout

The discovery phase of the project was conducted with the assistance of a communications consulting firm. This included an audit of the existing MBARI website, a review of peer websites, defining audiences, setting requirements, and a review of suitable content management systems. This phase was completed with the delivery of a vision document outlining the path forward, including personas representing typical MBARI web visitors; recommendations for a content management system; and technical, content, and user-experience requirements for a revised MBARI website.

Mini ROV Upgrades

Project leads: Dale Graves, Charles Paull
Project manager: Alana Sherman
Project team: Larry Bird, Frank Flores, Chad Kecy, Tom Marion, Mike Parker
Collaborators: Scott Dallimore, Geological Survey of Canada, British Columbia

The mini ROV, a compact fly-away ROV capable of operating on ships of opportunity around the world was upgraded to include a five-function manipulator arm and additional serial ports for future instrumentation, and the construction of a dedicated control-room. Housing the control room in a 10-foot shipping container makes transport of the ROV system easier and allows the crew to begin operations quickly on a ship. In September 2013, the mini ROV returned to the Arctic for a second successful scientific expedition. During 12 days of science operations there, the vehicle completed 17 dives.

Monterey Bay Time Series

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

The Monterey Bay Time Series continued in 2013 with day cruises aboard the R/V *Rachael Carson*, three cruises along the California Cooperative Oceanic Fisheries Investigations (CalCOFI) Line 67, moorings, glider deployments, regional ecosystem modeling, and intense involvement in the Central California CANON campaign. Cool conditions observed in Monterey Bay for the past 15 years continued in 2013. An unusually large number of whales, reported at one point to be over 300, frolicked in the area in late summer and early fall (see page 38). The cool temperatures have also been associated with a decadal trend towards lower oxygen and higher carbon dioxide at depth. Time series of sea-air carbon dioxide at the M1 mooring, the longest running autonomous ocean chemistry time series of its kind, reflect a similar increasing decadal trend.

Mooring Maintenance

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

MBARI moorings have provided over 20 years of time-series observations and are considered as model systems for the network of coastal observatories planned for U.S. coastal waters. A number of MBARI scientists as well as researchers at other institutions use data from the moorings. The moorings also serve as platforms for specific scientific investigations and instrument development. The M1 mooring has been the platform for the development of the pCO_2 analyzer and for the Monterey Bay Time Series (see previous item). In 2013 in collaboration with the National Data Buoy Center, a redesigned mooring was deployed near the historic M2 site.

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; Patricia Matrai, Bigelow Laboratories for Ocean Sciences, East Boothbay, Maine; Donald Perovich, U.S. Army Corps of Engineers, Hanover, New Hampshire; Paul Shepson, Purdue University, West Lafayette, Indiana; William Simpson, University of Alaska, Fairbanks

The Arctic Ocean is expected to be impacted rapidly and dramatically by climate change. To monitor the remote ocean basin, MBARI developed a low-cost, high-precision system for measuring the partial pressure of carbon dioxide in the atmosphere and deployed it on buoys that are moored in sea ice. MBARI also developed the capability to add sensors (CO_2, pH, oxygen, fluorescence, temperature, and salinity) to measure seawater conditions under the ice. A total of 10 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 Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Katherine Dunlop, Rich Henthorn, Brett Hobson, Eric Martin, Hans Thomas
Collaborators: Giancarlo Troni, University of Michigan, Ann Arbor

Work progressed on the development of a low-altitude, high-resolution seafloor mapping capability combining multibeam sonar with stereo photographic imagery. Three ROV surveys were conducted in June in Monterey Canyon at sites likely to exhibit fine-scale change, and therefore of interest for repeat mapping. All three low-altitude surveys lie within the one-meter lateral-resolution bathymetry of a 2009 Mapping AUV survey. Two of the surveys were repeated on a December cruise, with the survey system augmented by a lidar laser scanner. These surveys reached the goal of bathymetry resolution of five centimeters and photo mosaics from stereo photography at a resolution of two millimeters. The initial lidar tests were so detailed that individual clams could be seen in the image.

Ocean Margin Ecosystems Group for Acidification Studies (OMEGAS)

Project lead/manager: Francisco Chavez
Project team: Alba Cobo-Viveros, Gernot Friederich, Jules Friederich, Monique Messié, Jeff Sevadjian, 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

The OMEGAS consortium uses multi-site field investigations along the U.S. west coast from Oregon to Santa Barbara and laboratory experiments to study the ecological, physiological, and evolutionary responses of sea urchins and mussels to variation in ocean acidification. MBARI provides pH sensors and advice on ocean chemistry as well as leading the oceanographic studies off Central California. Research to date 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. Mussels and urchins appear to have the capacity to acclimate to the different ocean acidity, although long-term adaption remains uncertain. A surprising discovery has been the strong role that biology plays in regulating ocean chemistry in the intertidal. The daytime consumption of carbon dioxide by photosynthesis and the associated nocturnal increase by respiration results in changes in pH that can be as large as, or greater than, that driven by physical processes such as upwelling.

