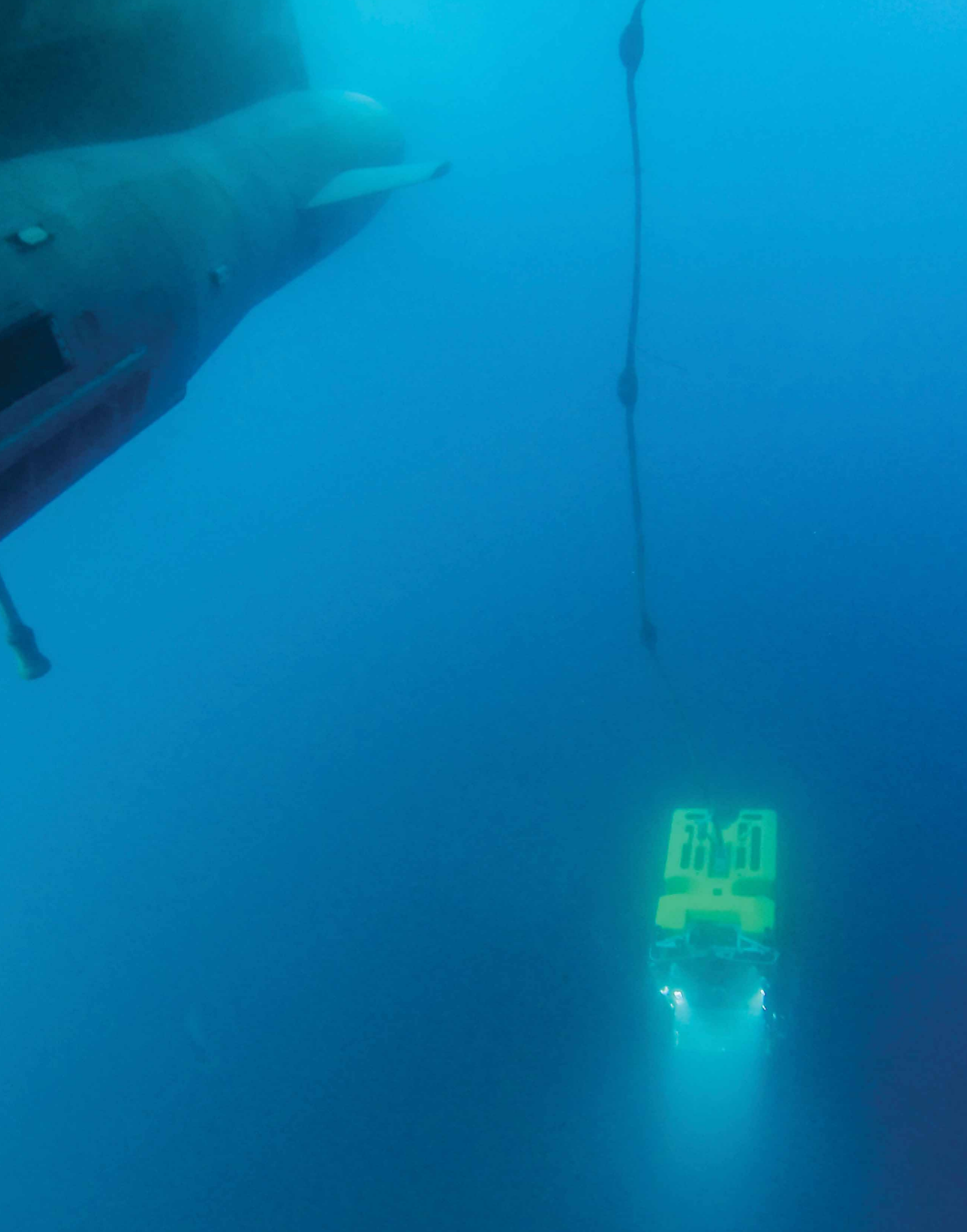
MBARI

Monterey Bay Aquarium Research Institute

2015
Annual Report



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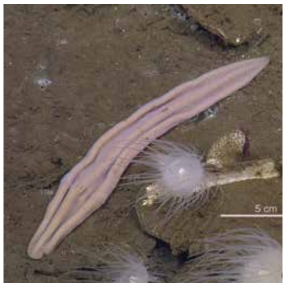
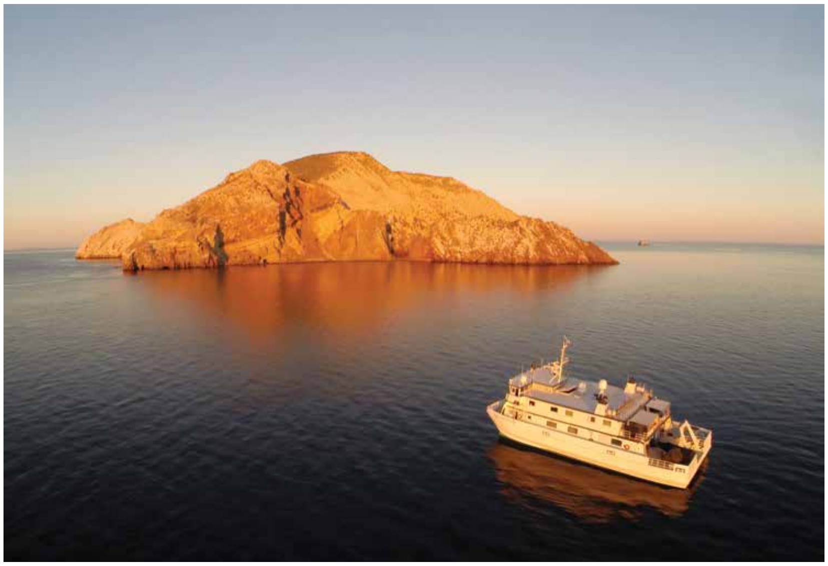


From the Masthead

Each year we celebrate new science discoveries, technological breakthroughs, and collaborations that were not necessarily anticipated. Glancing through the pages of this year's Annual Report, you will see that 2015 was no exception to that pattern.

The year began with a three-month expedition to the Gulf of California. MBARI's ships, the R/V *Rachel Carson* and R/V *Western Flyer*, seafloor mapping autonomous underwater vehicle (AUV), and two remotely operated vehicles (ROVs) supported seven different research teams over the course of the expedition. Participants included MBARI scientists and their Mexican collaborators who worked alongside representatives from the Monterey Bay Aquarium and the David and Lucile Packard Foundation to carry out studies from the sea surface to the seafloor and, in the process, visited some places never previously explored.

The Gulf of California holds special scientific appeal for many reasons. The warm water and expansive oxygen minimum zone are thought to be an analog of what Monterey Bay could become in the future given a warmer climate. Comparing the distribution patterns of species that live throughout the water column and on the seafloor of both regions offers a glimpse into how species cope with a warming ocean and an expanding zone of low oxygen, potentially providing a predictive capability for forecasting what lies ahead for our local waters. The deep seafloor of the Gulf also hosts volcanoes, impressive hydrothermal vents, and an array of faults marking the boundaries of major tectonic plates, all of which teem with life that exists in perpetual darkness. Not surprisingly, the expedition led to many discoveries and fascinating observations that rival science fiction. But none of those discoveries would have been possible without insightful scientists enabled by the mapping AUV, ROVs, and ships, as well as the engineers, technicians, ROV pilots, and crews who skillfully operated those platforms. The success of the 2015 Mexico expedition stands as a fitting tribute to David Packard's vision for MBARI as an organization that thrives on a synergy of science, engineering, and marine operations.



The R/V Western Flyer *at Isla San Pedro Mártir in the Gulf of California, as seen from a drone.*

Work within Monterey Bay and elsewhere also resulted in discoveries and breakthroughs. A notable point in MBARI's 26-year time-series study of local waters came on October 17, 2015, with an all-time high temperature recording—an indication of a climatic phenomenon known as El Niño. With the warm water came an amazing cadre of species normally found off Baja California or further south. Those ocean conditions are also thought to have played a role in fostering a massive toxic algal bloom off the coasts of much of California, Oregon, and Washington. The extensive bloom, closure of fisheries, and the resulting economic impacts that followed were so significant that it became a topic of a congressional briefing in Washington, D.C. MBARI's previous investments in sensors and samplers, both moored and mobile, played a key role in revealing the dynamics of this bloom in Monterey Bay. Those capabilities also contributed to a much larger scientific collaboration and public outreach effort thanks, in large part, to support from the National Oceanic and Atmospheric Administration (NOAA).

Serendipity often plays a role in discovery. For instance, a chance encounter with an animal known as a larvacean proved to be especially enlightening this year. Larvaceans play an important role in the flux of carbon through ocean food webs. To feed, they create a complex mucus structure that acts as a filter for collecting food particles. No one knows exactly how these small but incredibly important animals create these structures, and no one has ever been able to visualize their internal workings. A new laser-imaging tool designed to study animal-fluid interactions unexpectedly revealed a means of imaging the enigmatic structure in phenomenal detail. This find underscores the value in developing new tools and techniques for exploring the deep sea; it is never possible to predict what discoveries will be made given new observational and sampling capabilities, even in the well-plied waters of Monterey Bay. For this reason, long-term engineering developments that have the potential to transform ocean exploration and scientific inquiry remain one of MBARI's top priorities, spurring the mantra, "Develop locally, export globally!"

A perfect example of this strategy is seen in MBARI's role in the observation of the impact of fossil fuel-derived carbon dioxide entering the Southern Ocean—one of the more inhospitable places on the planet, yet one that is vitally important to modulating Earth's climate. This ambitious investigation requires making measurements of chemical and biological fluxes at many locations in the Southern Ocean over many years, which is impractical to do by traditional ship-based sampling. The key to solving this problem rested on a number of factors: chemical sensors developed at MBARI and partnerships with industry and academic institutions, combined with existing robotic floats that can collect basic information like temperature and salinity for years without human intervention. The result: a novel way to make the necessary measurements and receive the information via satellite. The amalgamation of basic research and development, industry and academic partnerships, and leveraging of existing technologies has opened a window into the Southern Ocean carbon cycle like never before. Sponsorship from the National Science Foundation and NOAA is helping to transfer the insights gained from this technology to the larger ocean sciences community, and in so doing is creating new opportunities for studying the global ocean carbon cycle on time and space scales that were but a pipe dream only a handful of years ago.

Reflecting on the past year's discoveries and advancements serves as a potent reminder that there is still a great deal to learn about the ocean and the life it sustains, particularly in the face of a changing global climate brought on by human activity. Innovation in the way we access, sample, measure, visualize, and assess the changing ocean is needed to further discovery, management, and conservation of this vital resource. At the same time we must encourage and welcome a new generation that will make the most of this opportunity. In that regard, 2015 was a watershed year for MBARI as long-term stewards of the institution Director of Marine Operations Steve Etchemendy and Chief Financial Officer Mike Pinto retired. Their replacements, Mike Kelly and Basilio Martinez, along with others who will soon join our staff, herald a new era of exploration and discovery as we continue our evolution.

Next year promises to bring its own discoveries and breakthroughs as we mount expeditions to the Canadian Arctic, Newfoundland, and the Pacific Northwest, as well as pursue a portfolio of other science and engineering projects in local waters. You can follow along by visiting our new website, as well as by subscribing to our Facebook and other social media sites. We look forward to hearing from you. 2016 is going to be an amazing year!

Chris Scholin,
President and Chief Executive Officer

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Monterey Bay as a Window to the World

Much of the work MBARI does at home in Monterey Bay off the coast of Central California provides insight to larger scale phenomena or results in technology that can be used to study the entire world ocean. Technologies developed by MBARI engineers and scientists often prove invaluable to learning about systems, processes, and changes that impact much of the world population. Trends in climate such as El Niño and larger-than-usual harmful algal blooms were part of these studies in 2015.

What is El Niño and how did it show itself in 2015?

In the late nineteenth century, fishermen in northern Peru came to expect a warm, southward current each year—they called it *El Niño* ("The Child" in Spanish) because it developed around Christmas time. Every three to eight years, this current was particularly strong and warm and resulted in high rainfall in this normally desert-dry location. Those years also saw a disappearance and mortality of the typical fishes, mammals, and seabirds of the region and an influx of tropical species. It was the combination of these unusually strong events that came to be known as the El Niño phenomenon.

Fishermen and coastal dwellers had been observing the effects of El Niño for decades but it was not until the late 1960s that the warming of the coastal ocean off Peru was linked to large-scale changes in the atmosphere. El Niño has since been studied extensively but it remains unpredictable, particularly when it comes to forecasting the onset and intensity of an occurrence. Once started, however, the sequence of events that creates dramatic changes in both the atmosphere and the ocean is relatively well understood. Strong El Niño events, that occur every 15 to 25 years, have a significant impact on climate and weather patterns over a very large part of the world.

First, the largest and steadiest low-pressure system on the globe, the Indonesian Low, named because it sits over Indonesia, is displaced eastward. Anomalous westerly winds from the low's new location initiate Kelvin waves, large-scale oceanic waves that propagate eastward along the equator, carrying water that is usually piled up in the western Pacific towards the Americas. This raises sea level in the east and pushes down the thermocline—the layer of water that marks the transition from the warmer temperatures above to the cooler water below. When these waves reach the South American coast, they propagate toward the poles. The deeper thermocline alters the thermal structure of the normally cold eastern Pacific, increasing upper-ocean temperatures and decreasing biological productivity. These episodes

*Figure 1. The warm water brought in a large population of pelagic red crabs (*Pleuroncodes*; each animal is about 50 millimeters long), for this rare blanketing of a beach in Pacific Grove, California.*

keep moving the Indonesian Low eastward until it is thousands of kilometers from its average location. As it moves, new Kelvin waves are formed amplifying the anomalous conditions.

Unusually warm sea-surface temperatures (SST) along the equatorial Pacific from the international dateline in the mid-Pacific to the coast of Peru is the trademark signature of El Niño. Near the equator, the greatest changes to the ocean are the results of the Kelvin waves. But at higher latitudes, like California, the movements of the Pacific's usual low- and high-pressure systems are also responsible for anomalous conditions. That eastward shift of the Indonesian Low in turn shifts the location of the jet stream southward and brings moisture from the center of the Pacific through the Hawaiian Islands—the so-called pineapple express— to the coast of California, resulting in increased precipitation over California during an El Niño. In concert, subtropical Pacific high-pressure systems weaken, which creates a ripple effect as low- and high-pressure systems throughout the globe change their intensity and location.

Over the past 60 years, strong El Niño events have impacted the West Coast of North America in 1957-58, 1982-83, and 1997-98. Because of the scientific understanding at the time, the 1957-58 El Niño was originally interpreted as the beginning of a long-term shift in climate conditions rather than the interannual changes associated with El Niño. Decades later, the 1982-83 and 1997-98 events brought worldwide attention to what is now known as the dominant mode of climate variability over the past century. The 2015-16 event will be counted as one of the strong ones, associated with longer term shifts in climate due to human-induced changes.

Oceanographic conditions in the northeast Pacific had already been unusual prior to the 2015-16 event. Beginning in late 2013 a large area of anomalously warm water at the sea surface in the northeast Pacific began to develop, the so-called "blob". The warming had spread over the entire West Coast of North America and Mexico by the middle of 2014. This warming was not characteristic of an El Niño since it lacked the trademark anomalies in the tropical Pacific and the northeast Pacific warming was restricted to the sea surface.

The warming eased in the spring of 2015 with the onset of upwelling, which brings colder water up from depth, but returned in the summer as part of El Niño. The characteristic signature of El Niño developed in the equatorial Pacific during the late spring and summer of 2015 and further intensified in the fall. A wide variety of ecosystem changes have been linked to the unusual warming of the sea surface, including in a large bloom of algae that produced toxic domoic acid, which resulted in the delay of the California Dungeness crab season in the fall of 2015.

On October 17, 2015, the warmest daily average sea-surface temperature ever measured by MBARI's mooring just outside Monterey Bay during its 26-year history, 18.74 degrees Celsius, was recorded. The region saw an influx of tropical species normally found off Baja California or further south. One of the most notable being the pelagic red crab of the genus *Pleuroncodes*, which occasionally covered area beaches with a blanket of red not seen since 1982-83 (Figure 1). Well-known predators of these crabs, among them bluefin tuna, followed them northward. Another unusual visitor was the lizardfish (*Synodus lucioceps*), never reported in Monterey Bay prior to 2014. The combination of local, tropical, and offshore biota led to a dramatic increase in biodiversity along the Central Coast of California. The warmer water pushed the local biota inshore, in particular, forage fish like anchovies, leading to spectacular feeding displays by humpback whales near shore.

A popular name for the 2015-16 event, taken up handily by the news media, was "Godzilla" because it was predicted to be a very strong event. As of this writing, however, the jury is still out as to whether this will be the case. Following the large 1997-98 event, El Niños seemed to change character. Although warming periods were still detected, the anomalies were restricted to the central Pacific rather than stretching from the dateline to Peru. The Japanese nicknamed these events El Niño "Modoki," a word that means like but not the same. The 2015-16 event has some of these characteristics with larger anomalies in the central Pacific and weaker anomalies in the eastern Pacific along North and South America. Indeed, sea-surface temperatures in Central California retreated after the peak in October and, as of early 2016, had been well below temperatures observed during the same period in 1997.

A similar picture emerges from Peru where sea-surface temperature was unusually warm but well below levels measured in 1982 and 1997. Conditions indicate a strong El Niño but one less intense than 1982 and 1997. The strong anomalies in the central equatorial Pacific have kicked off the persistent, global atmospheric patterns called teleconnections and the United States is experiencing El Niño-like weather conditions.

The blob and El Niño together have resulted in conditions of unprecedented anomalies in the northeast Pacific relative to the last 50 years. This has led some to speculate that the prolonged warming may have more dramatic impacts on local marine ecosystems than other shorter-lived and more intense events. It has also fueled discussion regarding the influence of humans on climate and whether these unusual conditions are a result of human activities related to fossil-fuel emissions. An alternative scenario is that we are seeing a new climate regime that is being revealed in our relatively short records. It is likely that there is some truth to these speculations. Continuing high-quality observations of our coastal and open ocean are paramount to developing a more reliable understanding of these changing conditions in the future.

Changing ocean conditions fuel production of toxic algae

As the sea warmed off the California Coast in 2015 and El Niño took form, another ocean phenomenon also showed up stronger than usual. In the spring, an exceptionally toxic algal bloom was detected in Monterey Bay and, as the summer wore on, the bloom spread farther than usual up and down the coast.

Photosynthesis by microscopic marine algae produces living matter and oxygen that support much of life on Earth. However, some algal blooms can harm marine life, human health, recreation, tourism, and the economic vitality of coastal communities. Such blooms are referred to as harmful algal blooms (HABs). HAB hotspots exist along the Central and Southern California coast. These regions have been the focus of a National Oceanic and Atmospheric Administration (NOAA) project examining natural and human-caused factors affecting water quality and HABs. A better understanding of the ecology and oceanography of these HAB hotspots will provide a foundation for prediction and mitigation.

During the spring bloom, a team of MBARI researchers working on the Controlled, Agile, and Novel Observing Network Initiative, known as CANON, collaborated with researchers from the University of California, Santa Cruz; Moss Landing Marine Laboratories; the University of Southern California; the Southern California Coastal Water Research Project; and NOAA to study the event. The MBARI team was led by John Ryan, Holly Bowers, and Yanwu Zhang. The impacts on the area food web were evident, including the appearance of dead seabirds and fishes on the beach in front of the MBARI facilities (Figure 2a). An examination of beached anchovies revealed that their guts were full of *Pseudo-nitzschia* (Figure 2b), a type of phytoplankton that can produce the potent neurotoxin domoic acid. Toxic blooms of this type have previously caused increased marine life mortality throughout the northeast Pacific.

The bloom in Monterey Bay was part of a larger HAB outbreak occurring throughout the greater Northeast Pacific. This outbreak resulted in the closure of fisheries in California, Oregon, and Washington. California Department of Public Health advisories for Monterey and Santa Cruz Counties warned consumers not to eat recreationally harvested mussels and clams, commercially or recreationally caught anchovies and sardines, or the internal organs of commercially or recreationally caught crabs. Over a larger scale, detection of persistent and dangerous levels of domoic acid in crabs motivated the health advisory that consumers avoid eating Dungeness and rock crabs caught between California's northern border and southern Santa Barbara County. The prolonged closure of the Dungeness crab fishery in California was a devastating development for local fishermen, seafood processors, and restaurateurs. Economic losses were so

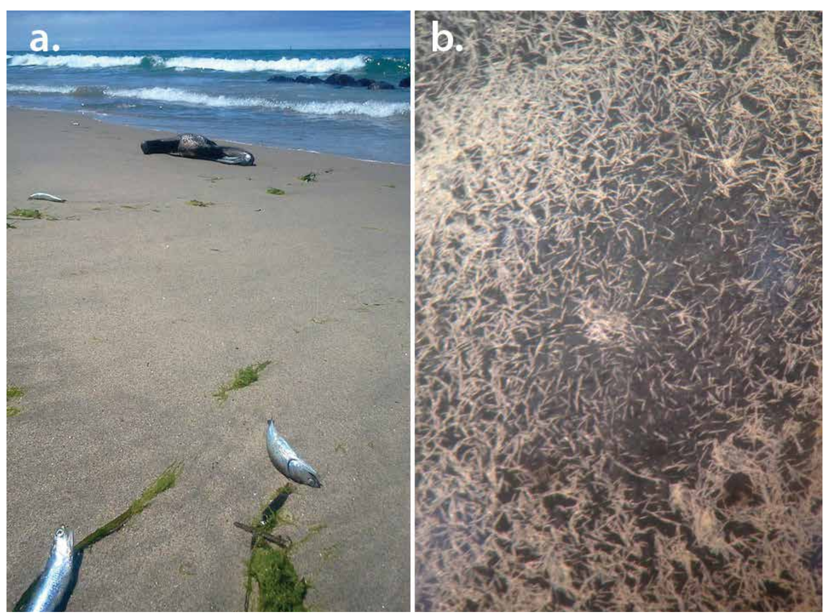


Figure 2. (a) Dead pelican and anchovies on the beach near MBARI. (b) View of anchovy gut contents through the microscope. Pseudo-nitzschia *cells (66 – 144 microns long) from the anchovies were not living and thus had no color from chlorophyll.*

great that the U.S. Small Business Administration offered low-interest disaster loans to commercial crab fishermen and other businesses affected by the closure.

This large-scale harmful algal bloom was also the topic of a congressional briefing in fall 2015. Federal, state, and academic institutions contributed to the testimony, describing the HAB as exceptionally persistent, widespread, and toxic. Its occurrence was linked to a warm temperature anomaly in the Northeast Pacific described as "the blob". Economic losses were estimated at $100 million, largely due to closures of razor clam and Dungeness crab fisheries. The fundamental research surrounding the HAB in Monterey Bay not only made headway scientifically, but also demonstrated how the knowledge gained impacted resource management and decision making.

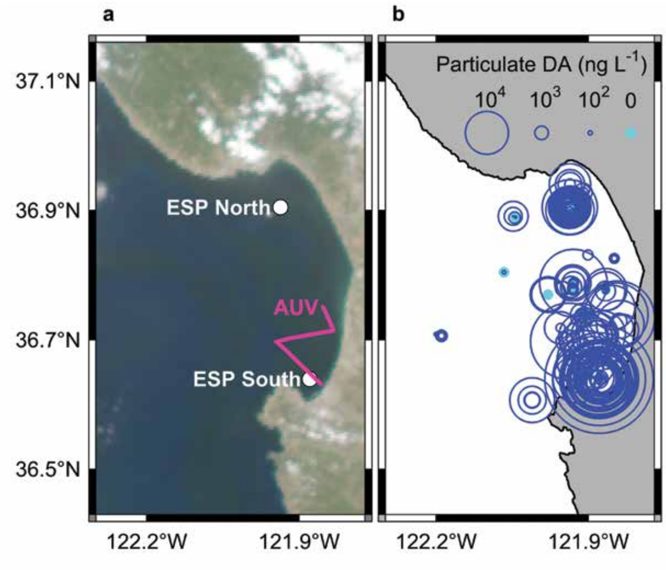


Figure 3. (a) True-color satellite image of Monterey Bay from May 15, 2015. Locations of the ESP moorings and Dorado *AUV surveys are shown. (b) Particulate domoic acid (DA) concentrations in nanograms per liter measured in samples from ESPs, ships, and the AUV.*

A number of MBARI instruments and platforms were employed in the study. Among them was the Environmental Sample Processor (ESP), an instrument that detects the genetic material of targeted species and toxins to determine their abundance. ESPs were deployed within known bloom incubation areas of northern and southern Monterey Bay (Figure 3a). Algal toxins were measured in samples acquired by ships, the *Dorado* autonomous underwater vehicle (AUV), and the ESPs. Persistent ESP sampling yielded detection of the highest toxin concentrations measured from sampling by any platform (Figure 3b, southern ESP site).

Pseudo-nitzschia australis has historically been the strongest domoic acid producer in Monterey Bay. Prior to this harmful algal bloom, monitoring showed that *P. australis* was present in low abundances. During spring the phytoplankton community composition rapidly evolved and *P. australis* became dominant. The ESP time-series revealed distinct patterns in the variation of algal toxin concentrations and the primary toxin-producing species, as well as variation in other *Pseudo-nitzschia* species (Figure 4a, b).

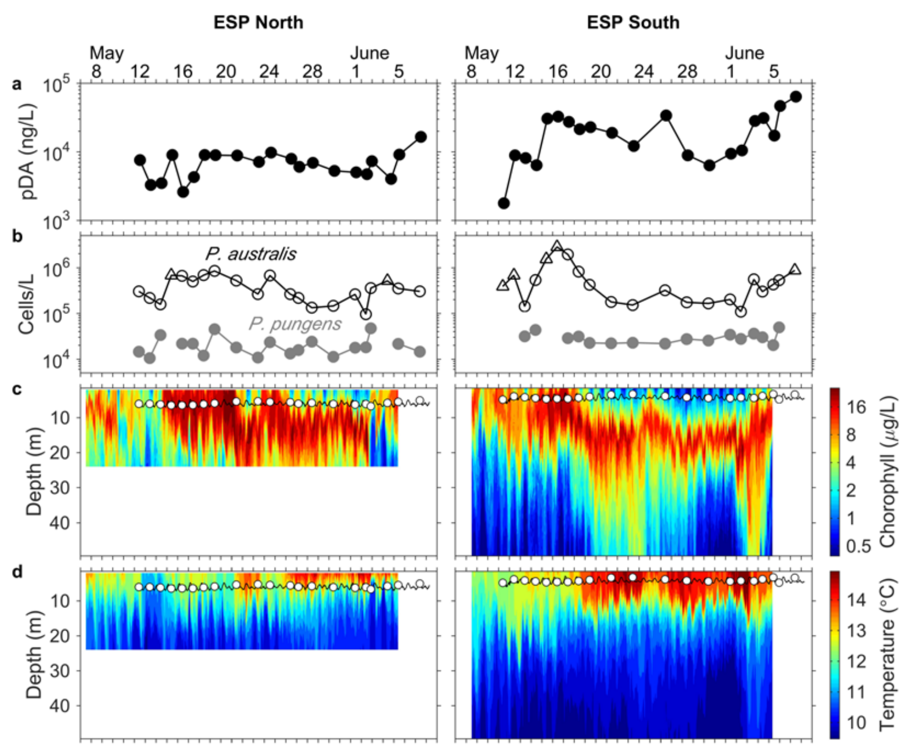


Figure 4. (a,b) Concentrations of particulate domoic acid (DA, the algal toxin) in nanograms per liter, and cells per liter of DA-producing phytoplankton at each ESP. (c,d) Water-column biological (chlorophyll in micrograms per liter) and temperature variations from autonomous profilers moored next to each ESP. ESP depth (black line) and sampling events (circles) are indicated.

Measurement of toxin production by species collected in the bay and grown in the lab confirmed the prominence of toxicity from *P. australis*.

Despite detection of similar cell concentrations at both ESP locations, toxin concentrations were much higher in the southern bay (Figure 4a, b). Examining this ecological distinction required observations of environmental differences between the northern and southern bay. Detailed environmental measurements were provided by autonomous vertical profilers deployed next to each ESP. The data gathered showed that the warm surface layer extended to a greater depth at the southern site, and that ESP sampling at this location was within that warm upper layer (Figure 4d). In contrast, sampling at the northern site was primarily below the shallower and less-developed warm surface layer. Further, the thicker warm layer at the southern site was associated with deeper occurrence of the densest phytoplankton populations (Figure 4c, d). This placed concentrated phytoplankton populations further below ESP sampling, thus making it more surprising that higher toxicity was detected at the southern site.