Ocean Observatories Initiative Cyberinfrastructure (OOI-CI)

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

MBARI continued to participate in the design and construction of the sensing and acquisition, data management, and infrastructure subsystems of the Ocean Observatory Initiative, a National Science Foundation-funded observatory effort that covers a diversity of oceanic environments. In 2013, the MBARI team evaluated the concepts being put forward by the other OOI-CI developers and provided documentation, reports, source code, and design artifacts for technologies that were developed at MBARI. The team modified OOI software to use the Open Geospatial Consortium (OGC) PUCK protocol which enables automatic instrument integration, operation, and data processing within sensor networks. In an effort to mitigate risks, MBARI engineers prototyped workflows for interactive quality-control and developed software for applying calibration information to data collected by OOI's Integrated Observation Network. The MBARI team was involved in design revisions of the software framework, along with corresponding implementation and integration testing, including user interface testing. The group also remained involved in the Marine Metadata Interoperability project, which continued to receive endorsement in the oceanographic community for its support of ontologies and terms.

Network equipment for the NSF-funded Ocean Observatory Initiative.

Pelagic-Benthic Coupling and the Carbon Cycle

Project leads: Alana Sherman, Ken Smith
Project manager: Alana Sherman
Project team: Larry Bird, Larissa Clary, John Ferreira, Rich Henthorn, Brett Hobson, Christine Huffard, Linda Kuhnz, Paul McGill, Susan von Thun
Collaborators: Jeffrey Drazen, University of Hawaii, Manoa; Henry Ruhl, National Oceanography Centre, Southampton, United Kingdom; Timothy Shaw, University of South Carolina, Columbia

The team's long-term studies at Station M in the abyssal northeastern Pacific are directed towards understanding benthic ecosystem dynamics and the role of the benthos in the global carbon cycle, in particular as it relates to climate change. In June, the project team visited Station M to service the instruments—the Benthic Rover, the Sedimentation Event Sensor, and a time-lapse camera—deployed at the site, to download the collected data, and to redeploy the instruments for another nine months. In the past few years, the camera and sediment traps documented the largest seasonal flux of particulate organic matter sinking to the sea floor in the past 24 years. Concurrently, the Benthic Rover measured the highest carbon consumption rates over the time series, as sediment communities consumed this record food fall.

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

Processing continued on the mooring data from the 2010 Philippine Sea Acoustics Experiment. Isotherms (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. Data files were also created for distribution to other scientists.

PowerBuoy

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

2013 improvements to the PowerBuoy longevity and reliability included a new mooring system, a new load cell, new hydraulic seals, new power cables, and a new tether. Much time was spent fine-tuning and testing the power-take-off system in the lab. The buoy was deployed for 22 days in May, generating an average of 247 watts, but a mechanical failure ended the deployment. The PowerBuoy was refurbished and deployed again in September for 35 days, generating an average of 283 watts. In an effort to recharge the AUV via the PowerBuoy, an acoustic baffle was integrated onto the directional acoustic transponder on one long-range AUV, a calibration was performed in the test tank, and the AUV successfully homed to an acoustic modem mounted on a Wave Glider deployed in Monterey Bay.

Precision Control Technologies for ROVs and AUVs

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

This project continued the development of terrain-based navigation techniques with the goal of enabling AUVs to perform return-to-site surveys. Methods are being explored that will enable AUVs to fly within meters of the seafloor to collect imagery of selected sites. The key advance is a set of algorithms that exploit the a-priori information available in existing high-precision bathymetry maps as a means of predicting and avoiding hazards. Work has also begun to develop techniques that will improve ROV localization using terrain-relative navigation based on the information available in the ROV's scanning sonar.

Respirometer Upgrade Extension

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

The team conducted a total of 16 science deployments of the Midwater and Benthic Respirometer Systems. The deployments reaped scientific data as well as lessons about the operation of system components, leading to further system refinements.

Safety Guidelines for the Failure Modes of Lithium Batteries

Project leads: James G. Bellingham, Paul McGill
Project manager: Paul McGill
Project team: Jon Erickson
Collaborators: Sebastian Osswald, Naval Postgraduate School, Monterey, California

Working closely with the MBARI Safety Committee, the team built an instrumented steel chamber for the destructive testing of lithium batteries. They ignited a total of 12 lithium cells while the temperature and quantity of evolved gas were measured. Significant findings include the observation that cell casings can rupture at places other than the pressure-relief vent, and that the failure of one cell can easily spread to adjacent cells. These tests will inform the design of future AUV battery packs and pressure housings.

Engineers Jon Erickson, left, and Paul McGill set up a test chamber for their research on lithium battery safety.

Salmon Ecosystem Simulation And Management Evaluation (SESAME)

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, University of California, Los Angeles; Eric Danner, Steve Lindley, and Brian Wells, Southwest Fisheries Science Center, Santa Cruz, California; Roger Nisbet, University of California, Santa Barbara

In situ and satellite observations were coupled with ecological models of the San Francisco estuary and the upper Sacramento river to support decision making for the conservation and better management of fisheries. Validation of the model is ongoing. The corresponding physical (temperature) and biological (food supply) solutions will drive a dynamic energy budget for Chinook salmon from the river to the ocean. The resulting coupled models are being used to explore variation in salmon growth and maturation, and the impacts of current and future water management, climate variability, and global change.

Self-Contained Plankton Imager

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

The Self-Contained Plankton Imager (SCPI) prototype was deployed several times in Monterey Bay for engineering tests. These tests successfully verified the system's image quality, battery capacity, depth rating, and image and video storage. SCPI produced individual and time-lapse images and video clips. It was tested on a variety of platforms including the ROV *Ventana*, a custom tripod, and full integration onto the long-range AUVs. As a result of the successful test deployments, two additional SCPI systems were built.

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

The team continued its effort to extend Open Source Data Turbine (OSDT), and to apply it to a number of production research infrastructures at several research institutions, including MBARI. The MBARI application is the Free Ocean Carbon Dioxide Enrichment (FOCE) experiment.

Support Engineering Upgrades and Explorations

Project leads: Kevin Gomes, Rich Schramm
Project manager: Kevin Gomes

This effort began the exploration of messaging systems to possibly replace the aging data manager system on ROV *Ventana*. The exploration also looked at methods to bridge real-time messaging systems with our data management infrastructure at MBARI. The lessons learned from this work will be applied to other infrastructure products at the institute as well as informing the selection of a control system upgrade for *Ventana*.

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

Project leads: James Barry, Peter Brewer, George Matsumoto
Project manager: William Kirkwood
Project team: Kent Headley, Robert Herlien, Chad Kecy, Chris Lovera, Thom Maughan, Tom O'Reilly, Edward Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborators: Jamie Dunckley and Steve Litvin, Hopkins Marine Station of Stanford University, Pacific Grove, California; Jean-Pierre Gattuso, Laboratoire d'Océanographie, Villefranche-sur-mer, France; David Kline, Scripps Institution of Oceanography, La Jolla, California; Donna Roberts, University of Tasmania, Australia; Brock Woodson, University of Georgia, Athens

The team continued with the development and installation of a shallow-water FOCE system in association with the kelp forest array at Hopkins Marine Station. The swFOCE underwent several infrastructure improvements and a small self-contained office space was built within the pump house building near the kelp forest site to serve as the operational control center for the system. The methods and technologies developed in building the shallow-water FOCE provided the framework for xFOCE, a modular, open-source generic version of FOCE.

Hoses to supply carbon-dioxide-enriched seawater to the Free Ocean Carbon Dioxide Enrichment equipment stretch across the beach in Pacific Grove, California, and out to the shallow-water FOCE site.

The project team reduced the complexity of the system design and initial investment required to develop and perform FOCE experiments to make it easily accessible to the broader science community. The swFOCE team has also assisted with the Antarctic FOCE (antFOCE) as a test case of some portions of the xFOCE.

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 during 2013 to transfer MBARI observatory technologies—software infrastructure middleware (SIAM), PUCK protocol, Shore-Side Data System, and OASIS mooring technology—to external observatory projects, industry groups, and standards organizations. The team continued support of the ALOHA cabled observatory at the University of Hawaii, which uses MBARI software for data collection and archiving. Cawthron Institute built a third mooring using MBARI controllers and the collaborators discussed potential platforms for the next generation of instrument controller. Support was provided to Seabird Electronics as part of the technology transfer of MBARI's high-resolution pH sensor design. The team supported MBARI-SIAM as open-source software.

This Cawthron Institute water-quality monitoring buoy uses MBARI-designed connector blocks.

Vertical Profiling Camera

Project leads: Paul McGill, Ken Smith
Project manager: Paul McGill
Project team: Rich Henthorn, Brett Hobson

This project explored the feasibility of building a vertically profiling camera (VPC) system to capture images of plankton and particulate organic matter in the water column at multiple depths. The project identified a vehicle, camera, and light that would operate in the extreme environment at 4,000 meter depth while consuming minimal power, allowing deployments of up to one year. A mooring string was designed to guide the vehicle and a budget was prepared to build the complete system. However, other imaging AUVs currently being developed at MBARI could influence the requirements and available technology for a VPC. For this reason, as well as the high cost of these systems, it was decided that development of the VPC should not continue.

Awards

David Packard Distinguished Lecturer
James R. McFarlane

President and Chief Executive Officer Chris Scholin (left) presents James R. McFarlane with the 2013 David Packard Distinguished Lecturer award in front of remotely operated vehicle *Ventana*. McFarlane is the founder and president of International Submarine Engineering, Ltd. which manufactured *Ventana*. McFarlane contributed to MBARI during the institute's formative years as a critical advisor to David Packard with his outstanding track record of designing and building undersea vehicles. McFarlane delivered a lecture at MBARI on November 6th titled "Genesis and metamorphosis of underwater work capability", reviewing different submersible vehicle designs and components that make them operate optimally.

Peter G. Brewer

Walker-Ames Distinguished Scholar, University of Washington

Charles Paull

Elected Fellow, American Geophysical Union

Invited Lectures

James Barry

California Academy of Sciences, San Francisco

San Jose State University, California

California State University, Monterey Bay, Seaside

Monterey Peninsula College, Monterey, California

Monterey Bay Aquarium, Monterey, California

Observatoire Océanologique de Villefranche sur Mer, France

James G. Bellingham

Naval Postgraduate School, Monterey, California

Neustar Technology Summit, Air and Space Museum, Chantilly, Virginia

Schmidt Ocean Institute Research Symposium, Honolulu, Hawaii

Innovation Center for Earth Sciences Workshop, U.S. Geological Survey, Menlo Park, California

Peter G. Brewer

University of California, Santa Cruz

Woods Hole Oceanographic Institution, Massachusetts

University of Washington, Seattle and Friday Harbor

Swire Institute of Marine Science, Hong Kong, China

University of California, Irvine

Monterey Bay Unified Air Pollution Control District, Monterey, California

Francisco Chavez

University of California, Irvine

Hopkins Marine Station of Stanford University, Pacific Grove, California

Romberg Tiburon Center for Environmental Science, Tiburon, California

45th International Liège Colloquium, Belgium

The Ramon Margalef Summer Colloquia, Barcelona, Spain

Keynote Presentation, Celebration of 40 years of the Ensenada Center for Scientific Research and Higher Education (CICESE), Ensenada, Mexico