Because ESPs were moored at a fixed depth and the maximum concentrations of phytoplankton descended below the ESPs during much of the study (Figure 4c, d), examination of the most densely concentrated HAB populations required other sampling methods. MBARI's *Dorado* AUV, equipped with algorithms for directing the acquisition of water samples using the gulper system, played a key role in this regard (Figure 5). This AUV system was deployed twice in the southern bay, where the ESPs reported higher levels of toxin (Figure 3b, 4a). Deployments occurred during contrasting phases of wind forcing, which dramatically altered the distribution of water properties and phytoplankton (Figure 6).

Figure 5. AUV Operations Engineer Duane Thompson sets a gulper water sampler into the AUV for a mission in Monterey Bay.

During the first AUV survey, on May 28th, phytoplankton populations were concentrated relatively deep in the water column. This biological pattern was associated with a relatively warm and nutrient-depleted upper ocean, which was in turn caused by relatively weak wind-forced upwelling during the preceding weeks. During the second AUV survey, on June 5th, the phytoplankton populations were much closer to the surface. This biological pattern was associated with a relatively cool, nutrient-enriched upper ocean, which was in turn caused by intensification of winds that contribute to upwelling. Salinity observations, which uniquely permit detection of contrasting water types, also revealed enhancement of water-column complexity associated with the upwelling event (Figure 6d).

For both AUV surveys, the *Dorado* AUV independently applied an algorithm designed to sample phytoplankton populations at their maximum concentration in the water column. The use of this algorithm led to the successful triggering of water samplers within different areas of a dense subsurface phytoplankton layer that extended throughout the southern bay (Figure 6).

AUV samples were returned to shore and examined in multiple ways. Microscopy revealed that this biological layer was dominated throughout by *Pseudo-nitzschia*, and further that the *Pseudo-nitzschia* populations were dominated by the larger size class which includes the most toxic species. Domoic acid measurements showed high concentrations throughout the southern bay plankton layer during both surveys. One focus of this study was the ecology of subsurface layers of *Pseudo-nitzschia*, and the AUV data clearly showed that the populations residing deeper in the water column were more toxic. These AUV observations provided valuable information to the staff at our partner institution, the Monterey Bay Aquarium, so that they could best manage their water filtration to avoid harmful consequences of the toxic algal bloom in exhibits.

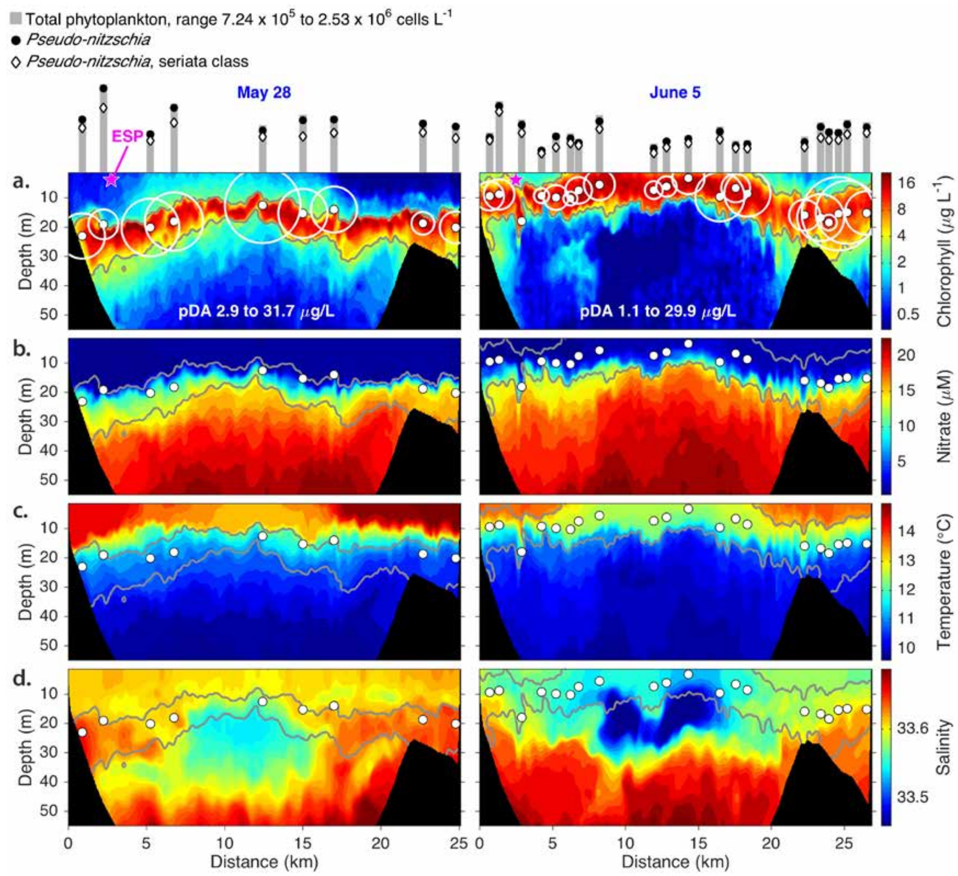


Figure 6. AUV surveys; track is shown in Figure 3a. Solid white circles show autonomously targeted sampling locations. Toxin concentrations are represented in the chlorophyll sections (panel a) by the size of the white circles around each sample location. Phytoplankton species composition is represented above each survey section (seriata is the larger of two size classes of Pseudo-nitzschia*).*

Throughout this intensive study, MBARI's Oceanographic Decision Support System (ODSS) and Spatial Temporal Oceanographic Query System (STOQS) provided a robust infrastructure for managing and understanding data from many observing assets. Extensive observations from MBARI's long-range AUVs, as well as gliders, will enable more thorough examination of the HAB environment, including its variation between the northern and southern ESP sites, and its variation in time in response to variable wind forcing of ocean circulation. Large quantities of water acquired by staff on ships supported experimental manipulation of the phytoplankton growth environment, so that phytoplankton responses can be understood in terms of the key factors regulating their growth and toxicity. Long-term observations from moorings and satellites, as well as ocean models that assimilate these data, will support examination of the regional warm "blob" in which this exceptional bloom occurred.

Collaboration between the NOAA project team and the MBARI CANON Initiative was highly synergistic. MBARI technologies focused upon the challenging arena of multidisciplinary ocean research yielded many insights into the complex ecology of an exceptional HAB event, one that affected the ecology and economy of the greater northeast Pacific and drew the attention of Congress. Just as the research benefited from these technology applications, so too did technology development benefit from being applied to the pressing and expanding global problem of HABs. The studies made it clear that researchers cannot rely solely on moored instruments and limited collections of water samples to fully characterize dynamic processes like HABs; it takes the combination of mobility, adaptability to the conditions at hand, and various sampling methods to piece together the evolution of moving targets such as algal blooms. With that in mind, MBARI scientists and engineers are developing a new generation of the ESP instrument for use with the long-range AUV to advance a combined persistence, intelligent sampling, and autonomous analytical capability.

How does a tiny larvacean impact the cycling of carbon?

All biological and physical processes in the ocean are governed by the physics of fluid motion. Fluid movement, both large- and small-scale, has significant impact on the organisms that inhabit the ocean and on global phenomena such as biogeochemical cycling. Understanding the constraints that the fluid environment places on organisms and geochemical processes is an important step to understanding how marine systems function and how they will ultimately respond to a changing ocean.

Fluid motion in the ocean cascades from large, global-scale currents to the microscale flows generated by feeding and swimming marine zooplankton. The oceanographic community has been very successful at developing a variety of instruments and platforms to investigate and measure global and mesoscale processes in the ocean. Unfortunately, these methods are limited by their temporal and spatial resolution, and cannot adequately detect fluid motion at size scales relevant to the vast majority of organisms in the ocean. Measurements of fluid motion at these scales could inform topics ranging from predator-prey interactions in midwater and the health of coral reefs, to the fate of hydrocarbons in the deep sea. Being able to measure fluid motion at these smaller scales will allow us to elucidate how organisms really interact with their dynamic, fluid world.

To address these challenges, engineers and scientists at MBARI are bringing the laboratory into the ocean by developing instrumentation that allows for small-scale, high-resolution temporal and spatial measurements of fluid motion. Particle image velocimetry (PIV) is a widely used laboratory technique among fluid-mechanics researchers to study the motion of flows over complex structures and those induced by various mechanical and biological systems (Figure 7).

PIV measurements require a high-speed and high-resolution camera, a high-powered and structured light source, and neutrally buoyant particles in a fluid. The availability of particles is essential to the technique, since their presence and motion is used to infer the motion of transparent fluid. Luckily, the ocean is filled with particulate matter that can be used to measure fluid motion. The relative positions of the camera and light source are fixed throughout the measurement, and specialized optics are used to create a light sheet that illuminates a plane perpendicular to the camera. The camera captures the motion of particles in the light sheet. Post-processing of these images is then used to determine the speed and direction of the fluid. These data can be used to quantify the variables related to force generation, energy expenditure, power, and performance.

A team of engineers and scientists at MBARI, led by Electrical Engineer Alana Sherman and Postdoctoral Fellow Kakani Katija, began developing an instrument called DeepPIV that can be used to conduct PIV measurements. This instrument is deployed on a remotely operated vehicle (ROV). It allows for the measurement of small-scale fluid motions from the sea surface to the seafloor. Due to its small size and testing capabilities, the MiniROV was used for initial development of DeepPIV instrumentation (Figure 8). As a proof-of-concept, the original design for DeepPIV involved deploying a laser with optics to create a laser sheet, where naturally suspended particle motion revealed in the laser sheet is captured by the MiniROV's high-definition camera. A one-watt, red laser is packaged within a housing that is attached to the MiniROV via a rigid arm. Controller electronics and sensors are included in a separate housing mounted on

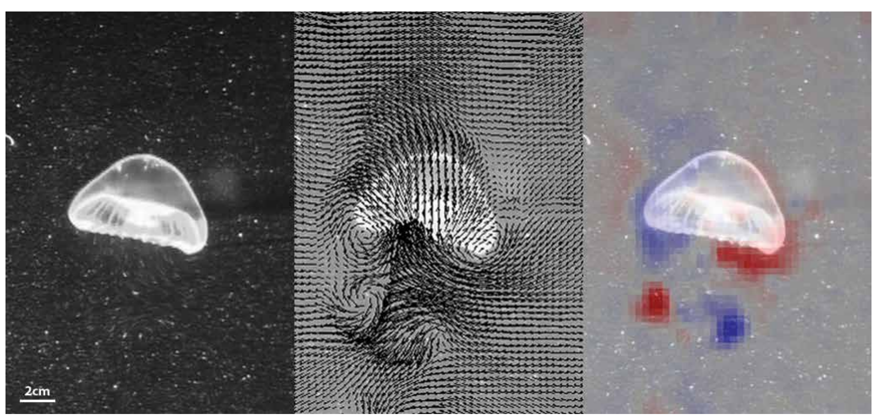


Figure 7. Laboratory studies using particle image velocimetry (PIV) have yielded insightful results including how background turbulence alters predation impact, comparative swimming and feeding performance of gelatinous zooplankton, and whether marine organisms can generate appreciable mixing in the water column. In this particular study of a swimming and feeding jelly, the feeding mechanisms were elucidated in the laboratory and compared with field conditions (image modified from Katija et al., 2011). Left, raw particle fields; center, velocity fields (black vectors represent local fluid speed and direction) corresponding to the same time step; right, vorticity fields represent rotational sense (red shows clockwise rotation; blue shows counter-clockwise rotation) in a fluid and informs the spatial extent of hydrodynamic signatures generated by a swimming and feeding organism.

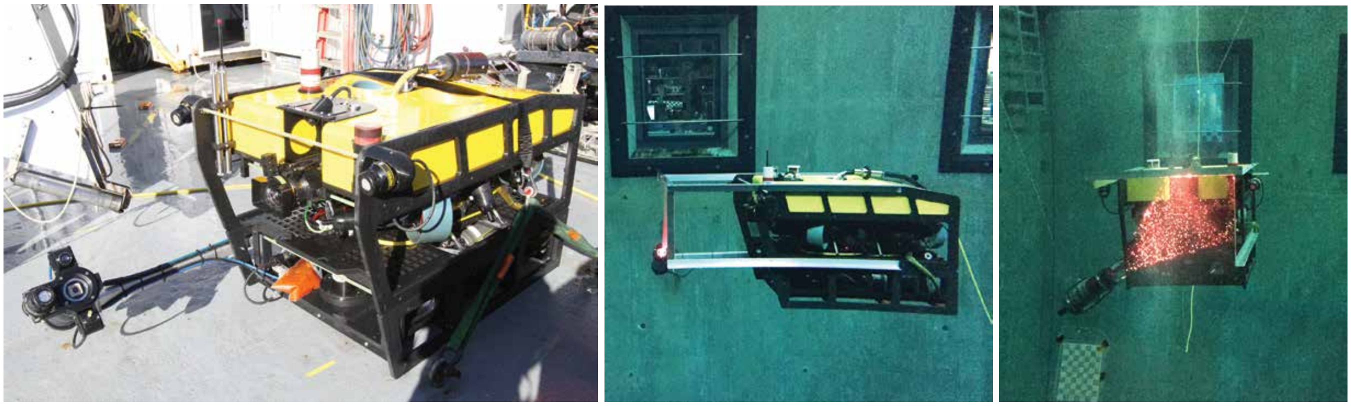


Figure 8. The DeepPIV instrument package is deployed using the MiniROV as a development platform. Left, the laser housing consists of a red laser, optics, and associated sensors and electronics, and is attached to the MiniROV via a rigid, aluminum arm. Center, early tests of the instrumentation were conducted in MBARI's test tank. Right, a sheet of bubbles was used to provide scattering particles for the laser sheet.

a toolsled under the ROV. In addition to the laser components, a camera and near-infrared light mounted in line with the laser sheet were added to help the ROV pilot align the instrument with the science target (Figure 8).

Development of any in situ instrument is a challenging process. Careful selection of scientific targets was necessary to test the proof-of-concept DeepPIV instrumentation. Since PIV requires the vehicle to minimize motion with respect to the science target, our first targets involved "stationary" midwater organisms such as larvaceans (Figure 9).

Larvaceans are important players in the flux of carbon through ocean food webs. These animals, which resemble tadpoles, excrete complex mucus structures commonly called "houses". By beating its tail to generate a current through the house, a larvacean filters and concentrates food that is later ingested by the animal. Once its filters become clogged, the larvacean abandons its house. The sinking of these carbon-rich mucus structures have been shown to contribute a third of all carbon reaching the seafloor from the upper layers of Monterey Bay. Monterey Bay is home to larvaceans *Bathochordaeus stygius*, *Bathochordaeus charon*, and an undescribed *Bathochordaeus species*, called the giant larvaceans because they have the largest known body size (to 10 centimeters long) and house structures (on the order of one meter in diameter) of all larvaceans. Learning the function and structure of these houses can therefore yield clues in our understanding of larvacean ecology and evolution, in addition to answering questions about their considerable role in transporting carbon through the water column.

The 13 DeepPIV deployments in 2015 provided a completely new way to visualize how these organisms and their houses function, shedding light on this complex but effective filtration process. Preliminary DeepPIV measurements of volumetric filtration rates by giant larvaceans in Monterey Bay have revealed that these organisms are filtering at rates nearly an order of magnitude larger than previously thought when compared to previous indirect studies using biomechanics and dye motion as a proxy. Although these findings are preliminary, these measurements seem to indicate that in addition to their role in the flux of carbon to the seafloor, the presence of giant larvaceans can have a significant impact on the processing of food and nutrients in the ocean. In light of these findings, further deployments of the DeepPIV to quantify the filtration rates of other filter feeders in

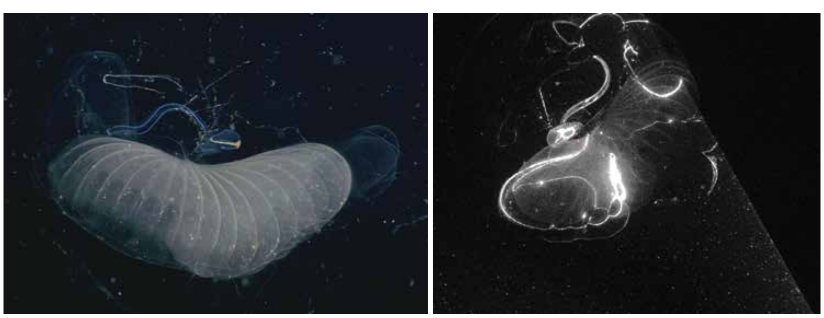


Figure 9. Snapshots of a giant larvacean Bathochordaeus *sp. using white light (left) and DeepPIV's laser sheet (right). White light illumination provides bulk information on the shape of the larvacean house and movement of the organism; the laser sheet reveals a two-dimensional cross-section of the organism within its house, where bright intensities correspond to the organism, the boundaries of the mucus house structure, and naturally suspended particles in the water.*

the midwater and on the seafloor (such as salps and sponges) could reveal how populations of these organisms alter food webs and the transport of nutrients throughout the water column.

The DeepPIV instrumentation has also been used in a novel way to reveal and visualize gelatinous and mucus structures that have not been identified or described before. Using the light sheet generated by the DeepPIV's laser, a cross-section of a gelatinous organism or mucus structure can be revealed (Figure 10, top panels). Moving the DeepPIV instrumentation through the object of interest results in a stack of images representing multiple cross-sections through the volume. In a technique similar in concept to medical magnetic resonance imaging (MRI), the stack of images can be used to reconstruct a three-dimensional model of the object (Figure 10, bottom panels). Using this technique, the three-dimensional structure of larvacean mucus houses has been created and used to show the function and internal flows generated in the house by the flapping larvacean tail.

Since gelatinous structures are difficult to collect and study in a laboratory environment, these novel visualization tools will allow scientists and engineers to study diaphanous and often complex structures in detail in the natural environment. For example, information gathered using DeepPIV has allowed three-dimensional reconstructions of organisms and structures whose delicate and complex structures could not otherwise be studied in the laboratory.

Initial deployments of DeepPIV have already shed light on the significance to the carbon cycle of the small, tadpole-like larvacean flapping in the ocean depths. As additional targets and questions are identified—through collaborators at MBARI and elsewhere—the utility of DeepPIV will likely continue to expand, building upon the early success of this new tool.

MBARI technology fills important niche in global climate studies

The Southern Ocean basin has a profound influence on Earth's climate and ecosystems. In most of the world's ocean, a layer of warm surface water acts as an insulator between the cold, deep waters and the atmosphere. This limits the flow of heat and carbon dioxide into the abyss. But in the Southern Ocean, the deep waters are exposed directly to the atmosphere due to strong cooling in winter and high winds. This allows the Southern Ocean to absorb much larger amounts of heat and carbon dioxide than other ocean areas.

One half of the oceanic uptake of carbon dioxide and 90 percent of the ocean heat uptake occurs in the Southern Ocean. These processes have a significant, moderating effect on the influence of fossil-fuel carbon-dioxide emissions on global climate by providing a conduit for heat and carbon dioxide to the vast reservoir of the deep sea. But as the Southern Ocean warms it is possible that deep mixing will weaken and the Southern Ocean may absorb less heat and carbon dioxide. Such a change would greatly accelerate the negative impact on climate that is associated with fossil-fuel emissions.

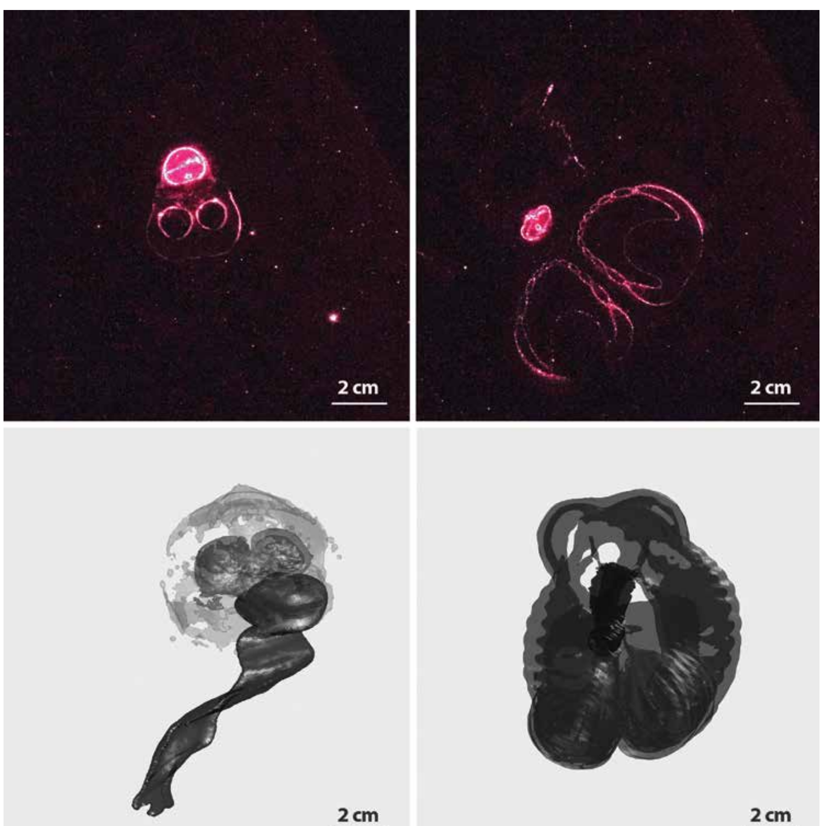


Figure 10. Top panels, the structured light deployed on DeepPIV can reveal the size and shape of complex, gelatinous or mucus structures. Bottom, during a DeepPIV deployment in August, a larvacean building a mucus house was observed, and three-dimensional reconstructions were generated from the start (left) to the end (right) of house construction.

In addition, the deep waters exposed at the surface of the Southern Ocean are naturally enriched in carbon dioxide from the respiration of marine organisms. These already high carbon-dioxide concentrations are being driven to even greater values by increasing carbon dioxide in the atmosphere. This has produced more acidic seawaters—waters with low pH values—that will eventually result in dissolution of calcium carbonate minerals, an ecological challenge to organisms that build calcareous shells. There is already evidence that calcareous organisms are being stressed by low pH conditions in the Southern Ocean.

Despite its importance to global climate and potential ecosystem shifts, the Southern Ocean is the least observed part of the world ocean. Few research vessels sail in these waters, particularly during the austral winter when storms and ice abound. Most of our understanding is based on computer models with limited observations to validate the results.

To address this challenge, MBARI Scientist Ken Johnson and his Chemical Sensors Group have teamed up with a core team of researchers—primarily from Princeton University, Scripps Institution of Oceanography, University of Washington, University of Arizona, and Climate Central—in the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program. Altogether, 23 principal scientists from 11 institutions are participating in the program, enabled by a variety of external funding sources, principally the National Science Foundation Division of Polar Programs, the NOAA Office of Climate Programs and the NASA Ocean Biology and Biogeochemistry Program.

The SOCCOM program has begun deploying hundreds of profiling floats (Figure 11) in the Southern Ocean that are equipped with pH and nitrate sensors designed, constructed, and calibrated by the MBARI team.

Profiling floats are free-drifting platforms that park at 1,000-meters depth. Every 10 days, a float descends to 2,000-meters depth and then rises to the surface making chemical and biological measurements along the way. The results are transmitted by satellite to MBARI, where they are made available in real time to the global research community and the public through the MBARI website. Floats can repeat this cycle hundreds of times over a lifetime of about six years. The data reported by sensors on the floats allow SOCCOM researchers, as well as other interested scientists, to track the major components of the carbon cycle, including ocean uptake of carbon dioxide. These sensors also provide an assessment of ecosystem metabolism through

Figure 11. SOCCOM scientists deploying a profiling float from the R/V Palmer *in the Southern Ocean in 2014.*

changes in dissolved oxygen, carbon dioxide, and nitrate concentrations. The long endurance of the floats allows seasonal and interannual variations in carbon cycling and metabolism to be determined in areas where samples may never have been collected otherwise.

The SOCCOM program began in 2014 by deploying 12 floats in the Ross Sea region as a technology demonstration. Seven of these floats were equipped with Deep-Sea DuraFET pH sensors developed at MBARI and 10 carried MBARI's in situ ultraviolet spectrophotometer (ISUS) nitrate sensors. These floats have provided the first-ever record of the year-round pH variability in open waters of the Southern Ocean (Figure 12).

A second set of 12 floats were deployed in the austral fall of 2014-15 near the Weddell Sea after incorporation of modest changes following a review of the data returned by the first set of floats. This second set of floats has recently completed a year of operation in ice-covered waters. These floats show remarkable phytoplankton blooms and shifts in the carbon system along the ice edge. This is a phenomenon that has been observed before, but never over a complete seasonal cycle.

Thirty-four floats and sensors were constructed in 2015 to be deployed during austral fall of 2015-16, primarily in the Indian Ocean sector of the Southern Ocean. Ten of those floats are already in the water and transmitting data. The program will continue for four more years with the deployment of an additional 30 to 40 floats each year.

As the program moves forward, the data will be assimilated into an ocean state estimate model operated at Scripps Institution of Oceanography. This type of model is similar to a weather model in the atmosphere, which uses data from hundreds of weather stations to refine its predictions. The ocean state estimate, one of the first of its kind that incorporates the cycling of carbon, will provide a synthesized view of ocean carbon uptake, net production of carbon (photosynthesis minus respiration), and export of carbon into the abyss. The results of the state estimate will then be used to assess and improve the performance of coupled ocean and atmosphere models that can predict future climate trends. Implementation of the SOCCOM project will, ultimately, result in a greatly improved understanding of the ocean-atmosphere climate system.

MBARI's long-term investment in developing sensor technology targeted to basic ocean science needs underpins this project, which takes those developments out into the greater world to study changes that impact all of humanity.

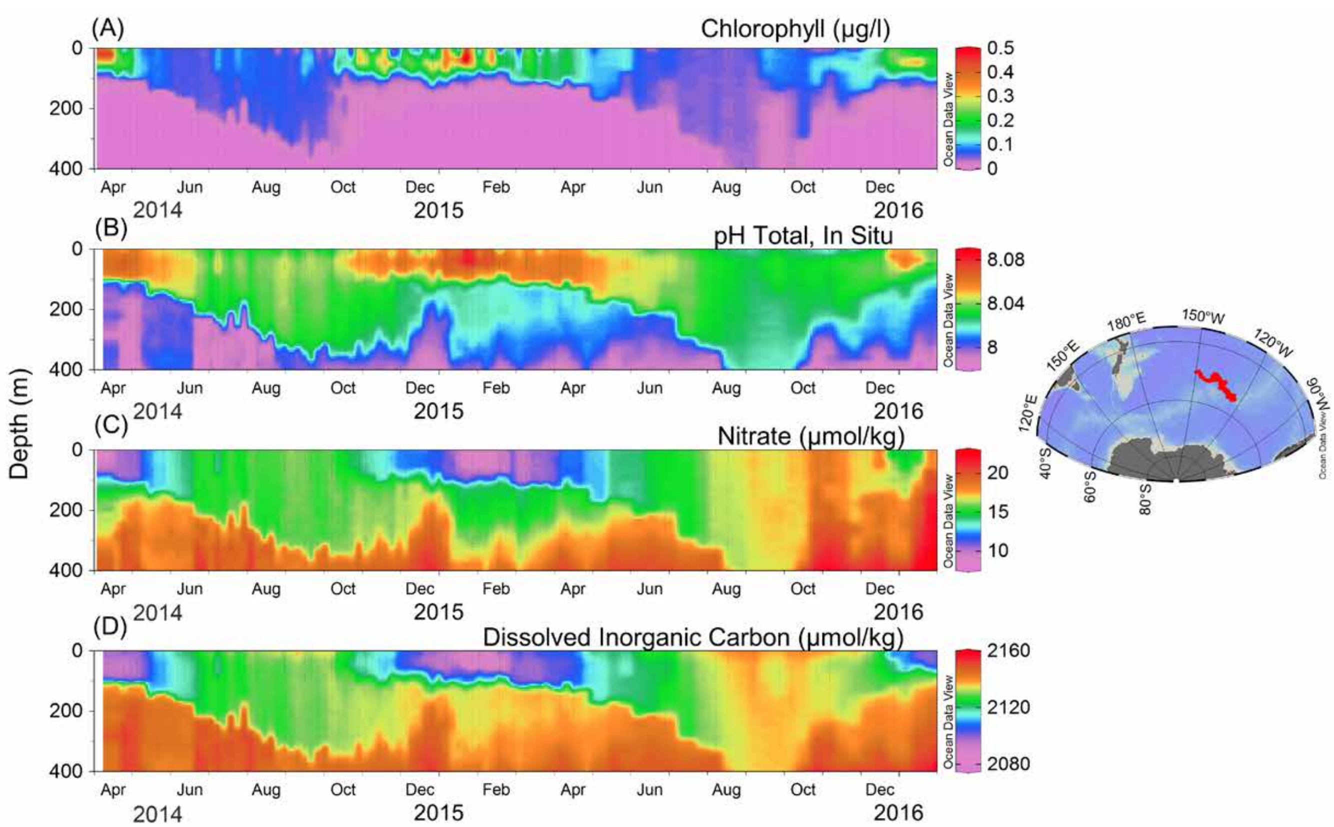


Figure 12. Twenty-two months of data from profiling float 9095, near 50°S, in open waters of the Pacific sector of the Southern Ocean. Portions of three annual phytoplankton blooms are reflected in chlorophyll concentration (A). Phytoplankton growth drives pH to higher values (B), as nitrate (C) and dissolved inorganic carbon (D) are consumed during production of organic matter during photosynthesis. The deep mixing that exposes abyssal waters to the surface is seen each September when properties become nearly homogeneous in the top 300 meters of water.

Bringing the public into the world of deep-sea research

Imagine seeing a remotely operated vehicle cruising along the walls of an undersea canyon. Dreamlike, but not a dream—this is the vision that greets visitors to the Monterey Bay Aquarium's new "Mission to the Deep" exhibit about MBARI. Entering the new exhibit, one is immersed in a virtual underwater world. As a scale model of MBARI's ROV *Doc Ricketts* rotates overhead, the vehicle's lights penetrate the darkness and highlight strange deep-sea animals projected on the walls. A blue-eyed vampire squid swims past and jellies more than a meter across float in and out of view. The 360-degree video projection system displays rocky canyon walls and underwater robots deep in Monterey Canyon. In this mysterious setting, visitors discover how MBARI's scientists and engineers use a variety of revolutionary new technologies to study the ocean (Figure 13). The program highlights the latest tools developed by MBARI engineers, including autonomous underwater vehicles that MBARI researchers use to explore deep-sea environments.

At the center of the exhibit, interactive displays allow children and adults to guide their own ROV dives, stopping at different depths to learn more about animals and research equipment in the deep sea. MBARI staff were integral to the creation of the new exhibit. MBARI scientists contributed their expertise and spectacular underwater videos to the exhibit. MBARI engineers designed and built the model of the *Doc Ricketts*, as well as the automated mechanisms that animate the model.

Visitors can learn even more about MBARI in the aquarium's newly revised auditorium program "Exploring the Deep Sea." Featuring live narration and stunning high-definition video, the program highlights the challenges of studying the deep sea and the amazing underwater technology that MBARI researchers use in their investigations. The program also provides a big-picture view of MBARI's history and the institute's ongoing research efforts to understand the changing ocean.

With more than a million visitors a year, the Monterey Bay Aquarium offers an exceptional outlet for education and outreach about MBARI research and engineering efforts. The remodeled "Mission to the Deep" exhibit and the revised auditorium program will provide opportunities to share with the public what MBARI researchers experience on a regular basis—discoveries in Monterey Bay that shed light on marine life and processes throughout the global ocean.

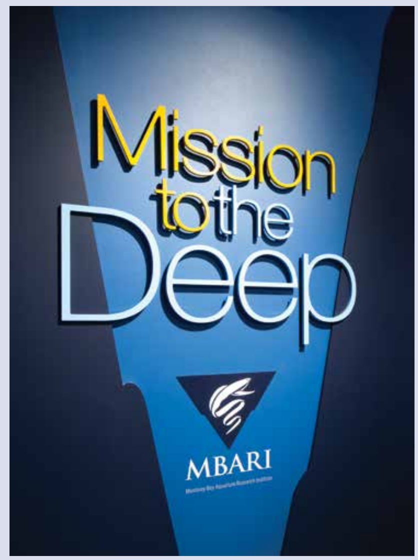


Figure 13. The Monterey Bay Aquarium exhibit invites visitors to experience a simulated dive into the ocean depths. Top, the entrance to the exhibit. Bottom, visitors can control dives from the interactive panel in the center of the room, while the model of an MBARI remotely operated vehicle mounted above surveys the canyon walls around the room.

Related web content:

Central and Northern California Ocean Observing System interactive El Niño data: www.cencoos.org/learn/elnino
Southern Ocean Carbon and Climate Observations and Modeling Program: soccom.princeton.edu
Southern Ocean Carbon and Climate Observations and Modeling data: www.mbari.org/soccom
Monterey Bay Aquarium Mission to the Deep: www.montereybayaquarium.org/animals-and-experiences/exhibits/mission-to-the-deep

Project teams:

Aquarium-MBARI Partnerships

Project lead/manager: George Matsumoto
Project team: Stephanie Bush, Judith Connor, Frank Flores, Kim Fulton-Bennett, Kevin Gomes, Dale Graves, Kakani Katija, William Kirkwood, Lonny Lundsten, Thom Maughan, Paul McGill, Melinda Nakagawa, Craig Okuda, Mike Parker, Josh Plant, Bruce Robison, Jose Rosal, Kyra Schlining, Jim Scholfield, Farley Shane, Jordan Stanway, Nancy Jacobsen Stout, and Susan von Thun
Collaborators: Hank Armstrong, Athena Barrios, Rita Bell, Alicia Bitondo, Christy Chamberlain, Mike Chamberlain, Paul Clarkson, Jim Covel, Jeff Doyle, Andrew Fischer, Randy Hamilton, Tommy Knowles, Koen Liem, Sue Lisin, Kenneth Maguire, Andrea McCann, Enrique Melgoza, Eric Nardone, Raul Nava, Chris Payne, Ken Peterson, Margaret Spring, Scott Stratton, Kim Swan, Jaci Tomulonis, Cynthia Vernon, Patrick Webster, and Mary Whaley, Monterey Bay Aquarium, Monterey, California

Controlled, Agile, and Novel Observing Network

Project leads: Francisco Chavez, Steven Haddock, Chris Scholin, Robert Vrijenhoek, Alexandra Worden
Project manager: Francisco Chavez
Project team: Marguerite Blum, Danelle Cline, Duane Edgington, Kevin Gomes, Brett Hobson, Brent Jones, Brian Kieft, Thom Maughan, Mike McCann, Monique Messié, Reiko Michisaki, Tim Pennington, Carlos Rueda-Velasquez, John Ryan, Jason Smith, Jordan Stanway, Chris Wahl, Yanwu Zhang

DeepPIV: Measuring Fluid Motion in the Deep Sea

Project lead: Alana Sherman
Project manager: Kakani Katija
Project team: Dale Graves, Chad Kecy, Denis Klimov
Collaborator: Bruce Robison, MBARI

Monterey Bay Time Series

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Marguerite Blum, Gernot Friederich, Jules Friederich, Brent Jones, Monique Messié, Reiko Michisaki, Erich Rienecker, Jeff Sevadjian, Chris Wahl

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: Holly Bowers, Francisco Chavez, Kevin Gomes, Brett Hobson, Scott Jensen, Brian Kieft, Denis Klimov, Roman Marin III, Mike McCann, Doug Pargett, Christina Preston, Brent Roman, Jordan Stanway, Yanwu Zhang
Collaborators: David Caron and Burt Jones, University of Southern California, Los Angeles; Raphael Kudela, University of California, Santa Cruz; G. Jason Smith, Moss Landing Marine Laboratories, California; Gregg Doucette, National Oceanic and Atmospheric Administration/National Ocean Service, Charleston, South Carolina; Yi Chao, National Aeronautics and Space Administration

Southern Ocean Carbon and Climate Observations and Modeling

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Hans Jannasch, Josh Plant, Carole Sakamoto
Collaborators: Steve Riser, University of Washington, Seattle; Joellen Russell, University of Arizona, Tucson; Jorge Sarmiento, Princeton University, New Jersey; Lynne Talley, Scripps Institution of Oceanography, La Jolla, California

Targeted Sampling by Autonomous Underwater Vehicles

Project leads: Francisco Chavez, Bruce Robison, John Ryan, Chris Scholin, Robert Vrijenhoek, Yanwu Zhang
Project manager: Yanwu Zhang
Project team: Brett Hobson, Brian Kieft, Denis Klimov, Rob McEwen, Ed Mellinger, Carlos Rueda-Velasquez, Jordan Stanway
Collaborator: James Bellingham, Woods Hole Oceanographic Institution

The 2015 Gulf of California Expedition

Mexico's Gulf of California holds special scientific appeal because of its nutrient-rich surface waters filled with life, its extensive layer of oxygen-poor water, and the many hydrothermal vents, undersea volcanoes, and zig-zag faults that have shaped its seafloor. A repeat visit to the Gulf in 2015 provided the opportunity to investigate whether changes in the Gulf that were observed between MBARI's 2003 and 2012 expeditions have persisted or intensified. It also provided an excellent occasion to explore new territory—an effort that paid off handsomely with the discovery of a previously unknown hydrothermal vent field.

In addition to studying the diverse physical environments and the fascinating creatures that inhabit them, MBARI scientists and their Mexican collaborators compared life in the Gulf to life in the extensively studied ecosystems of Monterey Bay. In particular, the warm, low-oxygen waters of the Gulf may offer a window into the future of Monterey Bay under some climate change scenarios.

Both MBARI ships, the research vessel *Western Flyer* and the research vessel *Rachel Carson*, participated in the three-month expedition, providing complementary capabilities for exploring the Gulf from its surface to the seafloor (Figure 14).

Precise seafloor mapping using the autonomous underwater vehicle (AUV) *D. Allan B.* enabled the research teams to target specific areas to sample and image using remotely operated vehicles (ROVs). During the February-May expedition the mapping team conducted 20 surveys of high-resolution bathymetry and sub-bottom profiles from the R/V *Rachel Carson*. The maps provided support for geological and benthic biological studies in a range of areas in the Gulf as well as offshore of Ensenada along the Pacific Coast of Baja California (Figure 17).

Figure 14. The mapping AUV is recovered to the R/V Rachel Carson *after the ROV* Doc Ricketts, *aboard the R/V* Western Flyer *(in the distance), was used to cut it free from a derelict fishing line. Part of the line can be seen still attached to the AUV antenna.*

Encountering a much warmer ocean

The season's strongest storm accompanied the first part of the R/V *Western Flyer's* transit south from Monterey Bay. After a quick stop to collect data and water samples close to home, the ship headed south toward Ensenada, where the researchers and ship's crew welcomed Mexican students and collaborators aboard. MBARI Director of Marine Operations Steve Etchemendy arranged a special colloquium for local students and faculty and Scientist Francisco Chavez gave a talk at a new maritime museum. It was a chance to strengthen our

Figure 15. MBARI invited our Mexican partners and local students to a special colloquium and to tour the R/V Western Flyer *in Ensenada. From left, Universidad Autónoma de Baja California (UABC) student Jose Edwin Morales-Torres, UABC Professor Héctor Bustos Serrano, UABC Professor Rubén Castro, MBARI's Rosemary Martino-Rodriguez; and Director of the UABC Research Institute of Oceanography Asdrúbal Martínez Díaz de León.*

ties with—and to thank—our Mexican partners in this expedition (Figure 15).

It was easy to see that conditions in 2015 were significantly warmer than those observed in 2012. Plans were quickly modified to include additional collections of data at the same locations sampled during 2012. The story was consistent throughout the journey south: 2015 was two-to-three degrees Celsius warmer (Figure 16). The main objective of the first leg of the expedition led by Francisco Chavez was to measure the biogeochemical transformations in the very stratified environment at the mouth of the Gulf of California over a shallow oxygen minimum zone. Researchers compared those measurements with those measured routinely in Monterey Bay. Drifters were deployed at the mouth of the Gulf and scientists carried out in situ and simulated incubation experiments along the drifter paths. Preliminary results showed that the region was more stratified and lower in oxygen and primary productivity than Monterey Bay. These differences were reflected in the location of the nutricline and chlorophyll maximum, which were deeper at the mouth of the Gulf of California. The position of these two features was further reflected in the intensity and composition of the food web with less-concentrated, smaller biota dominating the plankton at the mouth of the Gulf.

A significant achievement was the deployment of in situ incubation chambers hung under the drifters. These chambers used

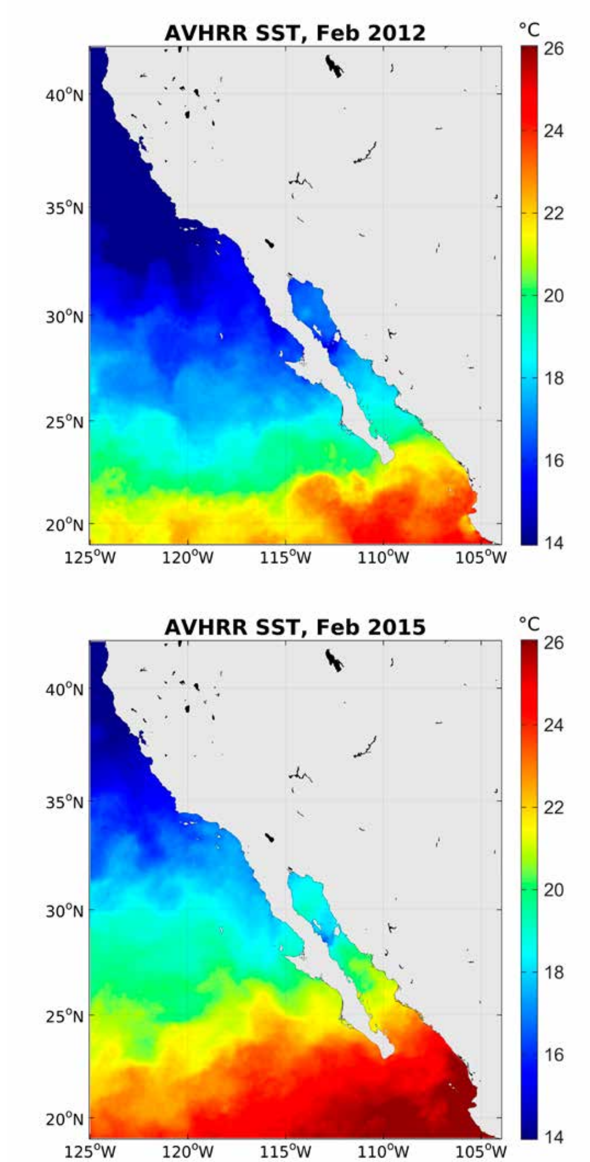
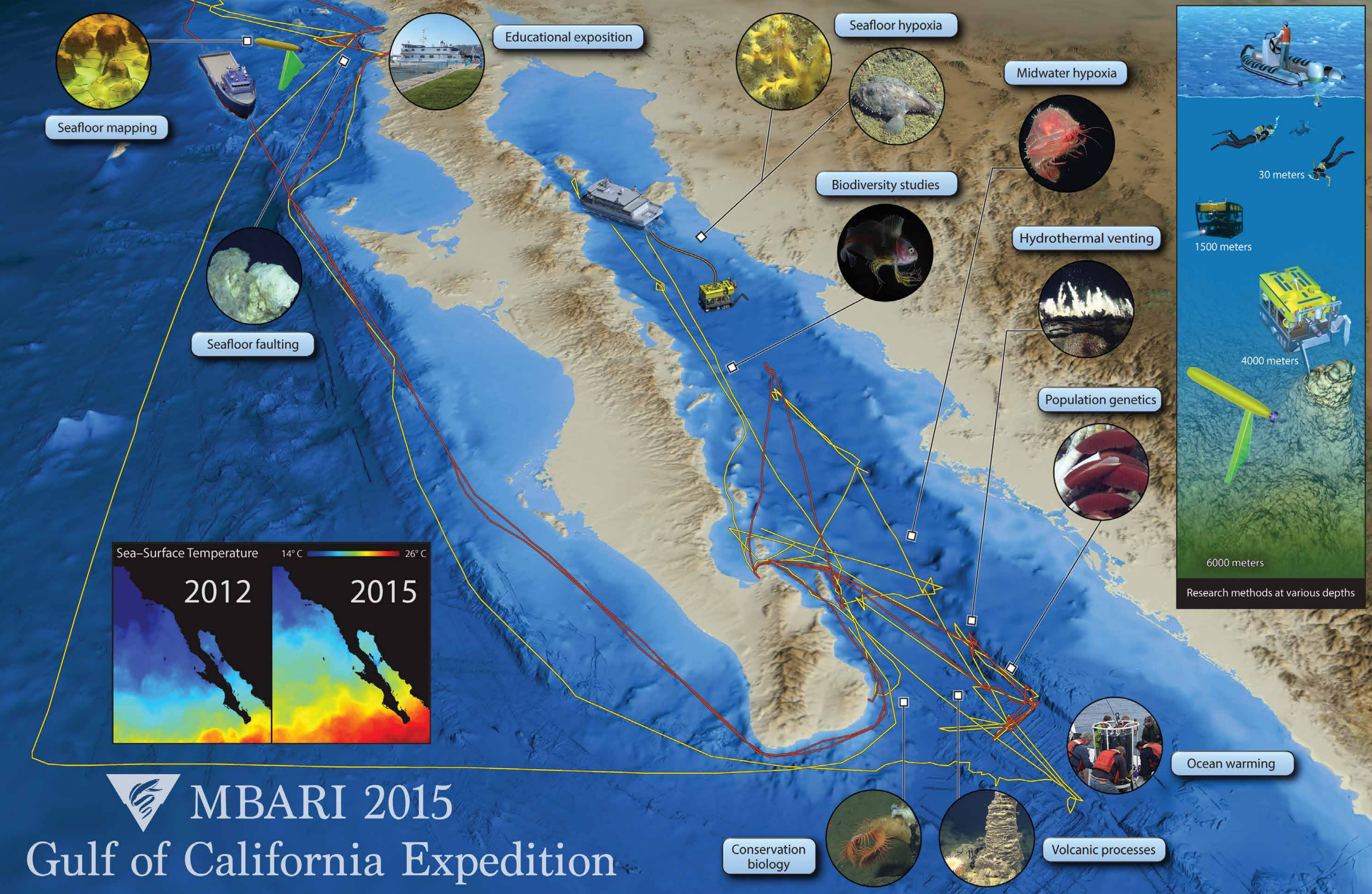


Figure 16. Comparison of sea-surface temperature along the west coast of California and Baja California in 2012 (above) and 2015 (below), showing a much warmer ocean in 2015.

Figure 17. (foldout image to right) MBARI's 2015 Gulf of California Expedition afforded seven different science groups the chance to conduct studies on a wide range of geological, ecological, biological, and physical features, and to compare these features and discoveries to those from other locales. The yellow line shows an approximation of the track covered by the R/V Western Flyer *with remotely operated vehicle* Doc Ricketts *(seen here in the northern end of the Gulf); the red line shows the track covered by the R/V* Rachel Carson *with the mapping AUV* D. Allan B. *(depicted here in the top left corner, off the Pacific coast). The inset at the top right shows the depths available to researchers via different methods and tools. The inset in the lower left shows the sea-surface temperatures were much warmer in the Gulf in 2015 than during the last MBARI expedition to the area in 2012.*


Seafloor mapping
Educational exposition
Seafloor hypoxia
Midwater hypoxia
Biodiversity studies
Hydrothermal venting
Seafloor faulting
Population genetics
30 meters
1500 meters
4000 meters
6000 meters
Research methods at various depths
Sea–Surface Temperature
14° C
26° C
2012
2015
Ocean warming
Conservation biology
Volcanic processes
MBARI 2015
Gulf of California Expedition

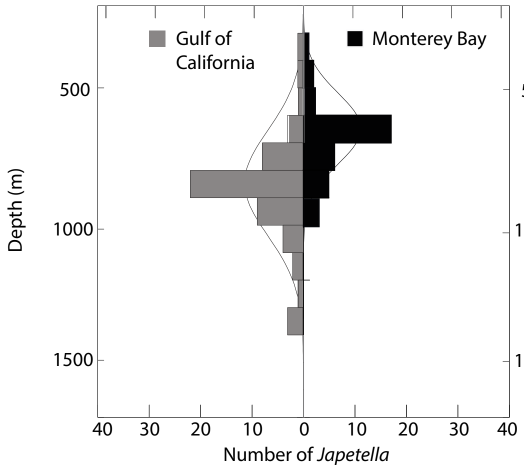


Figure 18. Plot showing at what depths the octopus Japetella diaphana *(right) was seen in the Gulf of California (2003, 2012, and 2015) and in Monterey Bay (2002–2015). The mean depth for these animals—which can grow to be 80 millimeters long—was approximately 200 meters deeper in the Gulf of California than in Monterey Bay.*

technology developed for the gulper water samplers routinely deployed on the *Dorado* AUV. They are ready to function on release; a timer actuates them to collect water and inject a tracer. A camera on the incubation chamber was used to confirm that they sampled successfully. These techniques are especially important in low-oxygen waters because handling the samples can contaminate them and alter the results. It is impossible to perform uncontaminated experiments when water is collected with bottles, then brought to a high-oxygen surface environment where water is typically placed into smaller bottles and experiments are performed.

The differing conditions found off the Baja Peninsula and in the Gulf of California compared to Monterey Bay provide insights into the top-to-bottom organization of ecosystems under different climatic conditions that would be difficult to achieve by observation of Monterey Bay alone.

The Gulf's oxygen minimum zone

Scientist Bruce Robison and his Midwater Ecology Group focused the second leg of the expedition on the Gulf's oxygen minimum zone (OMZ) and its influence on the ecology and physiology of midwater animals. This well-developed zone occupies a large vertical swath in the water, roughly one thousand meters tall. Monterey Bay also has a distinct oxygen minimum zone, albeit only about half the height of the Gulf's. However, remotely operated vehicle dives in Monterey Bay have revealed that the local OMZ has been expanding over the last 20 years. Coincident with this expansion has been a continuing upward shift in the centers of vertical distribution for several important midwater species. By comparing the depth distribution patterns of counterpart species in both regions it is possible to investigate the effects of OMZ expansion and perhaps gain a predictive capability for the future of Monterey Bay.

The vertical distribution patterns of key midwater species in Monterey Bay show considerable overlap with the boundaries of the OMZ and with each other, suggesting that proximity to well-oxygenated water allows them to occupy broad depth ranges. In the Gulf, the midwater community is strongly bimodal, with an abundance of midwater animals both above and below the broad core of the OMZ but with little or no convergence. Historical trawling data from the Gulf indicate that this pattern was not in evidence during the late 1960s and that its development may be correlated with an expansion of the Gulf's OMZ over the last 50 years. If this is the case, and if the OMZ in Monterey Bay continues to grow, researchers predict a similar consequence locally, leading to fragmentation and spatial re-alignment of animal communities.

To investigate these issues the midwater team employed both the ROV *Doc Ricketts* and the MiniROV to examine the depth ranges of the Gulf's principal midwater species (Figure 18). The vehicles' high-definition video cameras allowed for the identification and enumeration of the midwater species encountered, as well as their activity and behavior. Some specimens were brought up to the shipboard lab for measurements of their oxygen consumption characteristics which were compared with similar data for species from Monterey Bay.

The results show that in the Gulf, the OMZ has acted as a wedge, separating the midwater community into upper and lower elements. Above the OMZ, diversity and abundance were high, as many species appeared to have been squeezed upward. Within the OMZ, diversity and abundance were low, although some species have clearly adapted to this habitat with low metabolic rates and reduced activity levels. Below the OMZ, diversity and abundances were moderate; counterpart species were deeper than in Monterey Bay and quick predatory strikes were more common than continuous hunting. This OMZ wedge leads to separation of the different species, with potentially significant consequences for humans because many of the displaced species are food for commercially important animals.

Research during the midwater leg of the expedition also included the use of biochemical markers to trace the pathways of the food web and chemical analyses of many midwater species to quantify energy flux through the system. Data were gathered by a colleague for OMZ comparisons between the Gulf, Monterey Bay, and the eastern tropical Atlantic. Molecular biology studies helped to determine the phylogenetic and ecological relationships for a number of pteropod molluscs and pelagic worms. Finally, squids were a principal target of several concurrent studies, of their role as carrion on the deep seafloor, the degree of cannibalism in their feeding habits, and their behavior patterns in low- and high-oxygen waters.

Predicting the future is a risky business but if the Gulf is an indicator of what can occur locally in Monterey Bay, it appears that many important forage species—which are food for larger and some commercially valuable fishes—may disappear or relocate in the water column. It seems likely that they will be replaced by smaller and/or gelatinous species and that this change may be accompanied by a shift in top predators to those which can tolerate low oxygen, such as larger gelatinous species and squid.

How low oxygen affects the deep seafloor

The Gulf of California is an exciting place in many ways, from the natural beauty of its landscape, beaches, and sea surface, to secrets hidden beneath the waves. As noted above, the oxygen minimum zone (OMZ) in deep waters of the Gulf is one of those secrets. Although most tropical to subtropical waters in the Eastern Pacific have a well-developed OMZs with much-reduced oxygen levels beneath the surface (about 100-1,200 meters deep), the strong Gulf currents lead to a pronounced gradient in the depth and intensity of the OMZ from north to south.

In the southern Gulf, waters just 100 meters below the surface carry only 10 percent of surface oxygen values and drop to one percent by 1,000 meters. In the mid-Gulf region, waters are well oxygenated to depths of about 250 meters, but in the core of the OMZ near 1,000-meters depth, waters are cold (five degrees Celsius) and hypoxic (two percent of surface oxygen values). In contrast, waters at that depth in the northern basins of the Gulf are warm (11 degrees Celsius) and well oxygenated (15 percent of surface), and are unlike the waters for hundreds to thousands of miles away (Figure 19). This strong oceanographic gradient provides an excellent opportunity to determine if the distribution and abundance of organisms on the seafloor vary along this gradient. Perhaps even more important, because recent research indicates that the OMZs throughout the world ocean are intensifying with climate change and ocean warming, the extreme OMZ in the southern Gulf may represent the future ocean for regions—like Monterey Bay—with milder conditions at present.

This notion motivated the research direction in the Gulf of California for Scientist Jim Barry and his Benthic Biology and

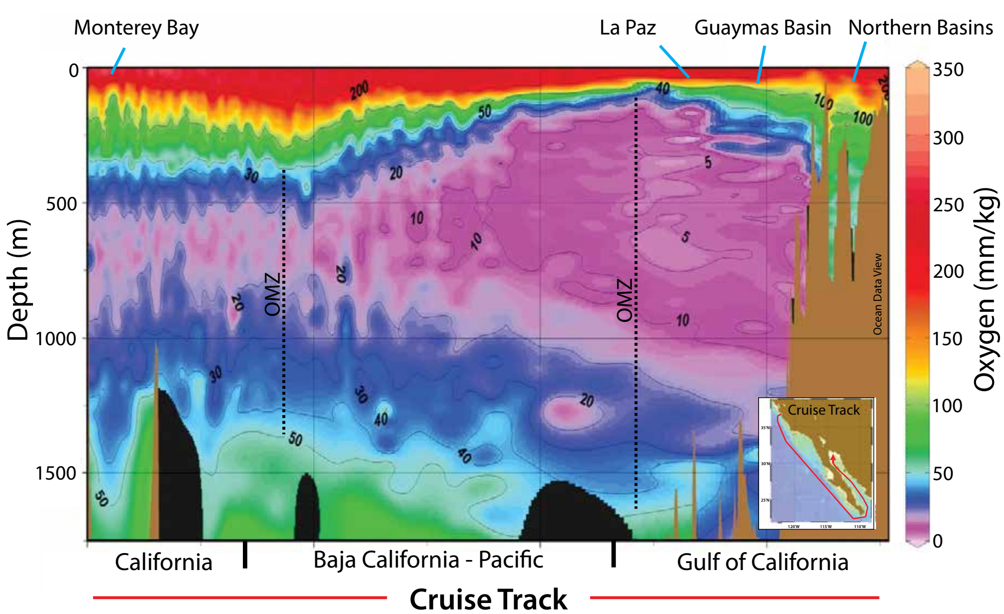
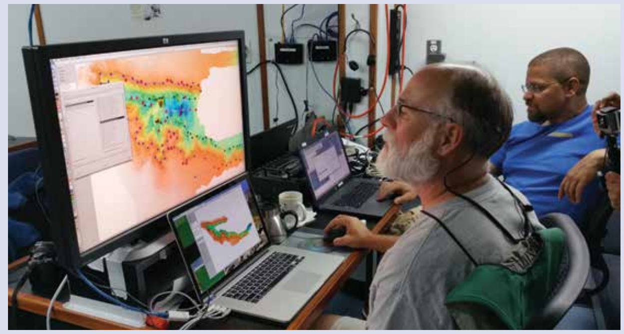


Figure 19. Oxygen levels from the surface to more than 1,500 meters depth along a cruise track from Monterey to the northern Gulf of California (cruise track indicated in inset). Note the increasing breadth and severity of the OMZ (purple) along the southern Gulf and the contrast with the northern basins.