First Technical Expert Workshop, Global Ocean Observing System (GOOS) Biology and Ecosystems, and GOOS Biogeochemistry, Townsville, Australia

University of Tasmania, Hobart, Australia

American Geophysical Union, San Francisco, California

David Clague

University of California, Berkeley

University of Hawaii, Hilo

Judith Connor

California State University, Monterey Bay, Seaside

Stanford University, California

San Jose State University, California

Monterey Bay Aquarium, Monterey, California

Keynote Presentation, Alaska Marine Science Symposium, Anchorage

Kim Fulton-Bennett

Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

Steven Haddock

Observatoire Océanologique de Villefranche sur Mer, France

University of Marseille, France

Bodega Marine Laboratory, Bodega Bay, California

Oregon Institute of Marine Biology, Coos Bay

San Jose State University, California

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

Iowa State University, Ames

Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

Julio Harvey

Pacific Coastal and Marine Science Center, U.S. Geological Survey, Santa Cruz, California

Ken Johnson

The Collaborative on Oceanographic Chemical Analysis Workshop, Honolulu, Hawaii

University of Washington, Seattle

NOAA Pacific Marine Environmental Laboratory, Seattle, Washington

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

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

Our Global Estuary Workshop, Harbor Branch Oceanographic Institution, Fort Pierce, Florida

Plenary Presentation, Institute of Electrical and Electronics Engineers Sensors Conference, Baltimore, Maryland

Shannon Johnson

Monterey Bay Aquarium Project-Based Science Curriculum Workshop, Watsonville, California

Brian Kieft

Institute of Marine Engineering, Science, and Technology, Southampton, United Kingdom

Linda Kuhnz

Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

Gene Massion

Schmidt Ocean Institute Research Symposium, Honolulu, Hawaii

George Matsumoto

California State University, Monterey Bay, Seaside

Tribal Marine Science Workshop, Seldovia, Alaska

Monterey Bay Aquarium, Monterey, California

Association for the Sciences of Limnology and Oceanography, New Orleans, Louisiana

Charles Paull

Royal Society of New Zealand, Wellington

Schmidt Ocean Institute Research Symposium, Honolulu, Hawaii

American Geophysical Union, San Francisco, California

Kanna Rajan

Case Western Reserve University, Cleveland, Ohio

University of Porto, Portugal

Bruce Robison

Workshop of the Global Ocean Biodiversity Initiative Pelagic Working Group, Glasgow, Scotland

National Endowment for the Humanities' Steinbeck Institute, Salinas, California

Aquarium of the Pacific, Long Beach, California

Steve Rock

Plenary Talk, Institute of Navigation International Technical Meeting, San Diego, California

Leslie Rosenfeld

Moss Landing Marine Laboratories, California

California Offshore Wind Power Forum, University of California, Davis

John Ryan

U.S. Geological Survey, Santa Cruz, California

Stanford University, California

Brian Schlining

Moss Landing Marine Laboratories, California

Chris Scholin

University of California, Santa Cruz

Monterey Bay National Marine Sanctuary, Monterey, California

Genomic Observatories Second Workshop, Smithsonian Institution, Washington, D.C.

Barney Oliver Award Ceremony, Agilent, San Jose, California

Hopkins Marine Station of Stanford University, Pacific Grove, California

Monterey Bay International Trade Association, Salinas, California

Center for Ocean Solutions, Stanford University, California

U.S. Geological Survey, Menlo Park, California

Melinda Simmons

International Congress of Protistology XIV, Vancouver, Canada

Esther Sumner

University of Washington, Seattle

Stanford University, California

U.S. Geological Survey, Santa Cruz, California

William Ussler III

Gordon Research Conference, Marine Molecular Ecology, Hong Kong University of Science and Technology, China

Workshop on Deep-Sea In Situ Enrichment of Environmental Microbes, Xiamen, China

Robert Vrijenhoek

University of California, Los Angeles

Shirshov Institute for Oceanography, Moscow, Russia

Museum of Zoology, Moscow, Russia

Helmholtz Centre for Ocean Research (GEOMAR), Kiel, Germany

Alexandra Z. Worden

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

Keynote Presentation, Annual Meeting of the Environmental Mutagenesis and Genomics Society, Monterey, California

International Congress of Protistology XIV, Vancouver, Canada

Stazione Zoologica di Napoli, Italy

Integrated Microbial Diversity Meeting, Whistler, Canada

Department of Energy Joint Genome Institute Genomic Technologies Workshop/Genomics of Energy and the Environment Meeting, Walnut Creek, California