Bringing science tools to help conserve a marine reserve



During the Gulf of California Expedition, Benthic Biologist Jim Barry contributed to the David and Lucile Packard Foundation's programs in support of marine conservation efforts near Cabo Pulmo. Barry and scientists from the Centro para la Biodiversidad Marina y la Conservación, the Universidad Autónoma de Baja California Sur, and Scripps Institution of Oceanography explored some of the southern deep Gulf. First, MBARI's mapping team aboard the R/V *Rachel Carson* surveyed a deep canyon off the well-established and successful Cabo Pulmo National Marine Park. The team used the data collected with the mapping AUV to produce high-resolution maps (Figure 20). MBARI's MiniROV was also used, launched from the R/V *Rachel Carson*, to collect video in this unique canyon (Figure 21).

Two weeks later, Barry and his group arrived on the R/V *Western Flyer* to conduct a deeper dive with the ROV *Doc Ricketts* in the canyon that had just been mapped. This canyon has remained unexplored but its depth and proximity to the coast led scientists to believe that it likely plays an important role in the local productivity and richness that make Cabo Pulmo such a special place.

The information acquired will be useful in describing any new species and processes that occur as a result of the unique geology of the canyon and will serve as a baseline study on the marine diversity and the results of successful conservation of the area since the late 1990s.

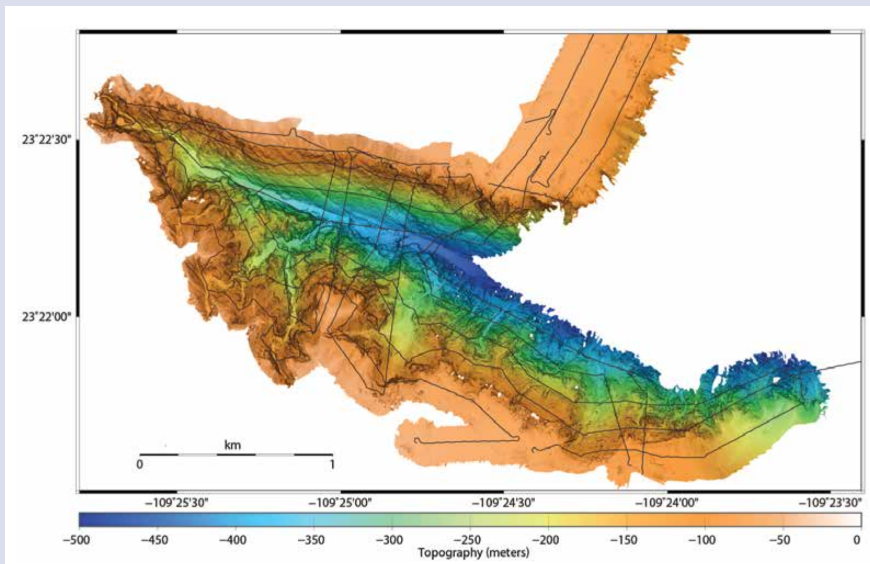


Figure 20. New map of the deep canyon off Cabo Pulmo, made from data collected with the AUV D. Allan B.*, then processed by Engineer David Caress (seen at computer) aboard the R/V* Rachel Carson. *At right is Hans Thomas, leader of the AUV group.*

Figure 21. A diver in the water with the MiniROV in Cabo Pulmo, with the R/V Rachel Carson *at the surface.*

Ecology Group. Oxygen minimum zones develop from the loss of oxygen to respiration and metabolism by all of the organisms inhabiting waters beneath the surface, from microbes to whale sharks. The loss of oxygen and increase in carbon dioxide in these deep waters, lead to a decrease in seawater pH, making the waters more acidic. The more acidic conditions may be stressful to marine life. These conditions are expected to increase in severity. To examine these issues, numerous video transects were performed along the seafloor using the ROV *Doc Ricketts* to span the depth range of the OMZ at sites from the southern Gulf off La Paz to the warm basins of the north. The research team also deployed a respiration system to measure the metabolism of several animals inhabiting the OMZ to examine their tolerance of hypoxic conditions.

Initial analysis of benthic video transects across the Gulf of California indicated a strong change in the abundance of many groups of organisms in parallel with changes in oxygen, temperature, and ocean pH. For example, *Lophelia pertusa*, a beautiful deep-sea coral found worldwide, is restricted to shallow waters (less than 200 meters deep) in much of the northeast Pacific, presumably due to the naturally low pH in the OMZ. *Lophelia* was found to depths below 600 meters in the Salsipuedes Basin of the Gulf of California, almost certainly due to the higher pH of these waters, which are less corrosive for corals (Figure 22). Other animals were tolerant of the very low oxygen levels in the oxygen minimum, such as the ambush predator anglerfish (Figure 23).

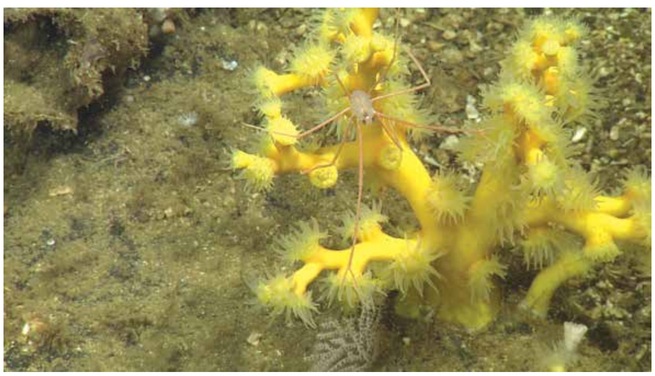


Figure 22. A deep-sea galatheid crab (about 21 centimeters long) on the coral Lophelia pertusa *at over 600 meters depth in the Salsipuedes Basin, northern Gulf of California.*

Figure 23. The ambush predator anglerfish, which can grow to 15 centimeters in length, thrives despite the low-oxygen conditions.

Seeing day-to-day fluctuations in animal life

Exploration in the Gulf of California has proven rewarding for biologists seeking to learn about interactions between species and the range of different species, and to find animals not previously known to science.

Scientist Steve Haddock and his Bioluminescence and Biooptics Group and their collaborators focused their work on gelatinous siphonophores and ctenophores that can dominate midwater ecosystems. Relatively recent research has brought to light the key role these animals serve in those ecosystems. These fragile and fascinating organisms are incredibly abundant, yet almost totally unknown. Insights into the genetic underpinnings of adaptation to extreme environments offer a window into the history of life and marine biodiversity.

Measuring the relative abundance and distribution of Gulf species will provide important information that can be used to anticipate how animals have evolved to survive and even thrive in challenging environments. The team found a great change in the abundance of animals present in 2015 from what they had seen on previous expeditions in 2003 and 2012. Nearly all the same species were present, but species that were dominant in one year were rare or even absent in others. This time around, there were no thick layers of giant larvaceans as seen on a previous expedition. While blue-water divers were stung mercilessly by the siphonophore *Rhizophysa* in past years, on this expedition the team saw only one tiny specimen and a few of the siphonophore's egg masses.

In addition to ROV dives, several members of the research team conducted daily blue-water dives, enabling them to observe in person the biota of the upper layer of the Gulf and to collect specimens in glass jars. These dives confirmed the significant daily changes that can happen in the water column. One day the divers saw an abundance of at least four different species of heteropods (comical-looking swimming snails), little ctenophores, and siphonophores, but the next day those animals were scarce. The researchers learned to make the most of every collection opportunity.

Figure 24. Researchers used a blue-light on this unusual fish, a juvenile Gadella jordani*, to test if its fins were fluorescent, only to determine that they were not. The only sample of this fish to be collected was 43 millimeters long.*

Figure 25. A sea spider (pycnogonid) was found tucked under the bell of a small jelly. These jellies can grow to 45 millimeters in diameter.

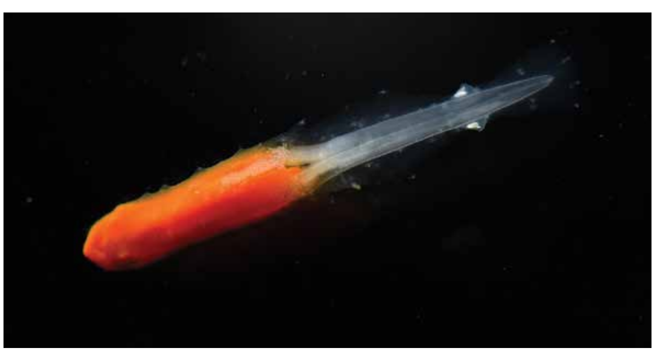


Figure 26. The remarkable chaetognath or arrow worm, Archeterokrohnia docrickettsae*, was described by Erik Thuesen and Steve Haddock from a single specimen found on our last trip to the Gulf in 2012 and was named in honor of the ROV* Doc Ricketts*. In 2015, the team saw at least half a dozen of these arrow worms (approximately 28 millimeters long) living just off the seafloor at the deepest ROV dive sites.*

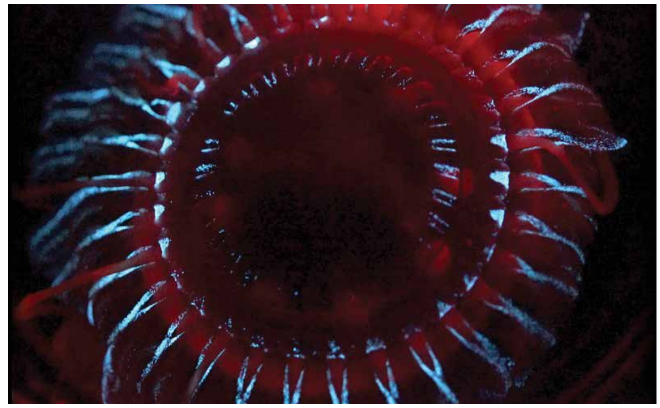


Figure 27. Most jellies exhibit bright green or blue bioluminescence. In some species like the medusa Atolla*, waves of light pinwheels spread along its body's surface.* Atolla *jellies range from 40 to 150 millimeters in diameter, depending on species.*

Among the significant finds were previously unreported fish (Figure 24), siphonophores, pelagic molluscs, and ctenophores. An unusual discovery was a specimen of a siphonophore species already under study by the research team. This specimen had retained its developmental stinging apparatus, unlike other specimens seen. Another was the discovery of a sea spider appearing to take cover under a jelly (Figure 25). Several specimens of the arrow worm *Archeterokrohnia docrickettsae* were seen just off the seafloor in the Gulf, in contrast to the 2012 expedition when a single specimen was found (Figure 26).

Haddock and his team were able to collect some ultra high-definition (4,000 pixel resolution) color video of animal bioluminescence (Figure 27). That footage, along with the many samples collected, will allow the team to tease out more details about marine life in the Gulf, including physiological studies to be conducted under a new National Science Foundation grant. Just one week after the completion of the cruise, Mexican collaborator Rebeca Gasca had already described two of the new species discovered and submitted a paper for publication.

All told, the expedition provided a chance to gather sufficient data to publish a thorough review of the diversity and ecological interactions of the Gulf's typical midwater inhabitants. Like the premise of many movies, the Gulf has an intriguing cast of quirky characters who have adapted to thrive in a challenging and fascinating environment.

Geologists reap rewards from meticulous mapping efforts

Understanding geologic events and the hazards they pose must be based on interpretation of events that happened in the past and any signs that a similar event will happen in the future. The hydrothermal vents and associated lava fields under the Gulf of California presented an attractive study ground for Scientist David Clague and his Submarine Volcanism Group. Clague's group teamed up with MBARI's seafloor mapping experts, led by David Caress, to first map, then sample an expansive region of hydrothermal vents that have not been previously explored in detail (Figure 28).

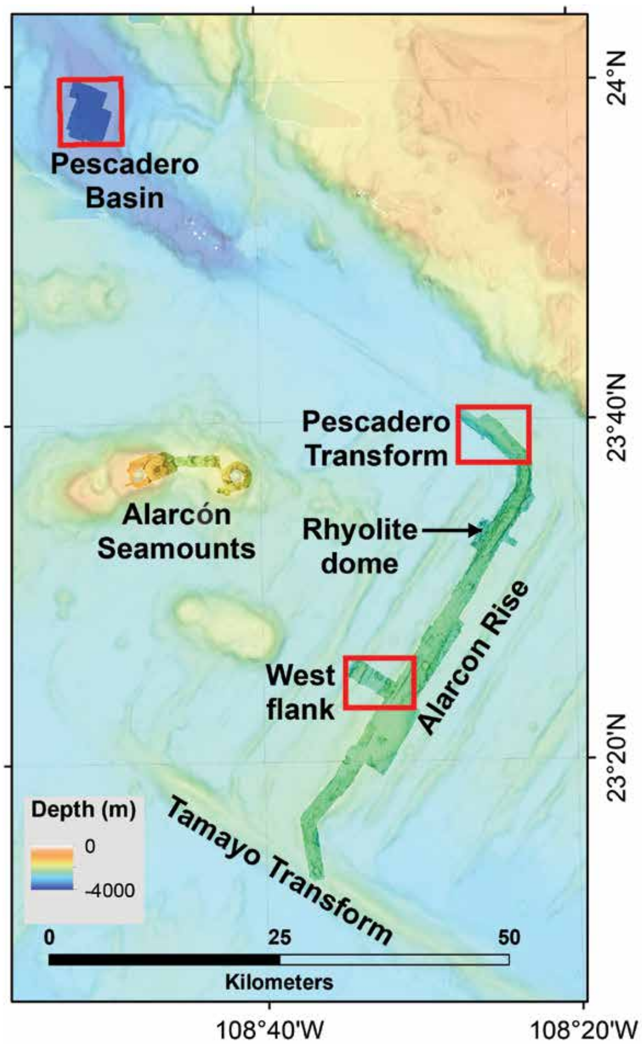


Figure 28. Map of the southern Gulf of California from the Alarcón Rise to the Pescadero Basin. In this and the other maps of this article, high-resolution MBARI mapping AUV-collected bathymetry overlies lower resolution ship-collected bathymetry. Locations of the maps shown in Figures 30, 31, and 32 are indicated by red boxes.

Clague's team set out to sample hot vent fluids from the active hydrothermal vent fields on the Alarcón Rise, as part of a broader study of hot springs on and near the Baja Peninsula by their Mexican collaborators. To accomplish this goal, gas-tight fluid samplers were obtained from colleagues at NOAA and the University of Washington to supplement MBARI's water samplers, then custom-fitted to the ROV *Doc Ricketts*.

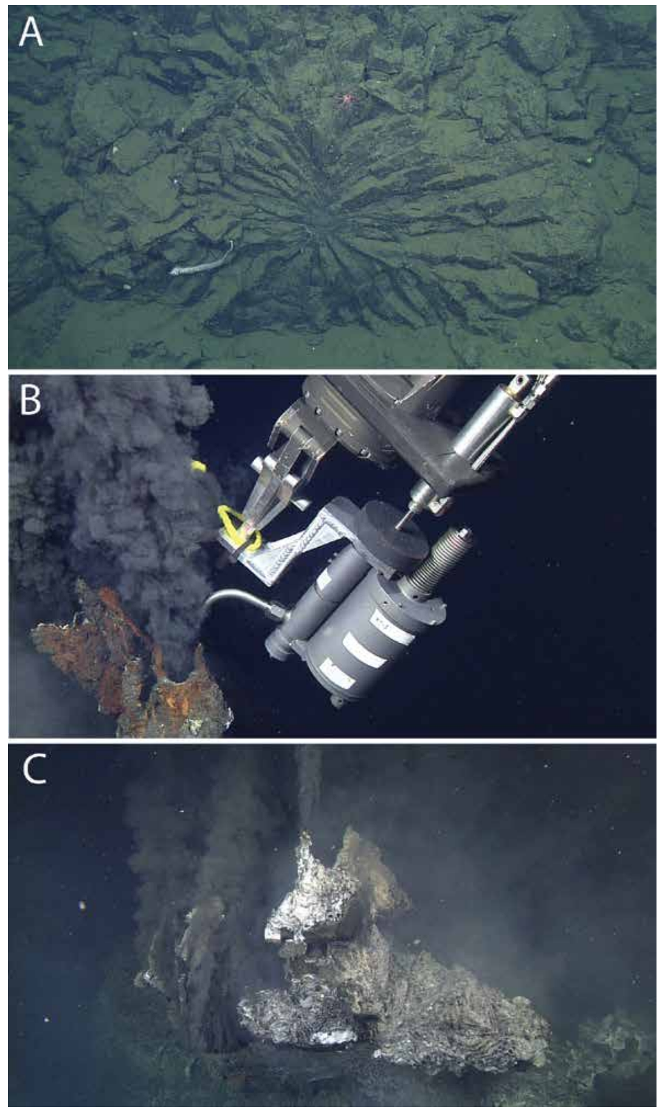


Figure 29. A) Cross-section of an enormous lava pillow at Alarcón Rise, showing the radial jointing pattern that developed inside the pillow when the lava cooled. The field of view is about four meters across. B) Hydrothermal fluids are collected from a black smoker in a vent field on Alarcón Rise. Field of view is about two meters across. C) An "upside down waterfall" at an 18-meter-tall hydrothermal chimney in a vent field on Alarcón Rise. Fluids up to 355 degrees Celsius exiting from under a flange of the chimney spill upward because they are less dense than the surrounding two degrees Celsius seawater. Field of view about three meters across.

Clague's first series of ROV dives explored one of the summits of the Alarcón Seamounts, as well as the northern third of the Alarcón Rise axis where a high-silica rhyolite dome was explored in 2012 (Figure 29). Three rock outcrops, each chemically distinct from the others, were found and sampled. Geochemical study of the samples suggests that the high-silica lavas were formed by cooling and shallow fractionation of normal mid-ocean ridge basalt in magma chambers below the axis, as opposed to having any continental crust introduced into the magma. The distribution of the high-silica lavas may indicate that the north-east end of the Alarcón Rise is colder than most other mid-ocean ridge segments, perhaps because of the proximity of the continental crust of main-land Mexico. The high-silica lavas have different surface textures and form flows with enormous pillows (Figure 29A) or are blocky, indicating a unique process of formation.

Further exploration of the hydrothermal vents discovered in 2012 revealed 340-350 degree Celsius fluids venting from two active black smoker chimneys (Figure 29B). The team then explored some chimneys at a vent field detected in the AUV maps collected three years earlier, but not yet observed with the ROV. These chimneys turned out to be taller (to 33 meters high) and venting hotter (332 to 359 degree Celsius) with more voluminous fluids than those at the other three active vent fields on Alarcón Rise. Some chimneys had horizontal flanges with shimmering vent fluids trapped underneath (see cover image). As the fluids spilled out from under the flanges, the clear fluid immediately precipitated sulfide minerals and became spectacular upside-down waterfalls of black "smoke" (Figure 29C).

Collection of samples along the west flank midway along the Alarcón Rise allowed for an assessment of temporal changes in lava composition at the ridge (Figure 30). The compositions of lavas at this part of the ridge have been similar over at least 12,000 years of activity. The samples also showed that lava flows do not increase in age

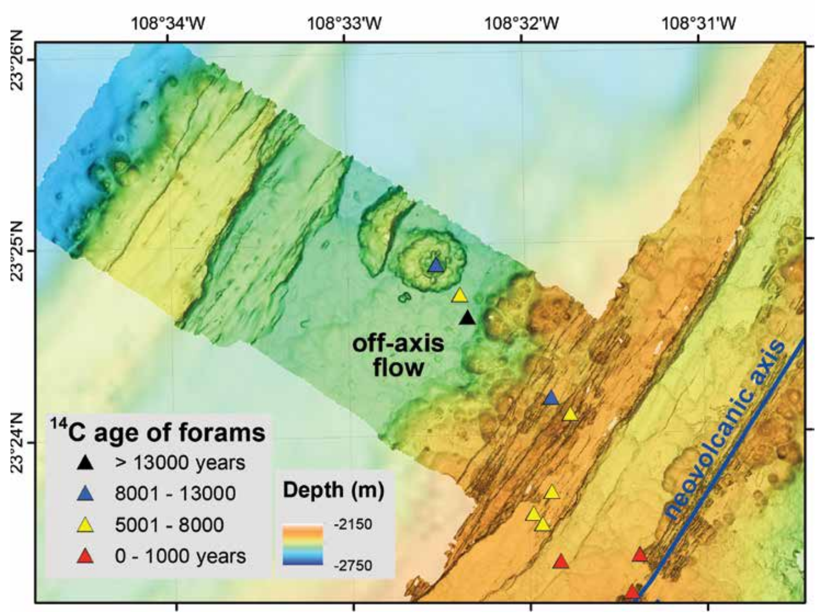


Figure 30. Map of the west flank of Alarcón Rise. The shells of tiny foraminifera (referred to as forams in this image) collected in seafloor sediments (triangles) were carbon dated to give the approximate age of the underlying lava flows. Sub-bottom profiles collected by the AUV show increasing sediment thickness away from the axis reaching a maximum thickness of about 35 meters at the northwest end of the mapped area. The cone and surrounding flows in the first valley to the northwest of the axis have less than three meters of sediment and radiocarbon ages younger than expected (less than 13,000 years instead of the predicted ~100,000 years).

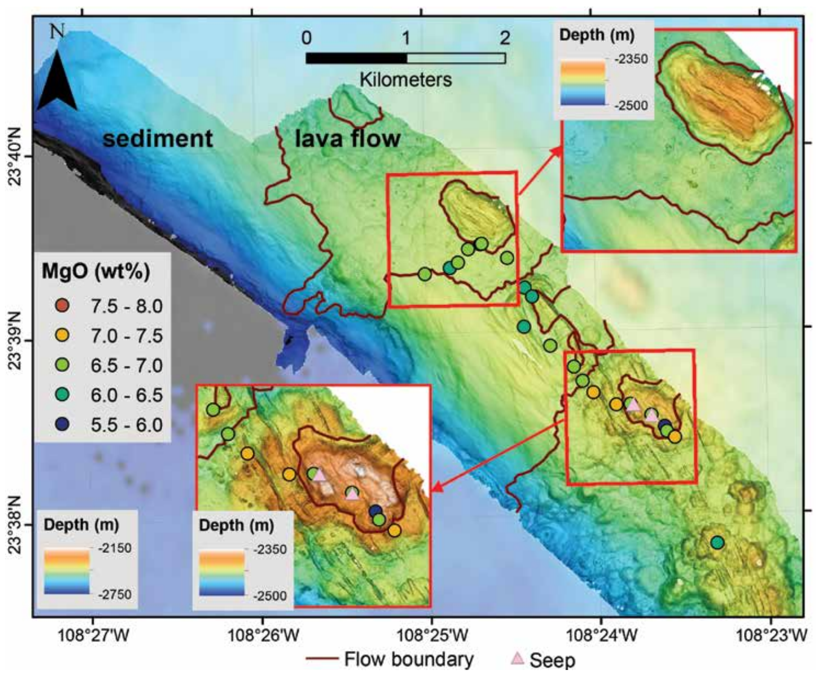


Figure 31. Map of Pescadero Transform, where magma intruded into thick accumulated sediment and pushed up sediment hills (inset maps). The lava also erupted through faults at the base of the hills to form surface lava flows. The individual lava flows differ slightly in their chemistry as reflected in the magnesium oxide (MgO) content of samples (colored circles). Low-temperature fluids host chemosynthetic communities (pink triangles).

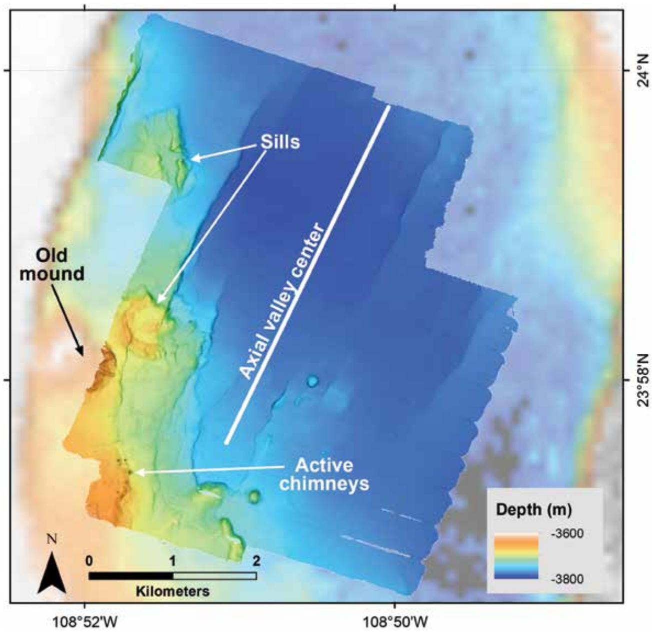


Figure 32. Map of the Pescadero Basin showing the location of the active hydrothermal chimneys, which were detected in the AUV bathymetry and CTD data. A large mound of calcite debris to the north on the faulted wall of the basin was a site of hydrothermal discharge in the past. Low sediment hills (labeled sills in this map) uplifted by lava intrusions are also present. Unlike at other mid-ocean ridge segments, the center of the axial valley shows no indication of volcanic or hydrothermal activity.

systematically away from the ridge axis, as predicted by simple seafloor spreading models.

An additional dive explored the Pescadero Transform Fault to the northeast of the Alarcón Rise, including the sampling of young flows and hills uplifted by injection of magma into the sediment (Figure 31). The abundant magma shows that the transform faults are not simply strike-slip faults, but must have stretched as well. The shear and movement on these faults indicate that the orientation of spreading in the southern Gulf of California continues to change.

As Clague's leg of this voyage approached its end, his team received hot-off-the-press maps from the AUV mapping team showing newly discovered active chimneys in the Pescadero Basin (Figure 32). With little time to spare and challenging weather conditions, the precise coordinates afforded by the new maps pointed to vents where fluid temperatures up to 290 degrees Celsius were then measured and valuable samples were collected.

The new vents turned out to be an amazing discovery: the chimneys were composed mainly of white calcite spires (Figure 33) and the fluids had high concentrations of hydrocarbons derived

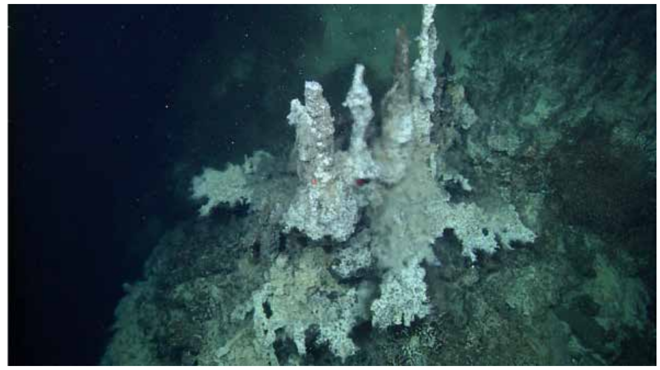


Figure 33. Calcite spires on an active hydrothermal chimney in the Pescadero Basin. Field of view about three meters across.

from organic carbon in the sediments that cover the floor of the basin. This unique find was the deepest high-temperature vent field known in the Pacific Ocean at the time of the discovery, and Pescadero is one of only four known sites located on thick sediment where hydrothermal-vent fluids contain hydrocarbons. It is rare to find hydrocarbon formation catalyzed by extremely high temperatures in the vents over relatively short timescales, in contrast to most known hydrocarbon production by organic material buried and compressed over geologic timescales.

The highly varied physical and chemical environments found on the Alarcón Rise, on the Pescadero Transform Fault, and in Pescadero Basin provided an unprecedented context for guiding studies of vent animal communities that took place during the subsequent leg of the expedition.

So close, yet so diverse

The discovery and exploration of hydrothermal vents and hydrocarbon seeps in the southern Gulf of California were an important backdrops for planning comparative biological studies by Scientist Bob Vrijenhoek and his Molecular Ecology Group. Despite the relative proximity of the various vent and seep habitat sites, remarkable differences were found in the biological communities that inhabit them.

Basalt-hosted vents on the Alarcón Rise (at a depth of 2,300 meters) were dominated by bright red giant tubeworms (*Riftia pachyptila*) clustered in thickets around cracks and small openings that emit dissolved sulfide gas (Figure 34). The brilliant red hemoglobin in their blood is needed to absorb oxygen. In sulfide-rich vent water, these tubeworms can grow up to two meters in length. Vent crabs (*Bythograea thermydron*) living among the *Riftia* thickets were looking to snip chunks of the brilliant red plumes. When crabs approached, the tubeworms quickly with-

Figure 34. Riftia pachyptila *tubeworms, which can grow to two meters in length, were found clustered in thickets around cracks in the Alarcón vent.*

Figure 36. Smaller Oasisia *tubeworms (50 to 75 millimeters in length) completely dominated hydrothermal mounds and chimneys in the Pescadero Basin.*

Figure 35. Calyptogena magnifica *at the base of a hydrothermal chimney.*

Figure 37. The Pescadero Transform area was dominated by thickets of Lamellibrachia barhami *and* Escarpia spicata *tubeworms that can grow to two meters in length and live for as long as 170 years.*

drew into their protective tubes. Large clams (*Calyptogena magnifica*) crammed into numerous cracks between the basaltic rocks at the base of hydrothermal chimneys (Figure 35). Up to 30 centimeters in length, these large clams had very fragile white shells. Large numbers of limpets (*Lepetodrilus elevatus*) grazed on the clamshells and tubeworm tubes. A serpulid worm found in the area appears to be new to science. The present findings extend the northern range limits for the clams, limpets, and crabs, which were previously only known from the East Pacific Rise to the south. *Riftia pachyptila* has the largest range, occurring from 27 degrees North in Guaymas Basin to 38 degrees South latitude on the Pacific-Antarctic Ridge, more than 7,000 kilometers.

Although nearby, animal communities at the deeper (3,800 meters) carbonate-rich Pescadero Basin vents differed greatly from the Alarcón vents. *Riftia* tubeworms occurred in small numbers and were typically surrounded or overgrown by dense thickets of smaller tubeworms related to *Oasisia jerichonana* (Figure 36). The clams, crabs, and limpets found at the Alarcón site were all absent, but another clam (related to *Archivesica diagonalis*), white squat lobsters (*Munidopsis*), and *Provanna* snails were all abundant.

Animal communities at hydrocarbon seeps on the Pescadero Transform Fault differed even more (Figure 37). *Riftia* and *Oasisia* tubeworms were absent, but immense thickets of other tubeworms (*Lamellibrachia barhami* and *Escarpia spicata*) dominated the site. The two clams seen at the other sites were absent, but dense patches of *Calyptogena pacifica* and *Archivesica gigas* clams were partly buried in the seep sediments. The Pescadero seeps and the Alarcón and Pescadero vents are only about 60 kilometers apart and within dispersal distance for the clam and tubeworm larvae. Understanding the biological and geochemical processes responsible for the community differences will be the focus of ongoing collaborations between the Molecular Ecology and Submarine Volcanism Groups.

Species composition at the Pescadero seeps was similar to that of other cold hydrocarbon seeps ranging from the Oregon margin to Monterey Bay, the Gulf of California, and the Costa Rica margin. Population genetic studies aimed at determining the connectivity among these distant localities are underway. Genetic studies will also determine connectivity of vent populations living in the Alarcón Rise and Pescadero Basin with southerly populations distributed along the East Pacific Rise. Connectivity studies should shed light on the distinct nature of the southern Gulf of California populations, thereby providing Mexican officials with the information needed to make informed decisions about the designation of future marine protected areas.

Shedding light on significant fault lines

Very little is known about recent seafloor deformation along two major faults off the coast of northern Baja California, even as scientists have greatly increased our knowledge of faults located on land near major metropolitan areas. Our poor understanding about these faults, or any submarine fault, is primarily due to the historical lack of high-resolution surveying and sampling techniques comparable to those used in the study of onshore faults. However, the advent of submarine robotic mapping and sampling vehicles promises to significantly improve our understanding of submarine fault systems.

The Continental Margins Group, led by Scientist Charlie Paull, used the last legs of both the R/V *Rachel Carson* and the R/V *Western Flyer* voyages to learn more about these faults (Figure 38). One of the two faults studied is believed to be continuous with the San Diego Trough Fault, and jointly they form a fault zone

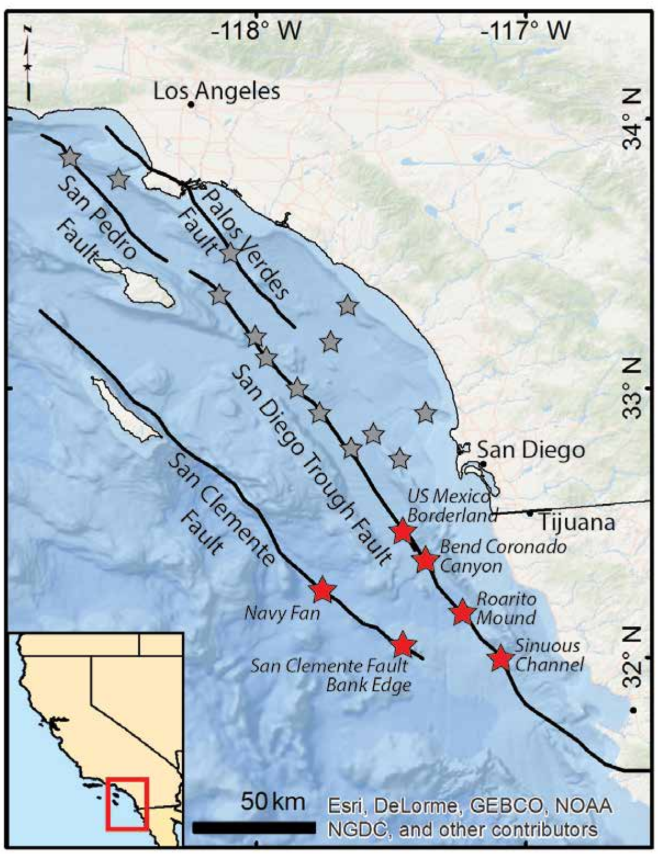


Figure 38. Locations of the earthquake faults off the U.S./Mexico border. Red stars indicate areas surveyed in 2015; gray stars mark earlier survey locations.

Figure 39. Example of an individual AUV survey. Note the ridges and basins flanking the fault, which are presumed to be created by bends in the fault plane. White box corresponds to the detailed panel shown in Figure 40, where the location of the most recent seafloor rupture is clearly visible.

of more than 300 kilometers, running from Ensenada, Mexico, past Los Angeles, California—in some places as close as 30 kilometers from shore. The second fault is the San Clemente Fault (approximately 225 kilometers long), which forms the eastern flank of San Clemente Island. Determining the frequency of events, style of deformation, and slip rate along these long submarine fault systems are critical to characterizing the seismic hazards to the adjacent coastal areas.

Detailed morphologic surveys were conducted at six sites, four along the San Diego Fault and two along the San Clemente Fault. The mapping AUV was deployed from the R/V *Rachel Carson* to provide ultra-high-resolution multibeam bathymetry and images of the sub-seafloor structures (Figure 40). The resulting detailed maps allow for the clear detection of small north-northwest to south-southeast trending scarps, frequently only tens of centimeters high, that developed within very recent sediment drape cover. Sub-bottom profiles show offsets of subsurface horizons, indicating these scarps are associated with faults produced by geologically recent surface ruptures. The existence of these scarps could not have been detected with ship surveys.

These small scarps are in turn flanked by larger elongated ridges and depressions (Figure 40), which are interpreted to be structures pushed up by compression or pulled apart by tension due to bends in the fault plane. Angular relationships of the strata on the flanks of these ridges, also revealed by the data collected with the AUV, indicate that these structures have developed over time and involve multiple ruptures on these faults.

The detailed bathymetric maps and sub-bottom profiles were used to locate sites where stratigraphic horizons offset by the fault are within 1.5 meters of the seafloor. These areas were sampled using a vibracoring system mounted on ROV *Doc Ricketts*, which is capable of collecting up to six cores per dive. The fault scarps were barely visible on the seafloor when viewed with the ROV camera. Without the AUV-generated maps the subtle seafloor deformation would have been overlooked. However, with the detailed maps and aided by accurate navigation, closely spaced core transects crossing the faults were conducted. These core samples are currently being analyzed.

As sediment accumulates on the seafloor it preserves skeletal remains of pelagic organisms that can be directly dated using carbon dating techniques. Because the date of deposition of the horizons where these samples are found precedes the time when the horizons were offset by the fault, these stratigraphic samples promise to help determine the frequency and timing of recent movements on this fault, which will be useful for seismic hazard assessment. The coupled use of the detailed seafloor surveys enabled by the mapping AUV and the precisely located sampling conducted with the ROV is now making it possible to comprehensively study submarine fault deformation and obtain detailed information about fault behavior similar to what can be obtained at faults on land.

A surprising discovery in the one-meter resolution bathymetry along the San Clemente Fault Zone was the presence of extensive patches of especially rough seafloor characterized by steep-sided

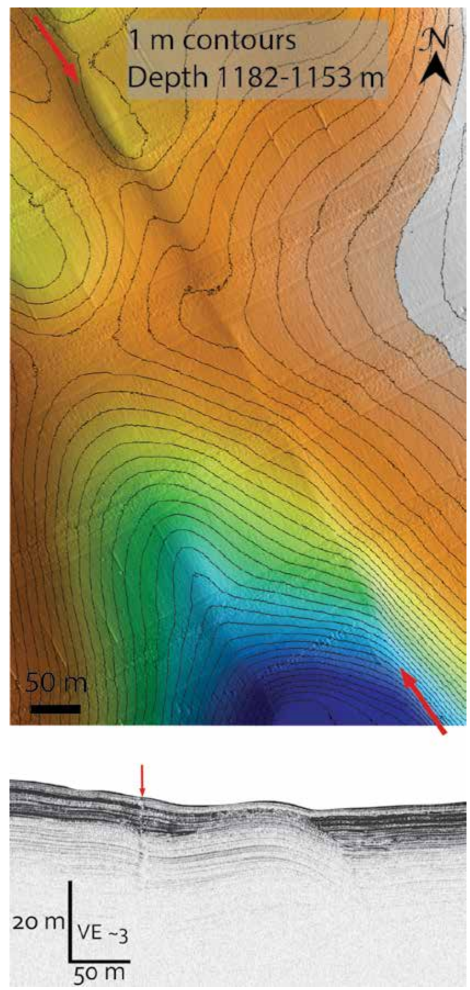


Figure 40. Upper panel illustrates the ability to detect fault scarps only tens of centimeters high from bathymetry collected with the mapping AUV. Depth ranges for the color scale are indicated. Offsets of fault-related horizons are visible in the sub-bottom profile at bottom. Red arrows indicate faults. Collectively, the bathymetry and sub-bottom data allow researchers to confidently identify the location of recent seafloor ruptures. The sub-bottom data are shown at a vertical exaggeration (VE) of three.

mounds 10 to 30 meters in diameter and up to 11 meters tall (Figure 41). These mounds occurred on both flanks of the fault. Observations and samples from one ROV dive showed these mounds are composed of variably colored clusters of material about one meter wide that accumulated on the sides and top of the mounds. Some clusters consist of white, fragile, vertical spires, suggesting active upward growth of chemical precipitates. Chemical analyses revealed these precipitates are composed of the mineral barite. The lightly colored clusters are partially covered with gelatinous and filamentous bacterial mats on their uppermost surfaces, which suggest microbes play an important role in the reaction of sulfate with dissolved barium in the seawater to settle out of solution as solid particles of barite. While a few similar barite mounds had been previously discovered along the San Clemente Fault, the high abundance documented in these surveys on this unevenly sampled short section of the fault zone suggests that massive barite deposits along the San Clemente Fault could be a frequent occurrence. Moreover, the relationship between these mounds and the faults is still poorly understood.

This work is another illustration of coordinating MBARI's robotic systems to generate detailed seafloor maps that subsequently guide imaging and sampling to disclose new insights into geologically active segments of the ocean floor.

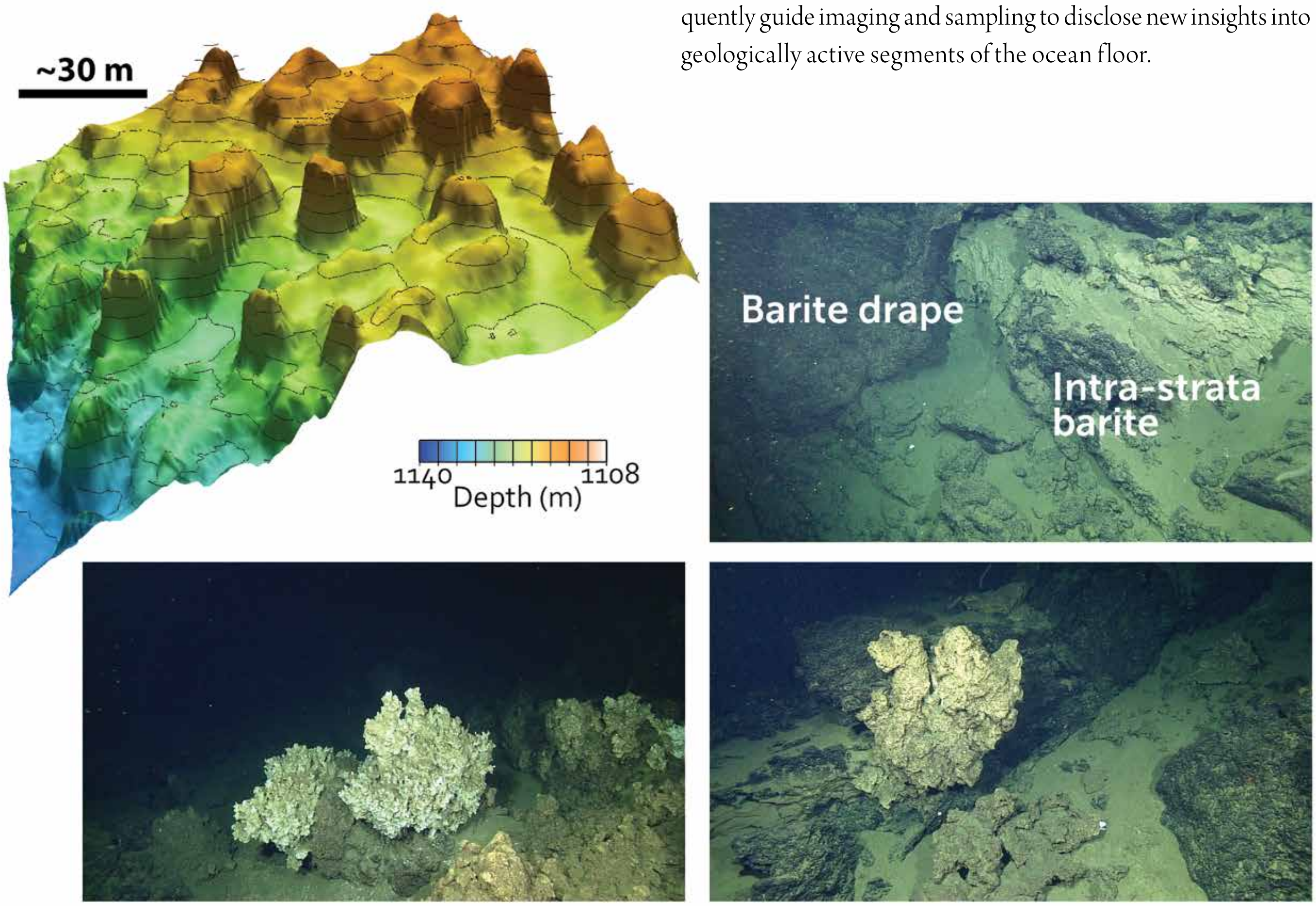


Figure 41. Perspective view showing the barite mounds (10-30 meters in diameter and 11 meters tall) topography (top). Depth ranges for the color scale are indicated. Below are images from the ROV of the mounds, which appear to be formed by the vertical accumulation of numerous one-meter clusters of barite.

Related web content:
Gulf of California Expedition: www.mbari.org/at-sea/expeditions/gulf-of-california-2015-expedition/

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Project team: Charles Boch, Kurt Buck, Chris Lovera, Josi Taylor, Patrick Whaling
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Continental Margins and Submarine Canyon Processes

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Collaborators: Daniel Brothers, Katie Coble, Tom Lorenson, Mary McGann, and Kurt Rosenberger, U.S. Geological Survey, Santa Cruz and Menlo Park offices, California; Scott Dallimore, Geological Survey of Canada, Sidney, British Columbia; Andrea Fildani, Statoil, Norway; George Hilley, Stanford University, California; Will Symons and Peter Talling, University of Southampton, United Kingdom; Daniel Parsons, University of Hull, United Kingdom; Jingping Xu, Ocean University of China

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Molecular Ecology and Evolution of Marine and Aquatic Organisms

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Project team: David Clague, Danelle Cline, Julio Harvey, Mike McCann, Charles Paull, John Ryan, Yanwu Zhang
Collaborators: Asta Audzijonyte, Commonwealth Scientific and Industrial Research Organisation, Hobart, Australia; Corinna Breusing, HOSST Graduate School, Kiel, Germany; Jennifer Fisher and William Peterson, Southwest Fisheries Science Center, Newport, Oregon; David Foley, Southwest Fisheries Science Center, Pacific Grove, California; Jonathan Geller, MLML, California; Magdelena Georgiva and Crispin Little, University of Leeds, United Kingdom; Shana Goffredi, Occidental College, Los Angeles, California; Elena Krylova, Shirshov Institute of Oceanology, Moscow, Russia; Steven Morgan and Eric Satterthwaite, University of California, Davis;

Greg Rouse, Scripps Institution of Oceanography, La Jolla, California; Heiko Sahling, University of Bremen, Germany; Verena Tunnicliffe, University of Victoria, Canada; Cindy Van Dover, Duke Marine Laboratory, Beaufort, North Carolina; Anders Warén, Swedish National Museum, Stockholm; Nerida Wilson, Western Australia Museum, Welshpool; Katrina Worsaae, University of Copenhagen, Denmark; Haibin Zhang, University of Science and Technology of China, Hainan

Monterey Bay Time Series

(See project team on page 16)

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: David Caress, William Chadwick, Brian Dreyer, Morgane Le Saout
Collaborators: Julie Bowles, University of Wisconsin, Milwaukee; Paterno Castillo, Scripps Institution of Oceanography, La Jolla, California; Liz Cottrell, Smithsonian Institution, Washington D.C.; Brian Cousens, Carleton University, Ottawa, Canada; James Gill, University of California, Santa Cruz; Tom Guilderson, Lawrence Livermore National Laboratory, California; Shichun Huang, University of Nevada, Las Vegas; Deb Kelley, University of Washington, Seattle; Anthony Koppers, Oregon State University, Corvallis; Tom Kwasnitschka, GEOMAR, Kiel, Germany; Jim McClain and Rob Zierenberg, University of California, Davis; Mary McGann, U.S. Geological Survey, Menlo Park, California; Florian Neumann and Ronald Spelz-Madero, Universidad Autónoma de Baja California, Mexico; Scott Nooner, University of North Carolina, Wilmington; Michael Perfit, Florida State University, Tallahassee; Ryan Portner, Brown University, Providence, Rhode Island; Ken Rubin, University of Hawaii, Honolulu; John Stix, McGill University, Montreal, Canada; Dorsey Wanless, Boise State University, Idaho; Jody Webster, University of Sydney, Australia

Zooplankton Biodiversity and Biooptics

Project lead/manager: Steven Haddock
Project team: Lynne Christianson, Séverine Martini

Emerging Technologies

The discoveries presented in this year's report were made possible by a wide range of engineering developments that began many years ago. For example, the ability to use an autonomous underwater vehicle (AUV) to create a detailed map of the seafloor that, in turn, guides deployment of a remotely operated vehicle (ROV) to conduct targeted video surveys and collect samples, rests on numerous capabilities that were gained over a very long period. Advances in vehicle design, underwater navigation, battery and sensor technology, low-power computing, software tools for generating maps and analyzing video footage, data storage and retrieval systems, and acoustic communications, are but a few of the fundamental engineering building blocks that are important in this regard.

Some of those advancements are a direct result of work done at MBARI, while others were made possible by leveraging new capabilities developed by others for basic research or commercial purposes. The integration of these disparate technical achievements, combined with MBARI's marine operational expertise, were instrumental in setting the stage for a host of unimagined discoveries. For that reason, MBARI continues to recognize the importance of investing in long-term engineering developments that have the potential to transform ocean exploration and scientific inquiry.

Active engineering research programs at MBARI today include those that emphasize endurance, imaging ability, sampling fidelity, and power supply to new sensors and platforms. In addition, the operational needs required for expanding observations in both space and time, and for carrying out complex process studies, increasingly call for coordinated movements of autonomous robotic devices operating from the ocean surface to the seafloor, and in concert with research vessels. All of these initiatives have spurred a need to enhance information management, analysis, and dissemination capabilities. These development efforts are at different stages of maturity; some are already contributing to scientific programs highlighted in this volume, while the impact of others may not be realized for years to come. Nevertheless, this collection of efforts offers a glimpse of some of the tools that MBARI will likely employ in the future (Figure 42). A closer look at some of these programs illustrates how fundamental engineering advancements made today act as catalysts that create new opportunities for furthering a new generation of ocean exploration and discovery. MBARI's ships and their skilled operators are foundational to this cycle by making it possible to field and recover new systems, and refine their operation.

Improving access to the deep sea

Documenting and understanding how the seafloor changes in response to biological and geological processes require a reliable and persistent sensory presence that can operate for long periods without human intervention. For example, a time-series study at Station M in the abyssal northeastern Pacific conducted over the past 27 years has reaped new insights into the dynamics of seafloor communities and the role of the sediment-water interface in the marine carbon cycle, as it relates to changing climate. How can researchers continue such work without relying on ships to service instruments left on the seafloor in an inaccessible and remote environment at 4,000-meters depth? The solution has been to develop autonomous instruments capable of making high-resolution measurements over the course of yearly deployments. The Benthic Rover (Figure 42A), the sedimentation event sensor, and the time-lapse camera (Figure 42B) on a sediment-trap array are some of the results of this effort. Advances in battery technology, low-power electronics, data storage, and robust electromechanical systems made it possible.

Another challenge rests with understanding and quantifying the role that submarine canyons play in transporting material from land to the deep sea. Previous work at MBARI revealed that periodic and dramatic movements of sediment down Monterey Canyon rapidly move large amounts of material toward the abyss, rearranging canyon terrain in the process. It is not possible to know exactly when and where in the canyon such an event may take place, so how can one measure these changes? Part of the answer lies with deploying a network of MBARI's benthic event detectors (Figure 42C), autonomous devices placed on the seafloor to sense and record the transport events. Using acoustic transponders, these instruments can transmit the motion they record to a receiver on the surface; changes in their location can be tracked even if buried by rocks and sand. Should they break free from the housing that keeps them on the seafloor, they will float to the surface and transmit a signal via satellite so they can be found and recovered. These instruments are one of the enabling technologies behind the international Coordinated Canyon Experiment (see page 41) that began in 2015 and continues into 2017.

Visualizing the seafloor and ocean interior

Many ocean science breakthroughs have stemmed from advances made in acquiring and processing multi-scale images of the seafloor and the organisms that live there, as well as the animals that inhabit the water column, to yield quantitative assessments that can be tracked over time. Obtaining such high-resolution images is a major challenge considering the vastness of the ocean and the need for repeated observations over long periods. Historically, MBARI has addressed this problem by using ROV-mounted cameras and custom video processing tools for quantifying animals and objects of interest, and for merging that information with environmental and habitat characteristics. After more than 25 years of observations it is clear that the ocean ecosystem in Monterey Bay and adjacent waters is changing. How can the observations be improved to better document the drivers and consequences of this change, and be enhanced to allow greater spatial and temporal coverage in the future? Two current projects at MBARI aim to be a part of the answer to this vexing question: development of a lidar sensor (a remote sensing technology that measures distance by illuminating a target with a laser and analyzing the reflected light) and high-resolution cameras for use aboard AUVs.

Lidar sensors are commonly used in terrestrial applications, and have only recently been made available for use in the deep sea. MBARI is working with 3D at Depth to explore the integration of that company's submersible lidar device with acoustic and optical imaging technologies to retrieve unprecedented images of seafloor features and animals as small as one millimeter. This capability allows detection of changes in individual animals and the terrain they interact with, relative to time and changing environmental conditions. The long-term goal for this work is to use lidar systems with acoustic and camera systems on a new generation of AUV (Figure 42D). This new vehicle will pass over and image very rugged terrain, including steep rock walls and narrow canyons that host a myriad of animals and important ecosystem processes. Advances in sensor technology and many engineering developments will be required to deploy an AUV that precisely navigates challenging bottom topography.

MBARI is also expanding its use of high-resolution cameras aboard AUVs that traverse the open ocean. The Investigations

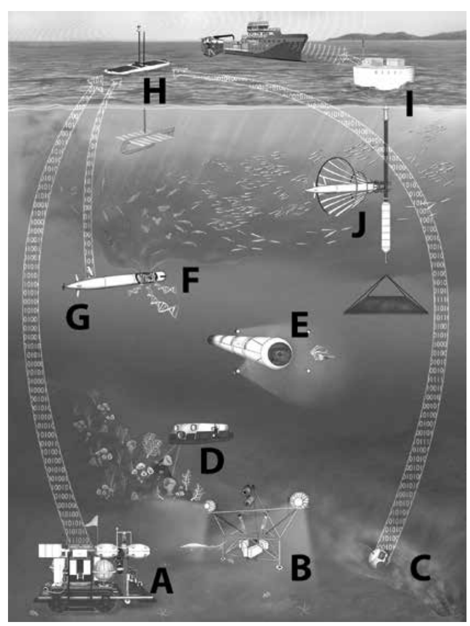
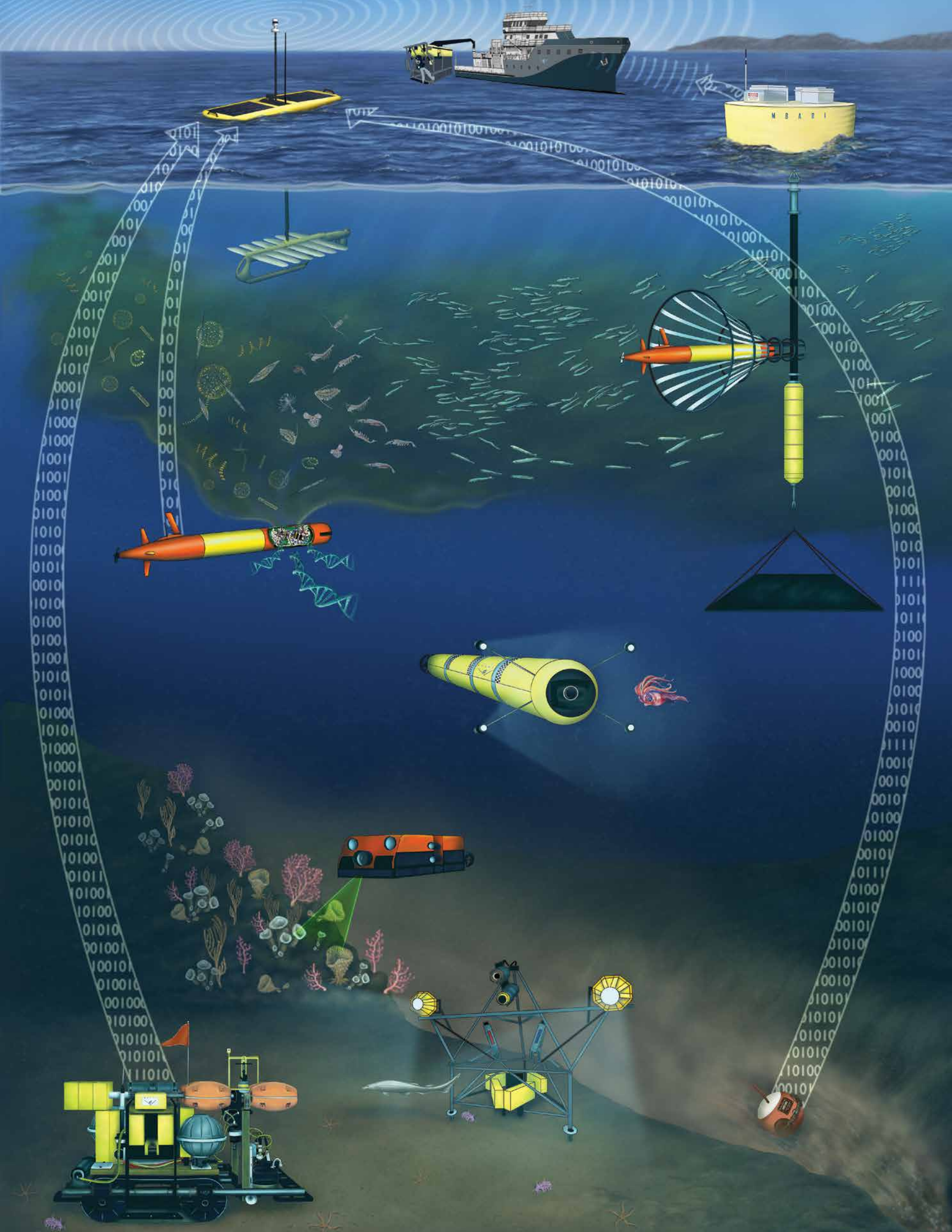


Figure 42. This conceptual illustration shows the range of emerging technologies in development at MBARI. Key to illustration: A) Benthic Rover, B) time-lapse camera, C) benthic event detector, D) conceptual autonomous underwater vehicle (AUV) with lidar imaging; E) midwater imaging AUV ; F) third-generation Environmental Sample Processor inside the vehicle; G) long-range AUV; H) Wave Glider communications hotspot; I) Power Buoy; and J) AUV docking system.