Department of Energy Genomic Science Meeting, Bethesda, Maryland

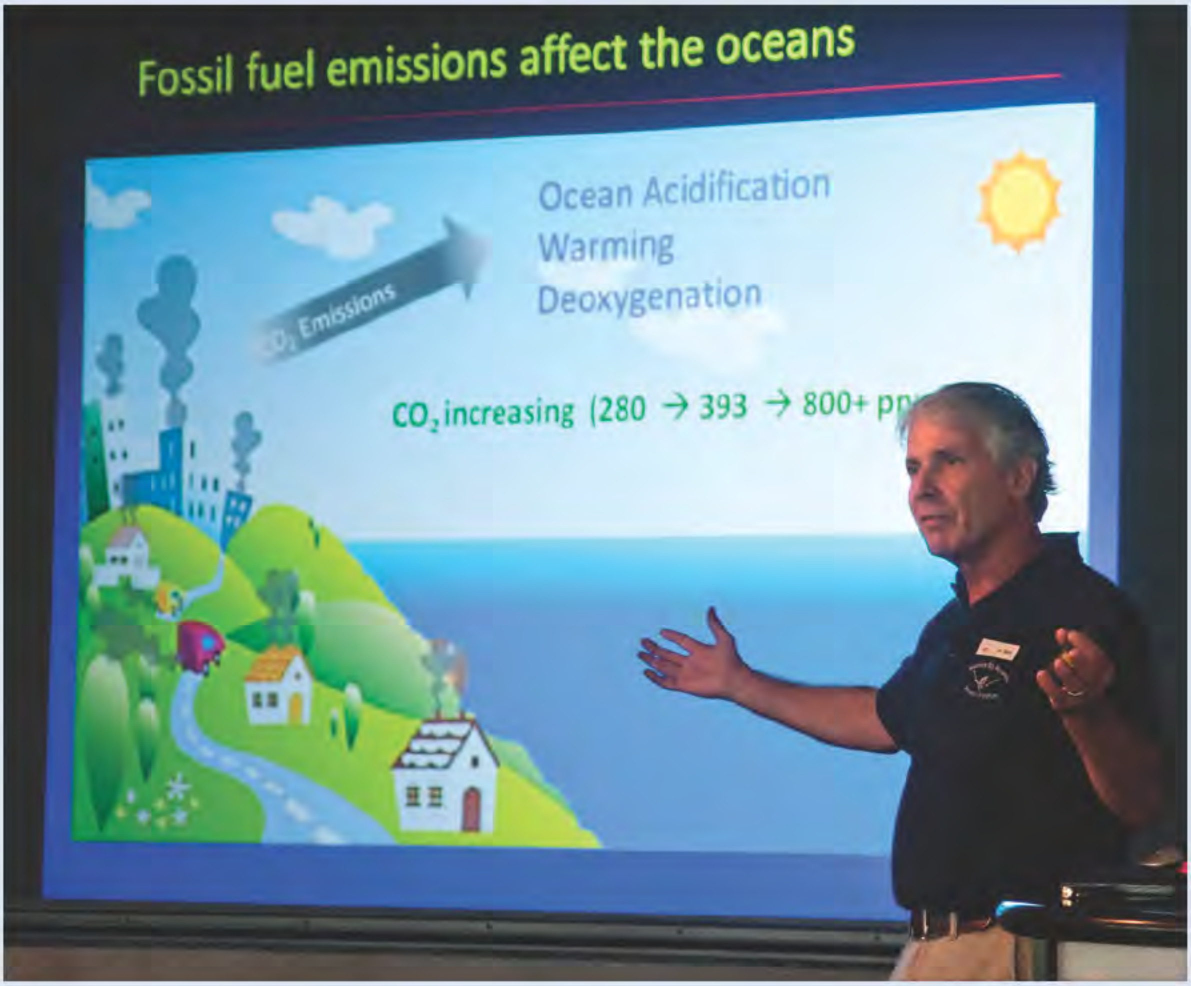
Oregon State University, Corvallis, Oregon

Yanwu Zhang

Experts Forum Lecture, University Town of Shenzhen, China

Tsinghua University Shenzhen Graduate School, Shenzhen, China

Tongji University, Shanghai, China



Senior Scientist Jim Barry explained the impact of carbon dioxide emissions to a packed auditorium at the 2013 MBARI Open House. The annual event gives the public a chance to meet the MBARI staff, learn about ocean research, and visit exhibits on the institute's technology developments and science. Barry and his group are conducting scientific inquiries to learn more about how the changes in the ocean resulting from carbon dioxide emissions are impacting ocean life. See story on page 7.

Mentorships

Nancy Barr, Judith Connor

Kelly Lance, graduate summer intern, California State University, Monterey Bay (science and technology illustration)

James Barry

Kendra Hart, undergraduate summer intern, Northern Arizona University (effects of ocean acidification on the chemosensory behavior of the deep-sea urchin *Strongylocentrotus fragilis*)

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

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

James Barry, Chris Lovera

Will Fennie, graduate student, Moss Landing Marine Laboratories (the effects of elevated carbon dioxide on the behavior and physiology of juvenile rockfishes *Sebastes spp.*)

James G. Bellingham, Julio Harvey, John Ryan

Heather Fulton-Bennett, graduate summer intern (holographic and molecular detection of zooplankton)

James G. Bellingham, John Ryan

Diane Wyse, graduate summer intern (laboratory calibration of optical sensors from autonomous underwater vehicles)

James Birch, John Ryan, Chris Scholin

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

Peter Brewer, Edward Peltzer, Peter Walz

Wilson Sauthoff, undergraduate summer intern, University of California, Davis (experimental determination of methane dissolution from simulated subsurface oil leakages)

David Caress, Brett Hobson, Ken Smith

Katherine Dunlop, postdoctoral fellow (benthic boundary layer community structure)

Francisco Chavez

Jason Smith, postdoctoral fellow (nitrogen remineralization in the ocean's twilight zone)

Alba Marina Cobo Viveros, graduate summer intern, Universidad del Valle (a synthesis of sea water pCO_2 along the western coast of the Americas)

David Clague

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

Jason Coumans, Ph.D. student, McGill University (petrology of the Taney Seamounts)

Charlotte Humphrey, Ph.D. student, Manchester Metropolitan University (bioerosion of reef limestones from Hawaii)

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

Ryan Portner, postdoctoral fellow (lithofacies of clastic deposits on seamounts)

Isobel Yeo, Ph.D. student, Durham University (formation of pillow ridges)