MBARI

of Imaging for Midwater Autonomous Platforms project is using imaging AUVs to conduct repeated surveys of animals found in the ocean midwaters as an eventual replacement for the present-day surveys that require ROVs. The ROV-based program has been phenomenally successful, but these routine time-series surveys require ships and sophisticated vehicles—capabilities and equipment that are not easily disseminated to other ocean scientists who lack the infrastructure available at MBARI. An AUV-based system offers many potential advantages in that regard, with exportability, scalability, and lowered costs of operations. Current development of the midwater imaging vehicle was made possible by modifying an existing AUV to carry a custom-built camera and lighting system (Figure 42E). The MBARI team is also increasing the depth capability of the camera system to 1,500 meters, fine-tuning the electronics and operations software, and conducting comparative transects with an ROV to validate this new means of acquiring high-resolution video from the ocean interior.

Targeted sampling to reveal ecosystem processes

The interplay of ocean physics and chemistry gives rise to patchy and ephemeral distributions of biological communities that ultimately drive nutrient cycling and food webs on a global scale—ecosystem processes that affect Earth's climate as well as human well-being. Traditional ship-based methods for detecting, tracking, and sampling such important and dynamic ocean features are often laborious and difficult to sustain long term. How can we overcome these limitations? Part of the envisioned solution is to enable autonomous vehicles to detect and sample ecologically important phenomena by using onboard sensors and water-sampling systems. To that end, present-day scientific insights into a variety of ecosystem processes are being used to derive algorithms that direct the larger and smaller AUVs to carry out targeted sampling. These activities take advantage of the vehicles' flexible performance, reliability, and growing endurance. This allows researchers to direct a small fleet of marine assets to specific regions of interest, such as chlorophyll patches and upwelling fronts, to make desired collections and measurements absent a human presence.

As AUVs become more adept at locating regions of interest and tracking their evolution over time, onboard water sampling systems are being refined to enhance the efficiency and accuracy of when and where a limited number of samples are acquired. One emerging capability is the use of the third-generation Environmental Sample Processor (3G ESP)(Figure 42F) that has been integrated with the long-range AUV (LRAUV) (Figure 42G). The new vehicle was originally built for collecting microorganisms and assessing their genetic makeup and activity in relation to fluctuating ocean conditions. In the course of the development, however, researchers discovered that the samples acquired using the 3G ESP also harbored DNA (so-called environmental DNA or eDNA, that originates from sloughed off skin, mucus, and excrement) indicating the recent presence of anchovies. Detection of eDNA has great potential for assessing the distribution and relative abundance of a wide range of animals, and as such is an active area of study. If proven useful, this new method for surveying animal populations would revolutionize and streamline basic research, resource management, and conservation practices by simply collecting water samples and subjecting them to universal DNA analysis. Being able to acquire such samples using an oceangoing AUV that can travel long distances for days to weeks would greatly enhance the utility of that method. This unanticipated opportunity has arisen from a merger of molecular biology, marine robotics, and the development of sophisticated software command-and-control systems.

Enhancing power availability and communications capabilities

Platforms and sensors deployed in the ocean all need a source of electrical power to operate. Generally, power is supplied by batteries, in some cases augmented using solar and wind generators. Recent advancements have focused on harvesting wave energy for propulsion and electrical power generation, to extend the mobility and endurance of oceangoing systems. These developments are having a profound influence on how ocean observations are being made now and how they will change the future.

The Wave Glider platform manufactured by Liquid Robotics, Inc., has proven to be exceptionally adept at converting wave energy for propulsion and station keeping, while using solar power electrical generation to drive sensors and data communications (Figure 42H). Engineers at MBARI have modified the Wave Glider to act as a communications hotspot for enabling data transfer between various platforms, and tracking of subsurface assets such as the LRAUV, the Benthic Rover at Station M, and the benthic event detectors used in the Coordinated Canyon Experiment. This Wave Glider alleviates the need to send a ship long distances to check on equipment or to stay on station while engineers transfer data from an instrument on the seafloor, offering substantial savings in terms of ship operations and staff time. Additional work associated with the communications hotspot project has included adding onboard safety features such as obstacle-free zones to keep the vehicle safe while it navigates autonomously. With these modifications, the Wave Glider is proving to have tremendous utility in supporting many different types of field programs, all of which benefit from a flexible and common set of core technical capabilities.

MBARI engineers are also developing a wave-energy-harvesting platform known as the Power Buoy (Figure 42I). The Power Buoy consists of a surface float attached to a subsurface plate with an electrical generator in between; as waves propagate under the surface float, the stretching motion relative to the bottom plate generates electricity. The power available is significant and potentially offers a more reliable source of energy than wind and sun over large regions of the ocean. By coupling this to an AUV docking system (Figure 42J), as well as integrating it with other sensors and acoustic devices, the Power Buoy has the potential to act as a staging, charging, and data-relay station for a host of autonomous systems that ply the ocean. When this capability is fully realized, it will have numerous applications for exploration and discovery in remote areas that can only be visited infrequently by ships.

Information management and dissemination

The trend towards enabling a more pervasive and persistent sensory presence, along with the increasing detail of measurements and images, produces a data deluge that demands concomitant advancements in information management and analysis systems. This challenge comes at a time when commercial entities are spurring a technological revolution in curating and mining vast amounts of information as a means of fueling discoveries that would otherwise be impossible for humans to do alone. At the other end of the spectrum lies the challenge of distilling the information and insights gleaned for end users including subject experts and policy makers, as well as the public at large.

To meet these needs, MBARI has spent considerable effort upgrading its data storage, processing, management, and dissemination infrastructure. One of the major initiatives in this regard is rooted in the very founding of MBARI: the use of video to record ROV dives, which in turn is processed by a human observer to yield quantitative assessments of animals and objects of interest that are cross-referenced with prevailing environmental conditions. To preserve the video records for the future, the original magnetic tapes used to record imagery must be converted to a digital format. In addition, acquisition of new images will phase out tape-recording in favor of direct digital capture, since traditional video tape technology will not be available in the future. While this transition may seem trivial, the undertaking is enormous and critically important for preserving raw footage from past dives, as well as for opening up new and more efficient avenues for automated image processing in the future.

The changing needs associated with information management also manifest themselves in how MBARI presents highlights of

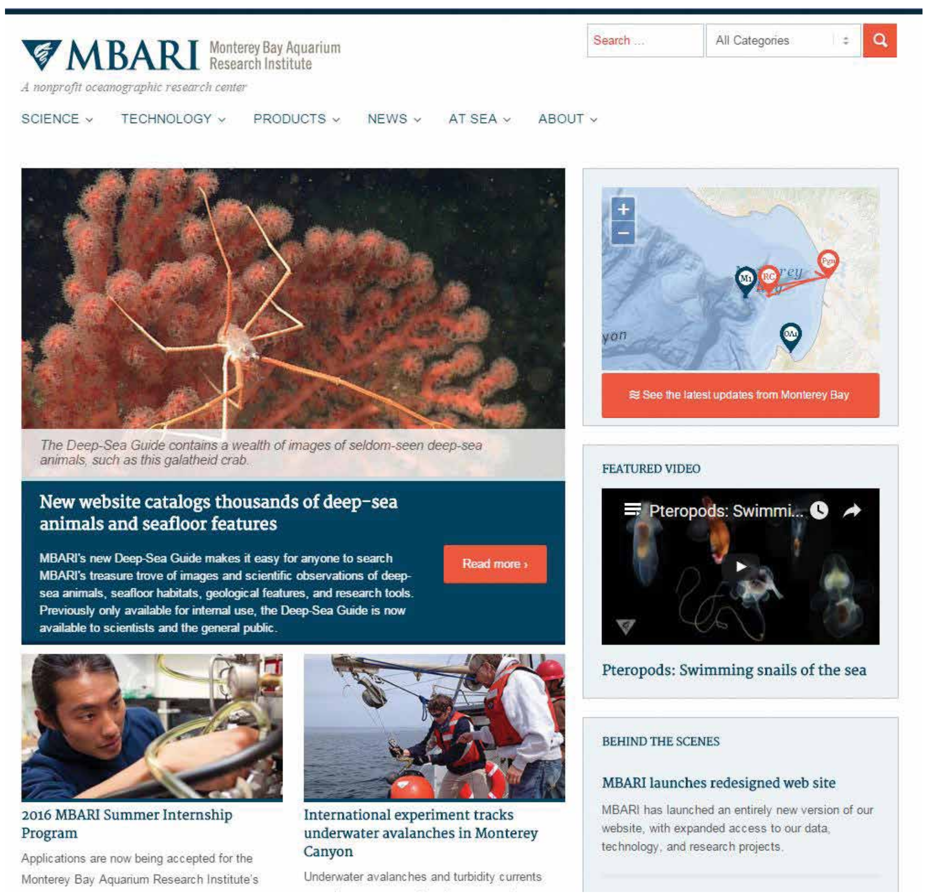


Figure 43. The new MBARI website is fully responsive for ease of use on different devices and is based on the WordPress content management system.

its work and makes the data it has collected publicly available. One element of this evolution resulted in a two-and-a-half year effort to develop a new website that employs a content management system and a responsive design so the site functions well on various devices and screen sizes (Figure 43). The new public interface provides expanded access to data products, disseminated technologies, video streams, images, and updates on current research projects. The site will continue to grow as new content is created, and to meet the interests and changing needs of those who seek to learn more about the ocean, its inhabitants, and its future.

Related web content:
MBARI website: www.mbari.org

Project teams:

Benthic Event Detectors
Project lead: Charles Paull
Project manager: Brian Kieft
Project team: Larry Bird, Dale Graves, Roberto Gwiazda, Bob Herlien, Denis Klimov, Mike McCann, Alana Sherman, Esther Sumner

Investigations of Imaging for Midwater Autonomous Platforms
Project leads: Mark Chaffey, Kim Reisenbichler, Bruce Robison
Project manager: Kim Reisenbichler
Project team: François Cazenave, Rich Henthorn, Rob McEwen, Brian Schlining, Rob Sherlock, Hans Thomas
Collaborators: Henk-Jan Hoving, GEOMAR Helmholtz Center for Ocean Research, Kiel, Germany

Ocean Imaging
Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Rich Henthorn, Brett Hobson, Eric Martin, Mike Risi, Hans Thomas, Giancarlo Troni

Pelagic-Benthic Coupling
Project leads: Alana Sherman, Ken Smith
Project manager: Christine Huffard
Project team: Drew Burrier, Kathy Dunlop, John Ferreira, Rich Henthorn, Brett Hobson, Linda Kuhnz, Paul McGill, Samantha Peart, Brian Schlining, Susan von Thun, Jessica Whelpley
Collaborators: Jeffrey Drazen, University of Hawaii, Honolulu; Jennifer Durden and Henry Ruhl, National Oceanography Centre, Southampton, United Kingdom; Timothy Shaw, University South Carolina, Columbia

Power Buoy
Project lead/manager: Andrew Hamilton
Project team: François Cazenave, Jon Erickson, John Ferreira, Rich Henthorn, Scott Jensen, Denis Klimov, Eric Martin, Jose Rosal

Sensors: Underwater Research of the Future (SURF)
Project lead: Chris Scholin
Project manager: James Birch
Project team: Holly Bowers, Kevin Gomes, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, John Ryan, William Ussler III, Kevan Yamahara
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Thierry Baussant, International Research Institute of Stavanger, Norway; Alexandria Boehm, Center for Ocean Solutions, Stanford University, California; Laurie Connell, University of Maine, Orono; Tim Davis, Great Lakes Environmental Research, Ann Arbor, Michigan; Edward DeLong, University of Hawaii, Manoa; Gregory Doucette, NOAA, National Ocean Service, Charleston, South Carolina; Clement Furlong, University of Washington, Seattle; Dianne Greenfield, University of South Carolina, Columbia; John Griffith and Steve Weisberg, Southern California Coastal Water Research Project, Costa Mesa; Steven Hallam, University of British Columbia, Vancouver, Canada; David Karl, University of Hawaii, Manoa; Stephanie Moore and Vera Trainer, Northwest Fisheries Science Center, Seattle, Washington; Mary Ann Moran and Vanessa Varaljay, University of Georgia, Athens; Cody Youngbull, Arizona State University, Phoenix

Wave Glider Based Communications Hotspot
Project lead: Mark Chaffey
Project manager: Brian Kieft
Project team: Tom O'Reilly
Collaborators: Joaquin Fernandez and Ivan Masmitja, Universitat Politécnica de Catalunya, Spain

External MBARI Website Upgrade
Project leads: Nancy Barr, Kevin Gomes
Project manager: Nancy Barr
Project team: Teresa Cardoza, Judith Connor, Meilina Dalit, Kim Fulton-Bennett, Joe Gomez, Annette Gough, Cindy Hanrahan, Dana Lacono, George Matsumoto, Reiko Michisaki, Melinda Nakagawa, Jennifer Patterson, Todd Ruston, Mariah Salisbury, Nancy Jacobsen Stout

Weird and Wonderful

When exploring the deep sea, we are often surprised by the unusual body shapes and animal behaviors we encounter. Here are two very different kinds of worms found in the depths, one a fairly primitive group and the second highly evolved. Another interesting recent observation was a squid that mimics one of its gelatinous neighbors to avoid being eaten by predators.

No guts, no glory

A discovery during the 2015 Gulf of California expedition helped solve an enduring mystery that has puzzled biologists for more than 60 years. The anomalous marine flatworm called *Xenoturbella*, discovered off the coast of Sweden decades ago, possessed no brain, guts, or anus (Figure 44). How exactly did it fit in the tree of life? Preliminary DNA studies led scientists to proclaim that the animals were degenerate molluscs, but it turns out the DNA came from clams that the worms ate—not of the worms themselves. Subsequent early molecular analysis placed these creatures as relatives of acorn worms or sea stars—entirely different groups. Now, the discovery of four new *Xenoturbella* species from the Gulf of California and Monterey Bay has resolved this mystery. Detailed analyses of the worms' genes and evolutionary relationships, conducted by MBARI researchers and collaborators, firmly placed these flatworms in the Xenacoelomorpha, which comprise the earliest branch in the tree of life for animals with bilateral symmetry. These bizarre worms provide a true glimpse into one of the earliest body plans in animal evolution.

Figure 44. Xenoturbella profunda *was discovered living among clams in the Pescadero Basin at 3,800 meters depth. It looked like a lost sock sitting on the seafloor. This worm is about 20 centimeters long.*

Worms in an array of colors, sizes, and habitats

Deep-sea acorn worms are highly gelatinous, fragile, seafloor creatures. Their delicate skin looks velvety when viewed up close. Although they are worm-shaped, these animals are more highly evolved compared with most other invertebrates (Figure 45). These worms were previously known only from shallow-water specimens that burrow in seafloor sediments. Scientists

Figure 45. This large acorn worm was a whopping 36 centimeters long and was seen at a depth of 2,350 meters in the Gulf of California. Like many of its kind, this new species in the genus Yoda *has a specialized way of vacuuming up sediment off lava rock. The ingested mud provides nutritious bacteria and other organic matter.*

have recently begun to discover just how many different body features acorn worms exhibit and the wide variety of deep-sea environments they inhabit. Some species have specialized head appendages, while others develop wing-like structures just below the head region. They can be transparent, brown, orange, yellow, or purple. Some burrow in mud, while many others have adapted to live on top of lava or other hard substrates. Most surprisingly, some have developed the ability to move from place to place by floating and drifting just above the seafloor. In just the past three years, ecological, taxonomic, and molecular work by MBARI and colleagues doubled the number of known acorn worm families in the class Enteropneusta and identified more than a dozen new species.

Hiding in plain sight

Using video observations from remotely operated vehicles, MBARI scientists described a peculiar case of a squid mimicking a gelatinous animal. Juveniles of the mesopelagic squid *Chiroteuthis calyx* were documented orienting and coloring their tail and body to closely match the common siphonophore *Nanomia* (Figure 46). Compared to the nutrient-dense squid, siphonophores bodies mainly consist of water, plus they possess numerous stinging cells. It is likely that the smaller and more vulnerable juvenile *Chiroteuthis* avoid predation as a result of mimicking the less palatable *Nanomia's* appearance and behavior, in essence hiding in plain sight. However, this mimicry is not consistent across life stages. As juveniles mature into subadults, when they are presumably better able to defend themselves in other ways, they lose their tail and therefore the ability to resemble *Nanomia*.

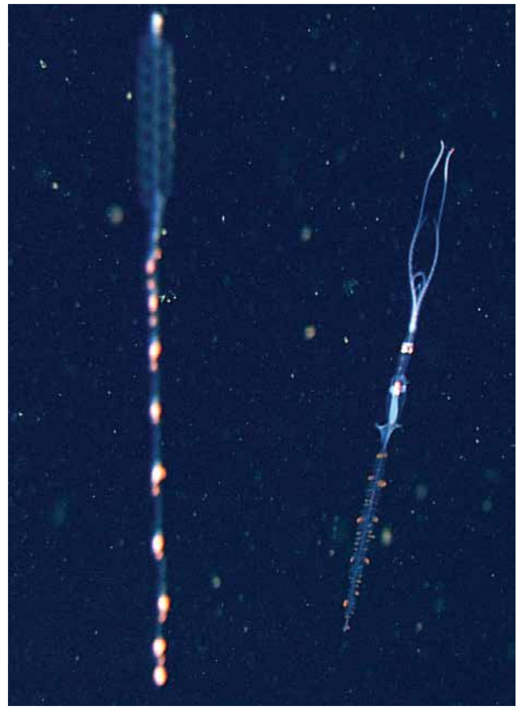


Figure 46. Nanomia *siphonophore (left) and juvenile* Chiroteuthis calyx *squid (right). The animals are about 20 to 30 centimeters long.*

Related web content:

Xenoturbella worm: www.mbari.org/deep-sea-worms-slither-around-the-bottom-of-the-animal-tree-of-life/
Acorn worms: www.mbari.org/bountiful-harvest-of-deep-sea-acorn-worms
Mimcry video: www.youtube.com/watch?v=zPf2UBwMhKY

On the Horizon

Return visits to significant research sites are important for assessing change over time as well as for conducting new experiments to learn about habitats, animals, or phenomena. To that end, MBARI scientists are planning return expeditions to Axial Seamount, Sur Ridge, and the Arctic in 2016. Other program highlights for the year are a large study of canyon dynamics, testing out new AUV capabilities, and a chance to host our technology peers at an important conference.

Pooling resources and talent to detect unseen landslides

Underwater avalanches and turbidity currents carry huge amounts of sediment, organic material, and pollutants down submarine canyons and into the deep sea. Yet geologists know very little about how sediment moves during these events. In what may be the most ambitious submarine canyon study ever attempted, MBARI Geologist Charlie Paull and his team, along with an international group of collaborators, placed dozens of sophisticated instruments in Monterey Canyon. This Coordinated Canyon Experiment promises to give scientists a uniquely detailed and comprehensive view of sediment movement within the canyon.

Figure 47: MBARI Geologist Charlie Paull watches as an array of instruments (a benthic instrument node) is lowered into MBARI's test tank in preparation for being placed on the seafloor during the Coordinated Canyon Experiment.

The two-year experiment began in late 2015 with the placement of 10 arrays of instruments (Figure 47) to monitor movements of water and sediment at depths of 200 to 1,900 meters and distances of four to 40 kilometers from shore. These instruments will measure currents, sediment concentrations, and the physical properties of the seawater. The instruments will be left in place for up to 18 months, documenting any flows that take place during that time. In addition to the fixed instrument arrays, four beach-ball-sized benthic event detectors were buried in the seafloor sediment. These instruments get carried along with the sediment during flows, recording the motion as they go. Sections of the canyon will also be mapped in high resolution to detect any changes in the topography.

The researchers hope to gather information on what triggers underwater sediment flows, how fast they move, and how far they travel. Early data returned to the team gave preliminary indication of a strong event during the first winter, but information collection and analysis will continue over the course of the experiment.

Paull is leading the project in collaboration with researchers from the United States Geological Survey, the Ocean University of China, the National Oceanography Centre in Southampton, England, and the University of Hull, England.

Mapping the Arctic Ocean edge

Paull will also lead an expedition to the Arctic. In the remote, ice-covered Canadian Beaufort Sea, methane has been bubbling out of the seafloor for thousands of years. Paull and his colleagues from the Geological Survey of Canada are trying to figure out where this gas is coming from, how fast it is bubbling out of the sediments, and how it affects the stability of the seafloor. In 2016 Paull will return to the Arctic to conduct AUV mapping and MiniROV sampling operations from a Canadian Coast Guard icebreaker. The 2016 expedition will further investigate areas of gas seepage and document gas-venting structures of the unstable seafloor. Paull plans to explore some poorly understood geomorphic features which appear to be unique to the margin of the Arctic and may be associated with freezing of sediments. The dynamics of gas venting at many of these sites is associated with either decomposition of glacial permafrost that was flooded during sea-level rise at the end of the last glacial period or of deeper gas hydrate deposits.

Oil and gas companies have known for decades that deep oil and natural gas deposits exist in the sediments below the Beaufort Sea. With the warming of the Arctic and the retreat of sea ice, these hydrocarbons have become more accessible. It remains unknown whether they can be extracted safely, economically, and without excessive environmental damage. Paull's collaborative research will provide insight into geological processes as well as important information for decision-makers involved in permitting oil and gas extraction.

Returning to the deep-sea oasis on Sur Ridge

Sur Ridge is a unique feature in the Monterey Bay National Marine Sanctuary where exploratory remotely operated vehicle dives led to surprising discoveries of expansive populations of deep-sea corals and sponges. The accessibility of these highly dense coral populations on Sur Ridge increases its importance for conservation and research in the sanctuary.

Since the initial dives, the site has been further mapped in high resolution with MBARI's *D. Allan B.* autonomous underwater vehicle so that researchers can better target future work and gain a better understanding of the seamount that hosts this rich deep-sea community. In 2016 Scientist Jim Barry will return to Sur Ridge in collaboration with his colleagues from the sanctuary to examine the distribution of corals and other megafauna in relation to topography. They will also focus on the relationship between corals and their potential predators, such as sea stars, and continue a small transplant experiment to learn about the potential for repopulating sites where the coral population has been damaged through fishing or other activities (Figure 48).

Figure 48: One aspect of the Sur Ridge research will focus on the relationship between bamboo corals and their natural predators, such as this Hippasteria *sea star (left; 15 centimeters) and* Tritonia *nudibranch (right; 20 centimeters).*

The researchers aim to identify key environmental and biological processes that influence the success of corals on Sur Ridge—and in deep-sea environments in general—including the potential effects of human activities. Sensitivity of corals to ocean acidification and hypoxia will be examined. These studies broaden our understanding of the roles of natural and anthropogenic factors influencing deep-sea coral communities. Each of these activities will contribute to conservation efforts through collaboration with the Monterey Bay National Marine Sanctuary.

Return to Axial Seamount

With the eruption of Axial Seamount in April 2015 for the third time since 1998, geologist David Clague and his research team are eager to return to the Juan de Fuca Ridge west of Oregon to analyze the changes that have undoubtedly ensued. This recent eruption at Axial followed a different pattern from those in 1998 and 2011 (Figure 49), in that the flows erupted on the north rift and north end of the caldera rather than the south.

While the placement of sensors on the seafloor have been a major step forward in understanding volcanic and hydrothermal processes in the marine environment, most geological events have long repeat intervals, on the order of decades to thousands or even tens of thousands of years. The larger events, and therefore those more likely to impact civilization, are less frequent occurrences. High-hazard events such as earthquakes, landslides, and

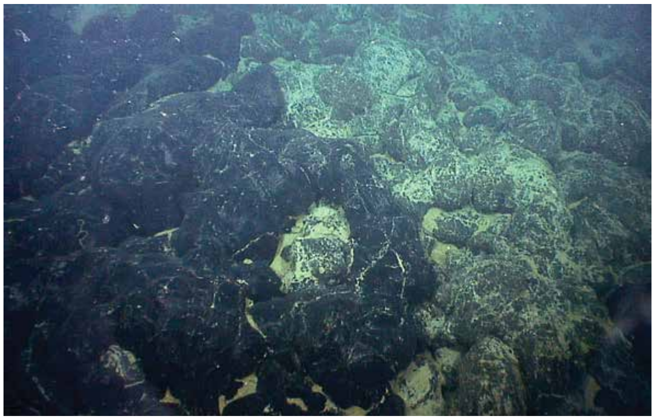


Figure 49. Dark fresh lava from the 2011 eruption at Axial Seamount flowed over lava from the 1998 eruption, which is coated with yellowish bacteria and sediment.

eruptions may have recurrence intervals so long that they are unlikely to be captured by sensing instrumentation, which must be deployed both long enough and in the correct area.

The ongoing volcanic activity on Axial Seamount gives researchers the perfect chance to add significant information to that collected by seafloor instruments. Clague's team plans to return to Axial Seamount, where they will make the most of MBARI's AUV mapping and follow-up targeted ROV sampling capabilities. They plan to establish a base map of seafloor elevation changes at the volcano as the summit re-inflates and the caldera floor rises in response to the addition of magma inside the summit magma chamber. These efforts will likely provide new and fundamental information about the behaviors of undersea volcanoes.

Orchestrating delicate surveys around an iceberg

Another challenge of working in the polar regions is how to navigate an autonomous underwater vehicle around free-drifting icebergs. The challenge is analogous to flying a space probe around an asteroid; since icebergs drift and rotate, normal latitude/longitude navigation used on AUVs does not work. With the help of NASA funding, the MBARI AUV team has routinely implemented terrain-relative navigation (TRN) aboard a vehicle to enable precise return-to-site missions. This capability is not easily available with existing acoustic, inertial, or map-based navigation solutions. In addition to the TRN system, the Iceberg AUV features cameras and sonars that can be pointed out either side of the vehicle as well as the normal down-looking orientation for seafloor exploration. Development of the system and testing in Monterey Bay has been put to use to assist projects to study rockfish habitat for The Nature Conservancy and Moss Landing Marine Laboratories.

In 2016 the team, led by Engineer Brett Hobson, will have its first opportunity to run the Iceberg AUV with TRN around icebergs. The vehicle will be shipped to Newfoundland, Canada, where the team will run missions offshore of St. John's. The first field expedition will locate, map, and perform return-to-site missions on at least one free-drifting iceberg. Following missions will collect pictures, measure salinity, temperature, chlorophyll, oxygen, and light levels, and fine-scale currents near the iceberg. One long-term goal of this effort is for NASA to use the knowledge gained mapping a free-drifting iceberg to further explore asteroids during future space missions.

Hosting marine technologists from around the world

MBARI will host the Marine Technology Society (MTS) and the Oceanic Engineering Society of the Institute of Electrical and Electronics Engineers (IEEE) joint conference in September at the Monterey Conference Center. MBARI Engineer Bill Kirkwood is serving as co-chair of the event. The conference serves as an important forum for scientists, engineers, and technology users throughout the world to present and discuss the latest research results, ideas, developments, and applications in all areas of oceanic science and engineering. MTS-IEEE Oceans '16 Monterey will feature expositions on ocean science, engineering, and policy over four days, with one day dedicated to tutorials and workshops, and three days of technical presentations, poster sessions, and exhibits.