Judith Connor

Nettie McMiller, undergraduate summer intern, University of North Carolina Chapel Hill (developing video and web information on the chemistry of the Gulf of California)

Duane Edgington, Kent Headley, Tom O'Reilly

Oriol Pallares, graduate summer intern, Polytechnical Institute of Catalunya (Internet protocol PUCK implementation and verification)

Kim Fulton-Bennett

Laura Poppick, graduate student intern, University of California, Santa Cruz (science communications)

Patrick Gibson

Andrew Leitholf, graduate summer intern, University of Akron (flow injection analysis of nanomolar ammonium concentrations via o-phthaldialdehyde fluorescence)

Steven Haddock

Liza Gomez Daglio, Ph.D. student, University of California, Merced (jellyfish diversity and biogeography)

Warren Francis, Ph.D. student, Carnegie Mellon University (coelenterazine and luminescence chemistry)

Alexander Jaffe, undergraduate summer intern, Harvard University (time-series analysis of VARS plankton data)

Séverine Martini, Ph.D. student, University of Marseille (oceanography of bioluminescence)

Meghan Powers, Ph.D. student, University of California, Santa Cruz (fluorescent proteins and photoproteins)

Alejandro Damián Serrano, undergraduate student, University of Valencia (ctenophore taxonomy and evolution)

Holly Swift, Ph.D. student, University of California, Merced (plankton evolution and genetics)

Uxue Tilves, Ph.D. student, Centro Superior de Investigaciones Científicas, Barcelona (jellyfish-fish interactions)

Christine Huffard, Linda Kuhnz, Ken Smith

Larrisa Clary, undergraduate summer intern (benthic megafauna population dynamics)

Claire Laguionie-Marchais, graduate summer intern, University of Southampton (benthic megafauna population dynamics)

Ken Johnson

Patrick Gibson, postdoctoral fellow (development of an ammonium analyzer)

Miguel Uzcategui, undergraduate summer intern, University of the District of Columbia (development of a low cost pCO_2 sensor)

William Kirkwood

Bailey Hoover, undergraduate summer intern, Colorado School of Mines (project Shearwater: preliminary design considerations)

Linda Kuhnz

Nancy Fernandez, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Adriana Gomez, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Silvano Paniagua, high school student, Pajaro Valley High School (the effects of water quality on macroinvertebrate density, biodiversity, and pollution tolerance)

Chris Lovera

Felicia Davidson, high school student, Pajaro Valley High School (how does the diversity of crabs differ at places with restricted water flow versus open water flow?)

Cristal Garcia, high school student, Watsonville High School (how does ocean acidification affect European green crabs)

Briana Lopez, high school student, Watsonville High School (how does ocean acidification affect European green crabs)

Abigail Melchor, high school student, Watsonville High School (how does ocean acidification affect European green crabs)

Marcos Perez, high school student, Pajaro Valley High School (how does the diversity of crabs differ at places with restricted water flow versus open water flow?)

Margarito Rodriguez, high school student, Pajaro Valley High School (how does the diversity of crabs differ at places with restricted water flow versus open water flow?)

Jesica Villegas, high school student, Pajaro Valley High School (how does the diversity of crabs differ at places with restricted water flow versus open water flow?)

Gene Massion

Nicholas Sohn, undergraduate summer intern, Swarthmore College (developing parameter estimation techniques for controller optimization of a coastal profiling float)

Mike McCann

Dylan Rolicheck, undergraduate summer intern, California State University, Monterey Bay (geospatial database administration)

Charles Paull

Tzu-Ting Chen, graduate student, National Taiwan University (mapping AUV data collected in the South China Sea)

Jon Furlong, M.S. student, University of Victoria (characteristic morphology, backscatter, and sub-seafloor structures of cold vents on the Northern Cascadia Margin from high-resolution autonomous underwater vehicle data)

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

Xavier Tubau, Ph.D. student, University of Barcelona (submarine canyons)

Kanna Rajan

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

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)

Emili Hernandez, University of Girona (path planning for autonomous underwater vehicles)

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

Kim Reisenbichler, Bruce Robison, Rob Sherlock

Ben Burford, undergraduate summer intern, California Polytechnic State University, San Luis Obispo (behavior and mimicry in the juvenile and sub-adult life stages of the mesopelagic squid *Chiroteuthis calyx*)

Bruce Robison

Alicia Bitondo, M.S. student, Moss Landing Marine Laboratories (ontogenetic morphological transformations in *Chiroteuthis calyx*, the swordtail squid)

Stephanie Bush, postdoctoral fellow (deep-sea squid ecology, pteropod biodiversity, and the collection and maintenance of deep-water octopuses and squids for the Monterey Bay Aquarium's *Tentacles* exhibit)

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

Julia Stewart, Ph.D. student, Stanford University (Humboldt squid in the northern California Current system)

Steve Rock

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

Marcus Hammond, Ph.D. student, Stanford University (benthic and iceberg 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)

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

David Stonestrom, Ph.D. student, Stanford University (benthic and iceberg mapping using AUVs)

John Ryan

Robin Accot, Ph.D. student, Universite du Quebec at Rimouski (participation in CANON/ECOHAB fall experiment)

Jennifer Broughton, Ph.D. student, University of California, Santa Cruz (phytoplankton ecology)

Chris 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)

Robert C. Vrijenhoek

Jenna Judge, Ph.D. student, University of California, Berkeley (molecular and morphological systematics of marine snails)

Gillian Rhett, M.S. student, Moss Landing Marine Laboratories (community composition of meiobenthos at whale falls in Monterey Bay)

Norah Saarman, Ph.D. candidate, University of California, Santa Cruz (molecular systematics of California *Mytilus* mussels)

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

Alexandra Z. Worden

Charles Bachy, postdoctoral fellow (genomic analysis of marine microbial eukaryotes and their viruses)

Chang Jae Choi, postdoctoral fellow (comparative genome/transciptome analysis of predatory nanoflagellates)

Jian Guo, postdoctoral fellow (influence of nutrients and carbon dioxide levels on algal growth)

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

Alexander Limardo, Ph.D. student, University of California, Santa Cruz (speciation among green algae and environmental factors influencing growth)

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

Melinda Simmons, Ph.D. student, University of California, Santa Cruz (microbial biological oceanography)

Susanne Wilken, postdoctoral fellow (ecology and physiology of marine mixotrophs)

Amy Zimmerman, postdoctoral fellow (nutrient-virus interactions in picoeukaryotes)

Publications

Ascani, F., K.J. Richards, E. Firing, S. Grant, **K.S. Johnson**, Y. Jia, R. Lukas, and D.M. Karl (2013). Physical and biological controls of nitrate concentrations in the upper subtropical North Pacific Ocean. *Deep Sea Research II*, **93**: 119-134, doi: 10.1016/j.dsr2.2013.01.034.

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Borowski, W.S., N.M. Rodriguez, **C.K. Paull**, and **W. Ussler III** (2013). Are ^{34}S-enriched authigenic sulfide minerals a proxy for elevated methane flux and gas hydrates in the geologic record? *Marine and Petroleum Geology*, **43**: 381-395, doi: 10.1016/j.marpetgeo.2012.009.

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Brewer, P.G. (2013). A short history of ocean acidification science in the 20th century: A chemist's view. *Biogeosciences Discussions*, **10**: 8715-8748.

Brewer, P.G. and **W.J. Kirkwood** (2013). Raman spectroscopy for subsea applications. In: *Subsea Optics and Imaging*, edited by J. Watson and O. Zielinski, pp. 409-433, Woodhead Publishing Limited, doi: 10.1533/9780857093523.3.409.

Buck, K.R., **J.P. Barry**, and S.J. Hallam (2013). *Thioploca* spp. sheaths as niches for bacterial and protistan assemblages. *Marine Ecology*, doi: 10.1111/maec.12076.

Chadwick Jr., W.W., **D.A. Clague**, R.W. Embley, M.R. Perfit, D.A. Butterfield, **D.W. Caress**, **J.B. Paduan**, **J.F. Martin**, P. Sasnett, S.G. Merle, and A.M. Bobbitt (2013). The 1998 eruption of Axial Seamount: New insights on submarine lava flow emplacement from high-resolution mapping. *Geochemistry, Geophysics, Geosystems*, **14**: 3939-3968, doi: 10.1002/ggge.20202.

Clague, D.A., **B.M. Dreyer**, **J.B. Paduan**, **J.F. Martin**, W.W. Chadwick, **D.W. Caress**, **R.A. Portner**, T.P. Guilderson, M.L. McGann, **H. Thomas**, D.A. Butterfield, and R.W. Embley (2013). Geologic history of the summit of Axial Seamount, Juan de Fuca Ridge. *Geochemistry, Geophysics, Geosystems*, **14**: 4403-4443, doi: 10.1002/ggge.20240.

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Dorrell, R.M., S.E. Darby, J. Peakall, **E.J. Sumner**, D.R. Parsons, and R.B. Wynn (2013). Superelevation and overspill control secondary flow dynamics in submarine channels. *Journal of Geophysical Research: Oceans*, **118**: 3895-3915, doi: 10.1002/jgrc.20277.

Dreyer, B.M., **D.A. Clague**, and J.B. Gill (2013). Petrological variability of recent magmatism at the Axial Seamount summit, Juan de Fuca Ridge. *Geochemistry, Geophysics, Geosystems*, **14**: 4306-4333, doi: 10.1002/ggge.20239.

Duffy, G.A., **L. Lundsten**, **L.A. Kuhnz**, and **C.K. Paull** (2013). A comparison of megafaunal communities in five submarine canyons off Southern California, USA. *Deep Sea Research II*, doi: 10.1016/j.dsr2.2013.06.002.

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Gomes, K., **D. Cline**, **D. Edgington**, M. Godin, **T. Maughan**, **M. McCann**, **T. O'Reilly**, **F. Bahr**, **F. Chavez**, **M. Messié**, J. Das, and **K. Rajan** (2013). ODSS: A decision support system for ocean exploration. *Proceedings of the Workshop on Data-Driven Decision Guidance and Support Systems (DGSS), 29th Institute of Electrical and Electronics Engineers International Conference on Data Engineering 2013*, Brisbane, Australia, 12 pp.

Hanif, A.W., W.D. Dyson, **H.A. Bowers**, J.S. Pitula, G.A. Messick, R. Jagus, and E.J. Schott (2013). Variation in spatial and temporal incidence of the crustacean pathogen *Hematodinium perezi* in environmental samples from Atlantic coastal bays. *Aquatic Biosystems*, **9**: doi: 10.1186/2046-9063-9-11.

Hariganeya, N., Y. Tanimoto, H. Yamaguchi, T. Nishimura, W. Tawong, H. Sakanari, T. Yoshimatsu, S. Sato, **C.M. Preston**, and M. Adachi (2013). Quantitative PCR method for enumeration of cells of cryptic species of the toxic marine dinoflagellate *Ostreopsis* spp. in coastal waters of Japan. *PLoS ONE*, **8**: e57627, doi: 10.1371/journal.pone.0057627.