The annual conference will raise awareness of potential threats to ocean health and highlight some of the engineering and scientific efforts to understand and address the impacts of those threats.

Related web content:
Oceans '16: http://www.oceans16mtsieeemonterey.org/

Behind the Scenes:
Management team welcomes two new senior managers

In 2015, MBARI welcomed two new members to the institute's senior management team. Basilio Martinez and Michael Kelly replaced retiring long-time senior managers as chief financial officer (CFO) and director of marine operations, respectively. MBARI's management team is charged with overseeing the institute's top-level operations—no easy task. Martinez's robust accounting skills and Kelly's breadth of experience in marine operations are essential supplements to the team's wide-ranging areas of expertise.

Basilio Martinez came to MBARI with over 10 years of senior-level experience in financial and accounting management and several years of experience in auditing (Figure 50). Before joining MBARI, he was vice president of finance and accounting at Peninsular Packaging in Hollister, California. During his 10-year stint there, the company grew from a $10 million to $180 million business. Martinez said he was attracted to MBARI, in part, by the institute's mission to achieve and maintain a position as a world center for advanced research and education and, at the same time, emphasizing its focus on excellence, innovation, and vision.

Mike Kelly has a comprehensive background working in marine operations (Figure 51). He previously served as director of the Ocean Observatories Initiative and senior program manager for the Consortium for Ocean Leadership in Washington, D.C. Prior to that he was vice president of operations at Ocean Power Technologies, a wave-energy technology company. He has worked extensively on seafloor cables and cabled ocean observatories, and has served as captain of civilian and military cable-laying ships. Kelly said he was drawn to the interdisciplinary collaboration at MBARI—the ability to support science through coordinated efforts of scientists, engineers, and marine operations. He is enthralled by the institute's organizational mission and structure that encourages timely responses to science questions and the emerging technologies that support exploration.

While MBARI embraced its newly appointed managers, the staff bid fond farewell to their long-term predecessors, Mike Pinto and Steve Etchemendy. Pinto served as the institute's CFO since 1999 and before that, as CFO at MBARI's partner, the Monterey Bay Aquarium, for 16 years. At MBARI, Pinto was essential in overseeing the modernization of the accounting systems as they moved from a paper-based system to web-based applications. Pinto was also heavily involved in the financial logistics of purchasing the R/V *Rachel Carson* and R/V *Zephyr*. In recent years, Pinto took the lead in coordinating MBARI's master planning effort, in preparation for upgrading and modernizing the campus.

Aside from his standard duties as CFO, Pinto did get a taste of what it's like to be a research technician and communicator. In 2001, he participated in a month-long research cruise in the Arctic Ocean, with the primary role of writing daily cruise logs

Figure 50. MBARI Chief Financial Officer Basilio Martinez.

Figure 51. MBARI Director of Marine Operations Mike Kelly.

Figure 52. Former Chief Financial Officer Mike Pinto on a research cruise in the Arctic.

for the MBARI website, as well as helping researchers gather data from a conductivity, temperature, and depth (CTD) instrument (Figure 52).

Etchemendy is an integral part of MBARI's history—he joined MBARI in 1989 as operations engineering manager, two years after the institute was established. Etchemendy was previously a pilot for the human-occupied vehicle *Alvin* and vice president of Deep Ocean Engineering. At the start of his 25-year run at MBARI, Etchemendy was hugely instrumental in developing and solidifying the institute's marine operations division. He was heavily involved in the outfitting of the R/V *Western Flyer* (Figure 53), R/V *Zephyr*, and R/V *Rachel Carson*, as well as the commissioning of the ROV *Tiburon* and purchasing of ROV *Doc Ricketts*. Etchemendy also played a major role in the execution of the Monterey Accelerated Research System (MARS) cabled observatory, which was installed in Monterey Bay in 2007. Both Pinto and Etchemendy made huge contributions to MBARI. They will be dearly missed.

Martinez and Kelly worked closely with Pinto and Etchemendy through the latter part of 2015, ensuring a seamless transition into the new year. When asked what he is looking forward to the most in his new role, Martinez reiterated MBARI's mission statement. He said, "I am looking forward to applying my past experience and combining that with gained knowledge to continue to help drive the organization towards excellence and innovation." Kelly said he's looking forward to "the opportunity to work closely with the people, ships, and undersea vehicles that support our science endeavors. It's refreshing to connect management decisions directly with what happens within labs and shops which support our science."

MBARI is looking towards a new era with big changes underway and strives towards excellence in not only its science and technology, but its staff. With Martinez and Kelly onboard, MBARI continues to maintain a bright future.

Figure 53. Former Marine Operations Director Steve Etchemendy, left, with MBARI Founder David Packard at the dedication of the research vessel Western Flyer *in 1996.*

Project Summaries

Below are brief summaries and listings of team members for MBARI projects supported by the David and Lucile Packard Foundation, but not otherwise highlighted in this report. Also included are projects that received significant funding from external agencies, as indicated in each entry.

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 and maintenance was ongoing for MB-System, the primary software used for processing and visualization of seafloor mapping data. Development of the Spatial Temporal Oceanographic Query System (STOQS) enabled effective integration of AUV data with a variety of data from other platforms. MB-System and STOQS were represented at national and international meetings.

AUV Science Operations Using Terrain Relative Navigation

Project leads: Brett Hobson, Charles Paull
Project manager: Brett Hobson
Project team: David Caress, Dale Graves, Rich Henthorn, Rob McEwen, Mike Risi, Steve Rock, Alana Sherman, Hans Thomas
Collaborators: Mary Gleason, The Nature Conservancy, Monterey, California; Rick Starr, Moss Landing Marine Laboratories (MLML), California

The project team routinely implemented terrain-relative navigation (TRN) aboard MBARI's NASA-funded Iceberg AUV to enable precise return-to-site missions. This capability is not easily available with existing acoustic, inertial, or map-based navigation solutions. The team also used TRN onboard MBARI's MiniROV along with a combined acoustic/inertial navigation system to precisely navigate from rock to rock in Monterey Canyon to look for depleted rockfish species with researchers at the Nature Conservancy and Moss Landing Marine Laboratories. Novel techniques are needed to accurately conduct fishery surveys in steep, rocky seafloor habitats where traditional trawls, tow-fish cameras, and drop cameras are ineffective.

Central and Northern California Ocean Observing System (CeNCOOS): Integrating Information for Decision-Makers

Project lead: David Anderson
Project manager: Aric Bickel
Project team: Fred Bahr, Jennifer Patterson
Collaborators: Jack Barth, Oregon State University, Corvallis; Barbara Block, Hopkins Marine Station of Stanford University, Pacific Grove, California; Rob Bochenek, Axiom Data Science, Anchorage, Alaska; Yi Chao, University of California, Los Angeles; Francisco Chavez, MBARI; Kenneth Coale, Jim Harvey, and Jason Smith, MLML, California; James Doyle, Naval Research Laboratory, Monterey, California; Chris Edwards, Raphael Kudela, and Andrew Moore, University of California, Santa Cruz; Rikk Kvitek, California State University, Monterey Bay; John Largier, University of California, Davis; Karina Neilson, Romberg Tiburon Center for Environmental Studies, California; Jeff Paduan, Naval Postgraduate School, Monterey, California; Frank Shaughnessy, Humboldt State University, California; Chad Whelan, CODAR Ocean Sensors, Mountain View, California

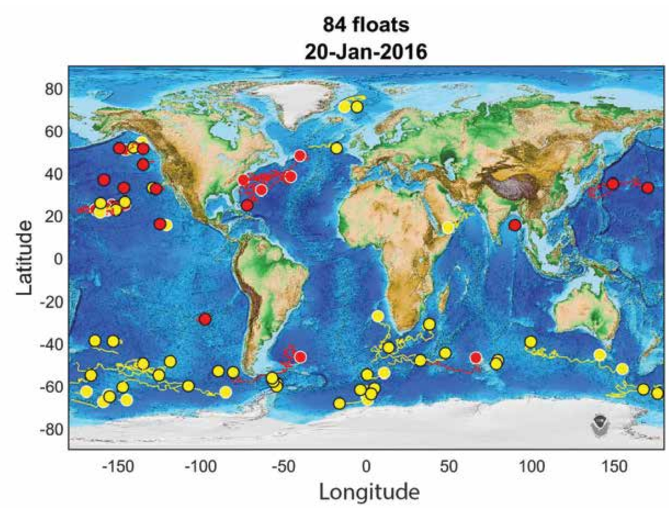
Investigators from 15 institutions operated 13 shore stations, two meteorological stations, 27 surface current-sensing high-frequency radar, three regional scale numerical models, two glider transects, and a data portal that provides access to the real-time continuous monitoring and legacy data. These "eyes on the ocean" support marine operations and coastal hazards readiness, monitor trends and variability in climate, and contribute to sustaining healthy environments and ecosystems. CeNCOOS observing was supplemented by support from the National Aeronautics and Space Administration (NASA) for studies on harmful algal blooms and from National Oceanic and Atmospheric Administration (NOAA) for ocean acidification and marine biodiversity work. Conditions in the Eastern Pacific were unusual in many ways—record warm temperatures (see page 4), a once-in-a-decade-magnitude harmful algal bloom (see page 6), and an ongoing drought that increased the salinity in bays and estuaries. These observations appear in the CeNCOOS data archive, and were described in publications and at regional meetings by CeNCOOS collaborators. CeNCOOS is funded in part through NOAA's Integrated Ocean Observing System program.

Chemical Sensors

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Hans Jannasch, Gene Massion, Josh Plant, Carole Sakamoto

Collaborators: Robert Carlson, Honeywell; Todd Martz, Scripps Institution of Oceanography, La Jolla, California; Steve Riser and Dana Swift, University of Washington, Seattle; Jorge Sarmiento, Princeton University, New Jersey

The team continued to develop chemical sensors and deploy them throughout the world ocean. The goal is to have a global network of chemical sensors on profiling floats that can observe carbon, oxygen, and nitrate cycles at the seasonal and interannual scale throughout the ocean. The cycles of these elements can be used to make quantitative estimates of air-sea carbon transport, net community production (primary production minus respiration), carbon export from surface waters to depth, and the ecosystem dynamics that control the flow of these chemicals. The team is also contributing to the Southern Ocean Carbon and Climate Observations and Modeling (SOCCOM) program (see page 12).



Current positions (circles) and tracks (thin lines) of the 84 profiling floats carrying chemical sensors built at MBARI. Red dots are floats with nitrate and oxygen. Yellow dots are floats with nitrate, oxygen and pH, in most cases.

Coastal Profiling Float

Project leads: Ken Johnson, Gene Massion
Project manager: Gene Massion
Project team: Paul Coenen, Brent Jones, Eric Martin, Paul McGill, Ed Mellinger, Jose Rosal
Collaborator: Dana Swift, University of Washington, Seattle

The Coastal Profiling Float completed a set of at-sea and tank tests successfully meeting all its functional requirements. Acquiring and processing the science data is an inherent part of the development effort and the team has developed the applications required to ensure the float is collecting reasonable science data. The team is currently running longer at-sea tests to prepare for the next milestone—long-term, autonomous deployments in Monterey Bay. In addition, two more floats were built for the CANON project and these floats are also undergoing at-sea testing.

The coastal profiling float.

Core Mooring Data

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

This project provides for the institutional support of core data from MBARI moorings. Scripts used to combine individual deployment quality-controlled Network Common Data Form (NetCDF) files were updated to accept both the original conventions and the new OceanSITES version 1.3 conventions. Combined hourly and daily NetCDF files were produced for all quality-controlled data, from August 1989 through July 2015. These data are made available to the general public through MBARI's OPeNDAP server and the Live Access Server.

Core Conductivity-Temperature-Depth (CTD) Data

Project lead: John Ryan
Project manager: Erich Rienecker
Project team: Marguerite Blum, Dale Graves, Reiko Michisaki, Edward Peltzer, Kim Reisenbichler, Bruce Robison, Rich Schramm, Rob Sherlock

Support continued on the maintenance, operation, calibration, and configuration of the core CTD instruments, electronics, and related hardware. The interface for CTD data viewing in real-time on the ships was further improved. Following implementation of dual oxygen sensors on both ROVs, production of near-real-time quality control plots was established. This enabled the detection and solving of issues in oxygen sensor performance. Comparisons of Winkler titration results to oxygen sensor data were used to improve quality control flagging in the core data stream.

Core Navigation

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

The collection, processing, and archiving of core data is provided on an institutional basis with oversight by the MBARI Data Users Committee. The project team maintained navigation hardware on the ROVs and ships, maintained and developed software for automated processing and archiving of navigation data, edited ROV navigation data, and monitored data quality. The team kept pace with the flow of incoming data and its integration into the video annotation database.

Cytometer Technology for Autonomous Platforms

Project leads: Denis Klimov, Tom O'Reilly
Project manager: Tom O'Reilly
Project team: Francisco Chavez
Collaborators: Roger Dellor, Kurt Kiesow, Heike Schmitz, and Lisa Ziccarelli, Jupiter Research Foundation, Los Altos, California; Rob Johnson and Heidi Sosik, Woods Hole Oceanographic Institution, Massachusetts; Stephen Jones and John Samson, 4Deep Inwater Imaging, Nova Scotia, Canada; Peter Lopez, New York University; Steven Steinberg, Southern California Coastal Water Research Project, Costa Mesa; Jarred Swalwell, University of Washington, Seattle

Shipboard cytometers already provide critical information about marine microbial communities and how they respond to environmental change. This project is investigating cytometer integration into autonomous vehicles such as the long-range AUV (LRAUV) and Wave Glider, which could enable long-duration microbial surveys without the need for an expensive crewed vessel, and possibly under the ice in climate-sensitive polar regions. Development continued on a bench-top flow-through imaging fluorescent microscope prototype and a concept of a submersible instrument. The benchtop prototype is intended to evaluate hardware, fluidic, electrical, optical, and software designs that might be adapted for an AUV-compatible instrument. The instrument is based on an Android phone as the control and processing platform, uses a standard microscope objective, and has two illumination sources. The submersible instrument is intended for use in shallow water and to be equipped with a low-pressure housing to reduce cost. The team also began planning a mobile cytometer/microscope workshop to be held at MBARI in 2016.

Demonstration Marine Biodiversity Observation Networks (MBON) for National Marine Sanctuaries

Project lead/manager: Francisco Chavez
Project team: Shannon Johnson, Mike McCann, Monique Messié, Reiko Michisaki, Kristine Walz, Kevan Yamahara
Collaborators: David Anderson, Aric Bickel, and Jennifer Patterson, Central and Northern California Ocean Observing System and MBARI; Ali Boehme, Rebecca Martone, and Jesse Port, Center for Ocean Solutions, Monterey, California; Steven Bograd, Lynn deWitt, John Field, Elliott Hazen, and Jarrod Santora, National Marine Fisheries Service; Jennifer Brown and Andrew DeVogelaere, Monterey Bay National Marine Sanctuary, Monterey, California; Maria Kavanaugh, Woods Hole Oceanographic Institution, Massachusetts; Frank Muller-Karger, University of South Florida, Tampa

This project seeks to 1) integrate, synthesize, and augment biodiversity information from ongoing programs; 2) provide geographically integrated time-series metrics of biodiversity and ecosystem health; 3) develop advanced methods, including environmental DNA technology and autonomous sample collection methods, for conducting biodiversity assessments; 4) bring biodiversity measurements together in databases with links to national and international databases; 5) relate the assembled information to social-economic context and provide it rapidly to stakeholders; and 6) develop a plan to transition the demonstration MBON into an operational system. In this first year of the five-year project, a new and novel pipeline for genomic analysis has been instituted and exciting results are being developed. Historical data are being entered into data systems with standard links to the outside world. This project is supported by funding from NASA and the University of South Florida, Tampa.

Differential Contributions of Archaeal Ammonia Oxidizer Ecotypes in Relation to Their Changing Environment

Project lead: Francisco Chavez
Project managers: Francisco Chavez, Jason Smith
Project team: Marguerite Blum
Collaborators: Christopher Francis and Bradley Tolar, Stanford University, California; Julie Granger and Julie Robidart, University of California, Santa Cruz

With funding from the National Science Foundation (NSF), samples for the genetic analysis of the diversity, abundance, and activity of ammonia-oxidizing communities and rates of nitrification, ammonium, and nitrate uptake by phytoplankton were collected during 10 Monterey Bay time-series cruises. Initial analyses of biogeochemical data reveal a temporal cascade in particle formation and nitrogen remineralization, starting with the spring phytoplankton bloom, followed by accumulation of ammonium and then nitrite in the subsurface waters at MBARI's M1 mooring. This trend is currently being explored on the genetic level using markers for ammonium and nitrite oxidation. Experiments were also conducted during the Gulf of California expedition, to study the physiology and kinetic traits of wild populations of ammonia-oxidizing microorganisms, and with the AUV to study small-scale variability in nitrification rates and the associated microbial communities.

EarthCube IA: Collaborative Proposal: Cross-Domain Observational Metadata Environmental Sensing Network

Project lead/manager: Carlos Rueda-Velasquez
Collaborators: Mike Botts, Botts Innovative Research, Inc., Madison, Alabama; Janet Fredericks, Woods Hole Oceanographic Institution, Massachusetts; Felimon Gayanilo, Texas A&M University, Corpus Christi; Krzysztof Janowicz, University of California, Santa Barbara

The NSF-funded project began in the fall, and the team has begun software development and the installation of the Marine Metadata Interoperability Ontology Registry and Repository for the Federation of Earth Science Information Partners (www.esipfed.org). MBARI has made significant progress in its participation in the overhaul of the repository, fixing software bugs and implementing enhancements. The project team worked on establishing concrete collaborations and introduced the project to the larger geoscience data management community via oral presentation and discussions at science meetings (http://earthcube.org/).

Ecology and Dynamics of Primary Producers

Project lead: Alexandra Z. Worden
Project managers: Sebastian Sudek, Alexandra Z. Worden
Project team: Charles Bachy, Larry Bird, Chang Jae Choi, Jian Guo, Magdalena Gutowska , Valeria Jimenez, Denis Klimov, Alexander Limardo, Camille Poirier, Lisa Sudek, Susanne Wilken, Amy Zimmerman
Collaborators: Stephen Giovannoni, Oregon State University, Corvallis; Rachel Harbeitner, University of California, Santa Cruz; Amala Mahadevan, Woods Hole Oceanographic Institution, Massachusetts; Victoria Orphan, California Institute of Technology, Pasadena; Maria Vernet, Scripps Institution of Oceanography, La Jolla, California

The team initiated collaborative research in the Bay of Bengal and Antarctica in 2015. Field work was also performed by team members on and near Curaçao and in the Eastern North Pacific. Several technologies were brought to fruition—one which allows exploration of algal growth responses to future climate conditions and two others that allow measurement of deep-sea water and sediment microbial community activities.

Postdoctoral Fellow Susanne Wilken processes samples aboard the R/V Western Flyer.

Education and Research: Testing Hypotheses (EARTH)

Project lead/manager: George Matsumoto
Project team: Christina Preston, Amy Zimmerman
Collaborators: Tracy Crews, Oregon State University, Newport; Ruth McDonald, Lincoln County School District, Newport, Oregon

Twenty-eight educators gathered in Newport, Oregon, for the 2015 EARTH workshop (http://www.mbari.org/products/educational-resources/earth/earth-workshops/earth-2015/), which was co-hosted by MBARI and the Oregon Coast Regional STEM Center Math Science Partnership and partially funded by a grant from the U.S. Department of Education. Speakers from both host organizations shared information to help teachers bring real data into the school curriculum. Two satellite workshops were hosted by previous EARTH participants and discussions for further dissemination of EARTH materials and workshop format have been ongoing.

MBARI Postdoctoral Fellow Amy Zimmerman, third from the left, works with EARTH educators to design a classroom activity using microbial data.

Fault Detection, Diagnosis, and Mitigation for Long-Duration AUV Missions with Minimal Human Intervention

Project leads: Brian Kieft, Yanwu Zhang
Project manager: Yanwu Zhang
Project team: Ben Raanan, Jordan Stanway
Collaborators: Mark Abbott and James Bellingham, Woods Hole Oceanographic Institution, Massachusetts

For autonomous underwater vehicles (AUVs) to be successful for long deployments, they must be vigilant and responsive in the face of subsystem failures and environmental challenges. Toward this end, the Office of Naval Research (ONR) provided funding for this project. The project team is developing methods for AUVs to autonomously detect faults and failures, identify the root cause, and choose the best response to allow the mission to continue if possible, and at least ensure the vehicle and data are recovered safely. The team designed and integrated a vertical-plane flight fault detector in the *Tethys*-class long-range AUV (LRAUV) code, to flag flight anomalies onboard the vehicle in real time. The work focused on detecting anomalies in vehicle performance, using the extensive repository of mission data as training sets. The successful algorithms have been implemented to be run in real time on an operational AUV. In an LRAUV field deployment, the detector registered an upward trend in the offset angle of the stern plane, which indicated a growing separation between the AUV's centers of mass and buoyancy. Based on these data, the engineering team uncovered mechanical degradation of the mass shifting actuating system that would have otherwise been very difficult to find. The detector is also able to recognize anomalies caused by multiple failures that leave the vehicle in an undesirable state.

Feasibility Study for Applying Cloud Infrastructure to Data Analysis Problems

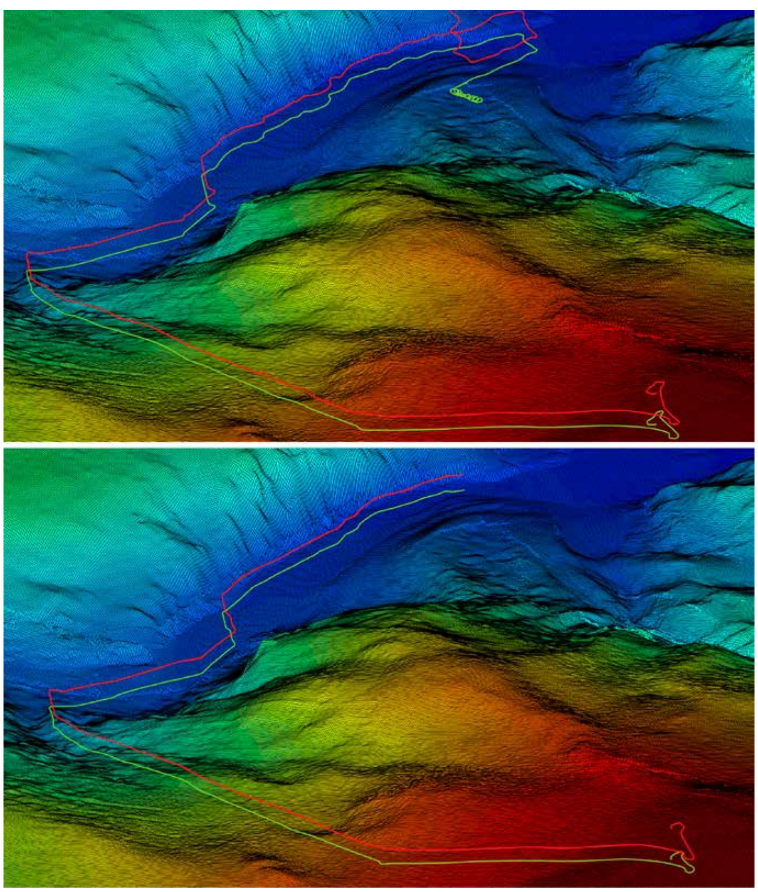
Project lead: Brian Schlining
Project team: Danelle Cline, Steven Haddock

The team investigated and evaluated cloud technologies that could be applicable to the analysis of a variety of data collected by MBARI. The costs, the level of specialized skills required to deploy and maintain applications, and maintenance requirements of cloud technologies were evaluated. The team deployed several tests on different cloud providers.

Full-Speed *Dorado* Simulator

Project lead: Rich Henthorn
Project manager: Rob McEwen
Project team: Kent Headley, Hans Thomas

The Dorado AUV program at MBARI has historically been limited by inadequate simulation capability. Previously simulations could only run in real time, rendering them essentially useless for missions of significant complexity, and impractical for use on the ship. This project has removed that constraint and simulations now run routinely at around 60 times real-time speed. This allows engineers to quickly verify both new vehicle code and complicated missions, possibly saving valuable sea time by avoiding the need to re-run a mission because the vehicle did something unexpected. The simulator includes nearly all of the same flight code that runs on the vehicle, which is coupled with the bathymetry maps to produce detailed and credible predictions. The simulation can now be run on board the ship quickly enough to react to last-minute mission changes, such as when a whale-watching boat unexpectedly appears in the designated test area or there is a sudden turn in the weather.



Top image shows data from a mission in which the AUV followed a wall. (The green trace shows the vehicle's path over the ground.) The bottom image shows a simulation of the same mission. The mission took an hour and 34 minutes, and the simulation ran in a few minutes.

Harmful Algal Bloom Forecasting

Project leads: David Anderson, Francisco Chavez
Project manager: Fred Bahr
Collaborators: Clarissa Anderson and Raphael Kudela, University California, Santa Cruz; Yi Chao, Remote Sensing Solutions, Inc., Monrovia, California; Dale Robinson, National Oceanic and Atmospheric Administration, Santa Cruz, California

Researchers implemented new algorithms for forecasting the presence of domoic acid and *Pseudo-nitzschia* California-wide, using optimally filled satellite ocean-color images and output from a regional ocean model run.

A High-Resolution Bio-Sensor to Simultaneously Measure the Behavior, Vital Rates, and Environment of Key Marine Taxa

Project lead/manager: Kakani Katija
Collaborators: Tom Hurst and T. Aran Mooney, Woods Hole Oceanographic Institution, Massachusetts; Kenneth Alex Shorter, University of Michigan, Ann Arbor

To address questions regarding marine animal behavior, physiology, and ecology, NSF funded the research team to develop innovative bio-sensor technology (the ITAG) for keystone, soft-bodied invertebrates, such as squids and jellies. The ITAG simultaneously measures fine-scale animal behaviors and samples high-resolution physical-biogeochemical environmental data. Importantly, these data are sampled affixed to the organism across temporal and spatial scales relevant to the animal, providing vital information about their basic biology and community interactions. The team integrated light, external temperature, and additional pressure sensors with accelerometers and magnetometers, identified sensors for dissolved oxygen and salinity, and tested deployment methods on jellyfish in Monterey Bay. The eventual ability to link behavioral and environmental data from free-ranging soft-bodied invertebrates will enable the study of baseline animal activity and climate-related environmental changes—such as ocean acidification and the ocean carbon cycle—which have the potential to significantly affect the health of the ocean.

Jellyfish tagging (a sample tag at right) will focus on Chrysaora fuscescens *(left) that are abundant in late summer in Monterey Bay.*

Iceberg AUV

Project lead/manager: Brett Hobson
Project team: David Caress, Doug Conlin, Rich Henthorn, Rob McEwen, Steve Rock, Hans Thomas

This is a NASA-funded project to develop the capability to navigate an AUV alongside a free-floating iceberg. Such a capability is analogous to flying a space probe around an asteroid and is challenging since icebergs drift and rotate, so normal latitude/longitude navigation used on AUVs does not work. During 2015 the team continued to develop tools and techniques to work along the steep walls of Monterey Canyon at 1,000-meters depth, which is as close to iceberg conditions as can be found nearby. The AUV features cameras and sonars that can be pointed out either side of the vehicle as well as the normal down-looking orientation for seafloor exploration. The team plans to test the AUV and new navigation techniques on icebergs offshore Newfoundland, Canada, in June of 2016.

An Integrated MBARI Time-Series Program

Project leads: Francisco Chavez, Bruce Robison, Ken Smith
Project manager: Monique Messié
Project team: Anela Choy, Kevin Gomes, Brett Hobson, Christine Huffard, Reiko Michisaki, Tim Pennington, Mariah Salisbury, Rob Sherlock, Alana Sherman

MBARI supports three time-series projects that span the water column from the surface ocean and midwater to the seafloor in one of the most productive and economically important areas of the world ocean. The goal of this project is to integrate the information from the three time series, both technically and scientifically. This provides an opportunity to track the flow of energy and organic carbon, including production and utilization, through the water column to the seafloor as well as determining climate-driven ecosystem changes. In 2015, the team focused on biology and developed ecosystem indices representative of ecosystem status and change over the 27-year time series. These include key taxa, biodiversity indices and statistical indices that capture synchronous variability among species. The integration of ecosystem data from the three time series into a common data repository is underway.