Harvey, J.B.J., A.F. Djunaedi, and **R.C. Vrijenhoek** (2013). Validation of a sandwich hybridization assay for marine copepod detection. *Journal of Experimental Marine Biology and Ecology*, **446**: 306-310.

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Hofmann, A.F., **E.T. Peltzer**, and **P.G. Brewer** (2013). Kinetic bottlenecks to chemical exchange rates for deep-sea animals—Part 2: Carbon dioxide. *Biogeosciences*, **10**:2409-2425, doi: 10.5194/bg-10-2409-2013.

Hofmann, A.F., **P.M. Walz**, **H. Thomas**, **E.T. Peltzer**, and **P.G. Brewer** (2013). High-resolution topography-following chemical mapping of ocean hypoxia by use of an autonomous underwater vehicle: The Santa Monica Basin example. *Journal of Atmospheric and Oceanic Technology*, **30**: 2630-2646, doi: 10.1175/JTECH-D-12-00249.1.

Houts, S.E., S.G. Dektor, and **S.M. Rock** (2013). A robust framework for failure detection and recovery for terrain-relative navigation. *Proceedings of the 18th International Symposium on Unmanned Untethered Submersible Technology*, Portsmouth, New Hampshire.

Hoving, H.J.T., W.F. Gilly, U. Markaida, K.J. Benoit-Bird, Z.W. Brown, P. Daniel, J.C. Field, L. Parassenti, B. Liu, and B. Campos (2013). Extreme plasticity in life-history strategy allows a migratory predator (jumbo squid) to cope with a changing climate. *Global Change Biology*, **19**: 2089-2103, doi: 10.1111/gcb.12198.

Hoving, H.J.T., L.D. Zeidberg, M.C. Benfield, **S.L. Bush**, **B.H. Robison**, and M. Vecchione (2013). First in situ observations of the deep-sea squid *Grimalditeuthis bonplandi* reveal unique use of tentacles. *Proceedings of the Royal Society B*, **280**: doi: 10.1098/rspb.2013.1463.

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Hurt, C., **S.H.D. Haddock**, and W.E. Browne (2013). Molecular phylogenetic evidence for the reorganization of the Hyperiid amphipods, a diverse group of pelagic crustaceans. *Molecular Phylogenetics and Evolution*, **67**: 28-37, doi: 10.1016/j.ympev.2012.12.021.

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On the cover: Frame-grab images from the video camera on remotely operated vehicle *Doc Ricketts* during a chemistry experiment off the coast of Northern California. The pilots first collected oil emanating from the seafloor at a depth of 1,600 meters by maneuvering a glass tube over the oil bubbles. Once a quantity of the oil was gathered the laser Raman spectrometer, at left in the lower photo, was trained on the tube. The green laser beam remained focused on the top part of the tube as it was slowly brought to the ocean surface (in top image) to determine what gases evolved from the oil (which appears blue in the lights) and filled up the headspace above it as water pressure eased on the ascent. See story on page 29.

Back cover: Undergraduate student Nicholas Sohn connects hoses on a coastal profiling float (See page 48) during his 10-week summer internship at MBARI. *Photo by Todd Walsh.*

Inside front cover: During an early morning pre-dive check, ROV *Doc Ricketts* Pilot Bryan Schaefer makes sure the push cores are properly stowed. The robotic arm in the right foreground is holding the probe head for the laser Raman spectrometer, which is seen on the cover of this book. *Photo by Peter Walz.*

Inside back cover: An aerial view of the research vessel *Rachel Carson* with ROV *Ventana* on its back deck. With its ample deckspace and interior, the *Carson* provides flexibility for ROV and AUV missions, or mooring and instrument deployments at sea. *Photo by Todd Walsh.*

Image credits, by page: 2 and 3: Todd Walsh; 4 (left): Steve Haddock, (right): Erik Thuesen; 8 (right): Kim Fulton-Bennett; 9 (right): Ken Johnson; 11 (left): Ken Johnson; 12 (far left): Todd Walsh; 13: Courtesy of the National Oceanic and Atmospheric Administration Northwest Fisheries Science Center; 14 (left and center): Adam Monier, (right): Todd Walsh; 15 (left): Scanning electron microscope image by Kurt Buck, (top right): Denis Klimov; 16 (left): Brian Kieft; 17 (top two images): Mark Chaffey, (bottom) Illustration by Eve Lundsten; 18: Illustration by Kelly Lance; 23 (top): Charles Paull; 24 (all): David Caress; 26 (top left): Scott Dallimore, Geological Survey of Canada; 27 (right): Jennifer Paduan; 28 (top): Mosaic of frame grab images constructed by Tom Kwasnitschka, GEOMAR; 29: Photo and illustration by Kelly Lance; 33 (left): Mosaic of frame grab images constructed by Lonny Lundsten; 34 (right): Holly Bowers; 36: Holly Bowers; 38: Denis Klimov; 39 (all): Todd Walsh; 42: Rob McEwen; 43 (left): Todd Walsh; 44: Randy Wilder; 45 (bottom): Randy Wilder; 46 (left): Kim Swan, (right): Todd Walsh; 48 (right): Todd Walsh; 49: George Matsumoto; 52: Courtesy of the University of Washington; 53: Thomas Hoover; 54: Peter Walz; 55: Paul Barter, Cawthron Institute; 56: Todd Walsh; 59: Todd Walsh

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