LRAUV: Coordinated Observations of Marine Organisms and Ocean Features

Project leads: Francisco Chavez, Brett Hobson, Chris Scholin, Yanwu Zhang
Project manager: Brett Hobson
Project team: Paul Coenen, Jon Erickson, Brian Kieft, Denis Klimov, Ed Mellinger, Craig Okuda, Tom O'Reilly, Ben Raanan, Carlos Rueda-Velasquez, Jordan Stanway

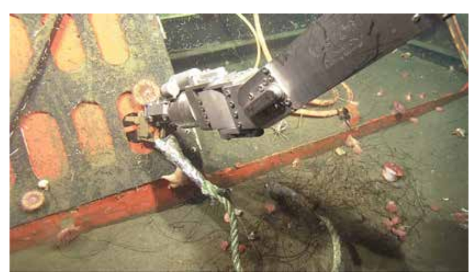
MBARI operates three LRAUVs that were developed for extended investigations in the upper 300 meters of the ocean. These AUVs have the ability to operate for up to two weeks covering 1,000 kilometers using rechargeable batteries or one month and 2,000 kilometers with disposable batteries. While usually deployed alone for time-series data collection or developmental testing, these three LRAUVs can work together to find, track, and sample moving ocean features like frontal boundaries, thin-layers, and upwelling zones. The team is perfecting collaboration between the AUVs to allow simultaneous investigations of the water around a drifting AUV to direct position adjustments and a telemetry path to shore-side investigators. These Lagrangian observatories are yielding new insights into the ecosystem evolution of planktonic communities, which may be the largest and least understood ecosystem on the planet.

From left, Ben Raanan, Brian Kieft, and Brett Hobson prepare to launch three LRAUVs from the R/V Paragon.

Monterey Accelerated Research System (MARS)

Project lead/manager: Craig Dawe
Project team: Ken Heller, Thom Maughan, Paul McGill

NSF provides funding support to maintain and operate the MARS cabled observatory in Monterey Bay. MARS is available to internal and external scientists and



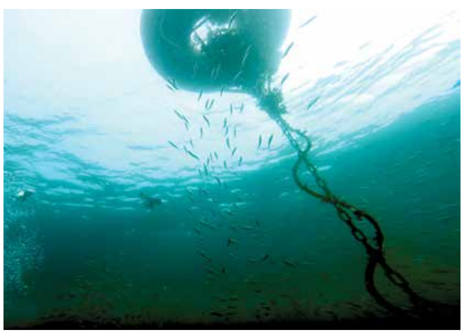
ROV Ventana*'s robotic arm disconnects a shackle during the placement of a hydrophone on the MARS observatory.*

developers as both a test bed and a research site. Since November 2008, MARS has been used to test and gather data from a variety of ocean instruments, including a seafloor seismometer, the Environmental Sample Processor, the Free Ocean Carbon Dioxide Enrichment system, the Sediment Event Sensor, and a camera that sends back video images of the seafloor in real time. Current projects connected to MARS include the Monterey Ocean Bottom Broadband Seismometer, operated by the Berkeley Seismological Laboratory, and a passive acoustic sensor, operated by a consortium of researchers.

Mooring Maintenance

Project leads: Francisco Chavez, Craig Dawe, Kevin Gomes
Project manager: Jared Figurski
Project team: Paul Coenen, David French, Craig Okuda, Rich Schramm

MBARI holds the record for the longest running autonomous chemical time series from the M1 mooring, measuring dissolved carbon dioxide in Monterey Bay since 1997. The continuity and quality of the data is due in part to the regular maintenance program conducted on the mooring systems. In 2015, the M1 mooring was successfully retrieved, serviced, and redeployed in July, and the collaboration between MBARI and the National Data Buoy Center continued on a second mooring until April when that mooring was finally recovered without replacement. In 2015, M1 reported 18.74 degrees Celsius (65.7 degrees Fahrenheit), the highest recorded temperature ocean temperature at the mooring since its deployment 26 years ago.



Divers regularly inspect and clean subsurface instruments on M1 mooring.

OASIS5

Project lead/manager: Craig Okuda
Project team: Bob Herlien

The OASIS5 controller is the next-generation controller in the 25+ year MBARI OASIS mooring system history. The team evaluated various microprocessor options and system architectures to replace older system components that are now obsolete. The new system was developed and an open source operating system was selected; it will fully utilize the existing year code base of instrument drivers and infrastructure. The completed system design is composed of three types of controller boards, all of which have been designed and prototyped. Development began on the software to test the new system and the team began porting the operating system and existing OASIS code base.

Ocean Acidification Instrumentation and Moorings

Project lead/manager: Francisco Chavez
Project team: Gernot Friederich, Jules Friederich, Jeff Sevadjian, Chris Wahl

Several external organizations—the Orange County Sanitation District in California, the University of Hawaii, and the El Centro de Investigación Científica y de Educación Superior de Ensenada in Baja California—provided funding to build and improve instrumentation and moorings to measure ocean acidification parameters (pCO_2, pH) in relation to other environmental variables. The interaction with external collaborators resulted in improved, hardened, and more stable moored systems and extended the array of observations made in Monterey Bay to Southern California and Mexico. The data sets will eventually provide a comprehensive view of changes in the central and southern California Current system. The project also allowed for further development of simpler and less expensive systems for measurement of underway pCO_2 from ships or autonomous systems. Measurements of total dissolved inorganic carbon were integrated with pH in a single laboratory system providing the means for a complete determination of the ocean carbon system from a single water sample.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter Brewer, William Kirkwood
Project manager: Edward Peltzer
Project team: Kakani Katija, Eric Martin, John Ryan, Farley Shane, Peter Walz
Collaborators: Colin Ingram, Andor Technology Ltd., Belfast, Ireland

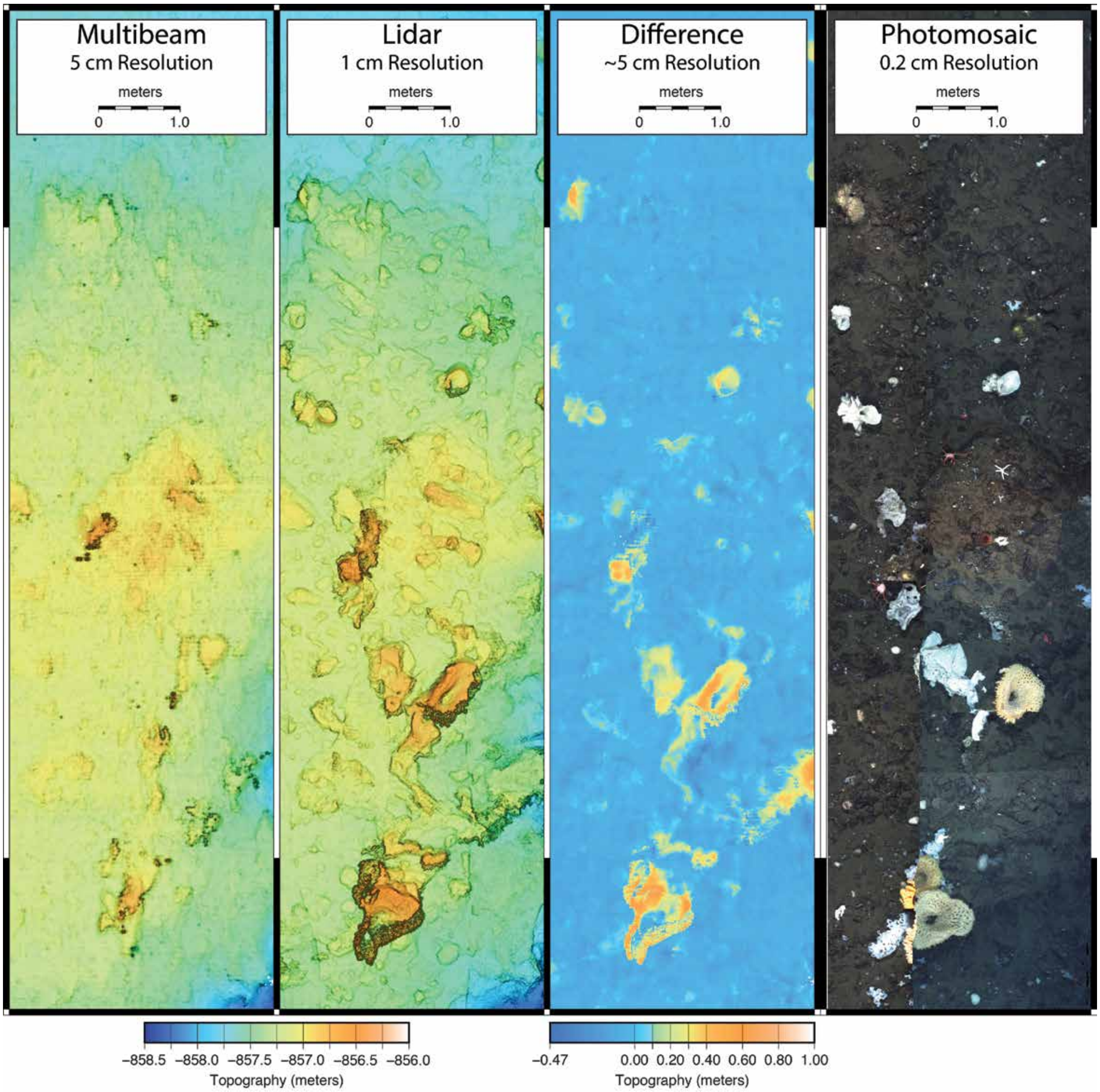
The team rebuilt the deep-sea laser Raman spectrometer system, upgrading the onboard computer and communications boards to maintain compatibility with advances in the ROV systems, and identified and tested a new high-power, pulsed laser for the next generation spectrometer. Field studies continued to focus on rising gas-saturated oil droplets to gather data to advance predictive models of gas and oil plumes in the deep sea. The sonar system on MBARI's ROV was used to image and track the rising droplet plumes. The team also began a new laser Raman study of the structure of water inside the tissues of living jellies, finding that the researchers could

Testing of the laser Raman Spectrometer on a living jelly in the lab before attempting sea trials on jellies in the wild.

easily interrogate the jelly tissues with the laser Raman spectrometer and obtain spectra generally free of interfering fluorescence. Early results were encouraging and the team will attempt to extend the utility of the laser Raman spectrometer from inorganic targets to living specimens. Members of the team also pursued two computational efforts—one that sought a simpler form of the speed of sound in seawater equation and another that involved a better form for parameterizing the oxidation rate of organic matter in the ocean.

Ocean Imaging

Project leads: David Caress, Charles Paull
Project manager: David Caress
Project team: Larry Bird, Doug Conlin, Andy Hamilton, Rich Henthorn, Brett Hobson, William Kirkwood, Eric Martin, Mike Risi, Steve Rock, Jordan Stanway, Hans Thomas, Giancarlo Troni



A three-meter-by-12-meter section of a low-altitude survey of the northern crest of Sur Ridge. These four maps show, from left to right, five-centimeter resolution multibeam bathymetry, one-centimeter-resolution lidar bathymetry, the difference between the lidar and multibeam bathymetry, and a two-millimeter resolution photomosaic. The multibeam is insensitive to the sponges and other soft animals, but the lidar maps these animals accurately. Consequently the bathymetry difference shows the location of the sponges, alive or dead, that can be seen in the photomosaic.

The team conducted low-altitude imaging surveys from ROV *Doc Ricketts*, with the survey system mounted within the ROV toolsled. The system consisted of a 400 kilohertz multibeam sonar, lidar, stereo cameras, strobes, and a Doppler velocity log-aided underwater inertial navigation system. Surveys were conducted at a depth of 1,850 meters around a node placed in Monterey Canyon as part of the Coordinated Canyon Experiment. The instrumentation was also used to survey sponge communities on the central and northern crests of Sur Ridge. All of these low-altitude surveys were within one-meter resolution mapping AUV surveys conducted during the year and will be repeated to detect change at a one-centimeter scale.

Ocean Margin Ecosystems Group for Acidification Studies

Project lead/manager: Francisco Chavez
Project team: 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 California, Santa Barbara; Brian Gaylord, Tessa Hill, Ann Russell, and Eric Sanford, University of California, Davis; Margaret McManus, University of Hawaii, Honolulu; Steve Palumbi, Hopkins Marine Station of Stanford University, Pacific Grove, California; Pete Raimondi, University of California, Santa Cruz

This National Science Foundation-funded project was a comprehensive effort to study the patterns and impacts of ocean acidification at the scale of a large marine ecosystem using a combination of laboratory and field experiments, and remote sensing. The grant enabled the formation of a coast-wide consortium of researchers from six institutions from Oregon to Southern California. A network of pH sensors, developed and built by MBARI, were placed on rocks and in shallow waters adjacent to rocky shores at a number of sites along the coast. Field, lab, and genomic studies were conducted on the performance of mussels and sea urchin larvae relative to ocean acidification. Results showed that mussel larvae grew less, had weaker shells, and lower tissue content when raised under elevated acidification, but adult mussel growth improved. Sea urchins were minimally affected but showed genetic changes under increased acid conditions.

The researchers also determined that periods of unexpectedly low pH are already occurring along the coast and are induced by upwelling events, with fewer such periods to the north where the upwelling is weaker. This implies that areas of the coast might provide organisms refuge from areas of intense ocean acidification. The results from the project have set the stage for investigation of broader ecosystem impacts as the climate inevitably changes.

Outline Video Annotation

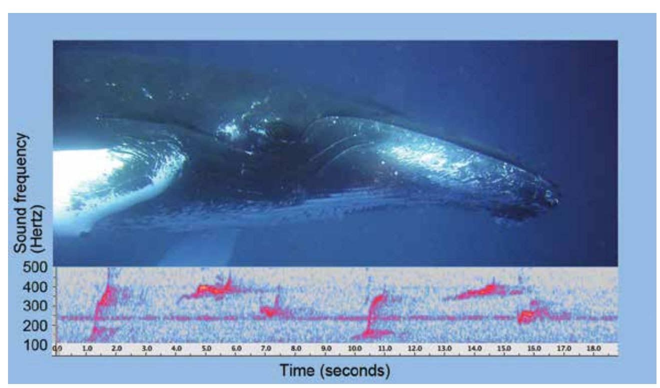
Project leads: John Ryan, Brian Schlining
Project manager: Nancy Jacobsen Stout
Project team: Mark Chaffey, Danelle Cline, Duane Edgington, Kevin Gomes, Linda Kuhnz, Lonny Lundsten, Mike McCann, Todd Ruston, Kyra Schlining, Rich Schramm, Susan von Thun

Significant 2015 milestones included the launch of the MBARI Media Management (M3) system, which forms the foundation for MBARI's next-generation video archiving infrastructure and the wide external release of the Deep-Sea Guide (dsg.mbari.org), an online tool allowing exploration of a wealth of information derived from MBARI's deep-sea observations. Video laboratory staff annotated over 600 hours of new video in 2015, bringing the current number of individual observations in the Video Annotation and Reference System (VARS) to over five million catalogued over more than 28 years. These data and the VARS software remain publicly available and are used by research labs around the world.

Passive Acoustic Sensing in Foraging Ecology Research

Project leads: Craig Dawe, John Ryan
Project manager: John Ryan
Project team: Danelle Cline, David French, Ken Heller, George Matsumoto, Paul McGill, Yanwu Zhang
Collaborators: Dave Cade and Jeremy Goldbogen, Stanford University, California; Andrew DeVogelaere and Lisa Uttal, Monterey Bay National Marine Sanctuary Monterey, California; John Joseph and Tetyana Margolina, Naval Postgraduate School, Monterey, California; Alison Stimpert, Moss Landing Marine Laboratories, California; Brandon Southall, University of California, Santa Cruz

The marine "soundscape" is a continuously changing mosaic of sounds that originate from marine life (communication and foraging activities), natural processes (breaking waves, rain), and the marine industry (shipping, construction, resource extraction). Listening in the sea is a rich exploration of marine ecology, including impacts of human activities on marine animals that use sound. This project began examining the soundscape of the Monterey Bay National Marine Sanctuary (MBNMS) from a listening point near the MARS cabled observatory. The power and communications infrastructure of MARS allows continuous high-resolution



Photograph of humpback whale above a spectrogram of calls from humpback whales recorded by the MARS hydrophone.

recording, essential to studying sounds that span a vast frequency range. During 2015 the ocean and shore-side components of the recording system were designed, built, and deployed. Nearly continuous recording has occurred since July. Research efforts were directed at automating production of spectrogram plots that permit visual browsing of the sound data, cataloging examples of marine mammal vocalizations, and developing automated detection and classification of vocalizations. Recordings have already revealed the local presence of beaked whales, which are highly susceptible to Navy sonar and which cannot be studied visually because of their infrequent and inconspicuous surfacing. Education efforts were directed at developing a prototype mobile exhibit that plays recorded animal vocalizations through a sound system capable of representing the low- to high-frequency range. Two workshops were held to engage the community of sound researchers and the MBNMS.

Photographic Benthic Observation System (PhoBOS)

Project leads: David French, George Matsumoto, Ken Smith
Project manager: George Matsumoto
Project team: Craig Dawe
The PhoBOS system was recovered from the MARS observatory. Repairs were made so that the system could be redeployed if any further interest in the camera system develops.

Precision Control Technologies for ROVs and AUVs

Project leads: Brett Hobson, Mike Risi, Steve Rock
Project manager: Steve Rock
Project team: Dave Caress, Rich Henthorn, Rob McEwen, Charles Paull, Hans Thomas

The team continued to develop enhanced navigation and control algorithms for use on ROVs and AUVs. For AUVs, work focused on enabling AUVs to perform return-to-site missions in support of MBARI's efforts to monitor deep-ocean sites for change. This work included improving and extending previously fielded terrain-relative navigation techniques as well as modifying AUV control to improve the safety with which one could fly low enough to capture images. For ROVs, work focused on improving an automated pilot aid for performing large-area surveys and the initiation of work to improve an automated pilot aid for tracking organisms in the midwater.

SeeStar Project

Project lead: Steven Haddock
Project manager: Chad Kecy
Project team: François Cazenave, Danelle Cline, Thom Maughan

Upgrades to the original SeeStar imaging system made the system more user-friendly to program and easier to build, and brought costs to fabricate the original system down by $500. The team switched to an Arduino main central processing unit to be more in line with the open-source community, as well as turning to almost all commercial off-the-shelf parts. New aluminum housings enable the extension of the system's depth rating to 1,500 meters. The team assisted researchers from various institutions—including the Farallon Institute, Oakland University, and the Noyo Center for Marine Science—and completed the online open-source build documentation to allow any researcher to build or modify their own SeeStar system. The team demonstrated the SeeStar II system at the Bay Area Maker's Faire in May.

Shallow-Water Free Ocean Carbon Dioxide Enrichment (FOCE) System Science

Project leads: James Barry, William Kirkwood
Project manager: George Matsumoto
Project team: Peter Brewer, Bob Herlien, Chad Kecy, Chris Lovera, Edward Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborators: Paul Leary, Steve Litvin, Nik Myers, Steve Palumbi, and Judy Thompson, Hopkins Marine Station of Stanford University, Pacific Grove, California

The shallow-water FOCE system was installed in shallow waters of Monterey Bay to enable experiments on the effects of ocean acidification on natural seafloor biological assemblages. MBARI developed a seawater enriching station on the shore of Hopkins Marine Station, where carbon dioxide can be added to seawater. That seawater was then pumped through a hose to the apparatus stationed about 500 meters offshore at a depth of 15 meters, where it could be mixed with ambient seawater before flowing into one of two experimental chambers on the seabed. Thus, one chamber and the organisms within it were continuously exposed to reduced pH waters, simulating future changes in ocean chemistry. Pumps, sensors, and cameras were connected to shore and the Internet. During 2015, the team worked on troubleshooting several problems with electronics systems and prepared for a full design review.

Streaming Data Middleware

Project leads: Duane Edgington, Kent Headley, Bob Herlien, Tom O'Reilly
Project manager: Duane Edgington
Project team: Edward Peltzer
Collaborators: Tony Fountain and Sameer Tilak, University of California, San Diego (UCSD); Matt Miller, Cycronix, Massachusetts

The team continued engagement in this three-year NSF-funded project, primarily staffed at UCSD, to extend the publicly available Open Source Data Turbine framework, and to apply it to a number of research data infrastructures at several research institutions. MBARI set up a local CloudTurbine node to internally serve instrument data streams from MBARI's FOCE experiment. An image data stream was added to record still camera images from the experiment chamber every five minutes. The team also continued to evaluate incremental feature updates of the open source "WebScan" data viewer application.

Technology Transfer: Observatory Software

Project leads: Duane Edgington, Kent Headley, Bob Herlien, Tom O'Reilly
Project manager: Duane Edgington
Project team: Paul Coenen, Kevin Gomes, Thom Maughan, Craig Okuda, Carlos Rueda-Velasquez, 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 team continued support of the ALOHA cabled observatory at the University of Hawaii, in the use of MBARI's infrastructure, applications, and shore-side data systems for data collection and archiving. The Cawthron Institute continued mooring deployment and development based on MBARI's OASIS mooring controller. Through this project, MBARI Engineer Tom O'Reilly was invited to join the IEEE Oceanic Engineering Society's Standards Initiative project, which aims to compile and disseminate information on standards, protocols, quality assurance procedures, and best practices that are important in ocean engineering.

Transforming USGS Ecosystems Observing Capacity with Long Range Autonomous Underwater Vehicles

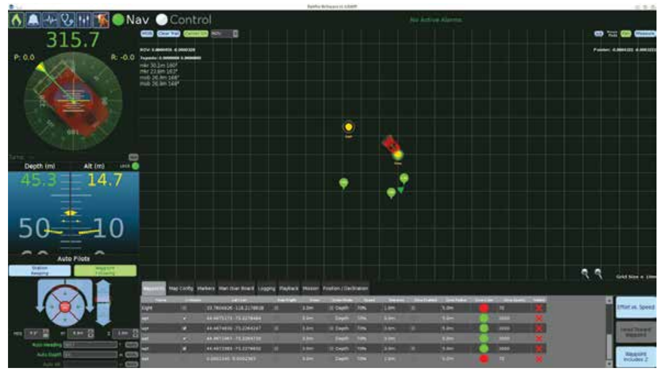
Project lead/manager: Brian Kieft

Preliminary discussions were held in preparation for a field deployment of an MBARI long-range AUV in Lake Michigan in 2016. This U.S. Geological Survey-funded effort aims to determine if increased nutrients exiting Green Bay are contributing to larger fish aggregations.

Ventana Control System Upgrade

Project leads: Douglas Au, Craig Dawe
Project manager: Craig Dawe
Project team: Michael Burczynski, David French, D.J. Osborne, Mike Risi, Rich Schramm

The team upgraded the control system for ROV *Ventana* to replace aging and obsolete components and software. The new control system integrates many standalone projects into a single system, including station-keeping, science tools, a fiber-optic control module, auxiliary-camera controls, and an independent navigation solution.



View of ROV Ventana's *new software interface for enhanced control of the vehicle.*

Wave Glider Feasibility Study

Project lead/manager: Thom Maughan
Project team: Chris Wahl
Collaborators: Ryan Carlon, Mike Cookson, and James Gosling, Liquid Robotics, Sunnyvale, California; Francisco Chavez, Jules Friederich, Brian Kieft, Paul McGill, Tom O'Reilly, Charles Paull, and Ken Smith, MBARI; Roger Dellor and Kurt Kiesow, Jupiter Research Foundation, Los Altos, California

The Wave Glider, an autonomous surface vehicle produced by Liquid Robotics, was maintained by MBARI staff with science instrumentation and additional radio and acoustic communications capability. During the final year of this three-year feasibility project, operations of the Wave Glider transitioned to MBARI's Division of Marine Operations. During 2015, engineering and operations support has also been provided for the Biogeochemistry Group in their field use of the SV2 Ocean Acidification Wave Glider.

View from a SeeStar camera system mounted on a Wave Glider, looking back at the R/V Paragon.

Awards

David Clague

Mineralogy, Geochemistry, Petrology, and Volcanology Distinguished Geologic Career Award, The Geological Society of America

Luke Coletti, Hans Jannasch, and Ken Johnson of Team DuraFET

Second Place Prize in Accuracy, Wendy Schmidt Ocean Health XPRIZE

Esther Sumner

Geological Society of London Lyell Fund

Susanne Wilken

Marie Curie Postdoctoral Fellowship

Alexandra Worden

Marine and Climate Fellowship at the Hanse Wissenshaftskolleg, Germany

Patent issued

William Kirkwood and Thom Maughan

Wireless Power and Data Transfer Device for Harsh and Extreme Environments

View from the office window

Working at sea can mean long hours, and time away from home, but it also provides views like this out the "office" window. R/V Western Flyer *Master Andrew McKee took this shot from the ship's bridge during the three-month 2015 Gulf of California Expedition. The photo won the "best of show" award in the 2015 MBARI staff photo contest.*

Invited Lectures

David Anderson
American Geophysical Union, San Francisco, California

Office of Spill Prevention and Response/Chevron Oil Spill Response Technology Workshop, Alameda, California

James Barry
Association for the Sciences of Limnology and Oceanography Aquatic Sciences, Granada, Spain

Monterey Bay Aquarium, Monterey, California

California State University, Monterey Bay, Seaside, California

The Carmel Foundation, California

Aric Bickel
Coastal and Estuarine Research Federation Conference, Sacramento, California

Holly Bowers
Marine Mammal Center, Sausalito, California

Peter Brewer
U.S. Geological Survey, Menlo Park, California

Stephanie Bush
San Jose State University, California

Monterey Bay Aquarium, Monterey, California

David Caress
Ensenada Center for Scientific Research and Higher Education, Mexico

Francisco Chavez
El Centro Interdisciplinario de Ciencias Marinas, La Paz, Mexico

Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida

Pacific Northwest National Laboratory, Richland, Washington

2014-2015 Pacific Anomalies Symposium, Scripps Institution of Oceanography, La Jolla, California

International Conference on Fish Telemetry, Halifax, Nova Scotia

Center for Marine Environmental Sciences, University of Bremen, Germany

Aarhus University, Denmark

Surface Ocean Lower Atmosphere Study Conference, Kiel, Germany

Lima Chamber of Commerce, Peru

Integrated Marine Biogeochemistry and Ecosystem Research IMBIZO meeting, Trieste, Italy

Group on Earth Observations Ministerial Summit, Mexico City

American Geophysical Union, San Francisco, California

Anela Choy
University of California, Santa Cruz

David Clague
Geological Society of America, Baltimore, Maryland

Judith Connor
Monterey Bay Aquarium, Monterey, California

Moss Landing Marine Laboratories, California

Kim Fulton-Bennett
Monterey Bay National Marine Sanctuary Exploration Center, Santa Cruz, California

Science Communications and Marine Public Information meeting, Sarasota, Florida

Steven Haddock
Monterey Bay Aquarium, Monterey, California

Sitka WhaleFest, Alaska

San Jose State University, California

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

Monterey Bay National Marine Sanctuary Currents Symposium, Seaside, California

Old Dominion University, Norfolk, Virginia

Julio Harvey
University of California, Santa Cruz

Ken Johnson
University of California, Berkeley

University of California, Santa Cruz

Stanford University, California

Kristineberg Marine Station, University of Gothenburg, Sweden

Global Ocean Ship-Based Hydrographic Investigations Program/Argo/International Ocean Carbon Coordination Project Conference, Galway, Ireland

Shannon Johnson
Sonoma State University, Rohnert Park, California

Monterey Bay Aquarium, Monterey, California

Kakani Katija
Hopkins Marine Station of Stanford University, Pacific Grove, California

TEDWomen Conference, Monterey, California

University of California, Los Angeles

Dalhousie University, Halifax, Nova Scotia, Canada

California State University, Monterey Bay, Seaside

American Geophysical Union, San Francisco, California

Brian Kieft
Liquid Robotics, Sunnyvale, California

William Kirkwood
National Institute of Ocean Technology, Chennai, India

Singapore Polytechnic University

Bremen University, Germany

University of Wurzberg, Germany

George Matsumoto
Webinar on Ocean Acidification, SouthWest Marine Educators Association

Monterey Bay Aquarium, Monterey, California

California Science Teachers Association, Sacramento, California

Tom O'Reilly
University of Bremen, Germany

Polytechnic University of Catalonia, Spain

Charles Paull
American Association of Petroleum Geologists, Asia Pacific Geoscience Technology Workshop, Wellington, New Zealand

Bruce Robison
Lawrence R. Blinks Memorial Lecturer, Hopkins Marine Station of Stanford University, Pacific Grove, California

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

Japan Agency for Marine-Earth Science and Technology, Yokosuka

Chris Scholin
University of Hawaii, Center for Microbial Oceanography: Research and Education, Honolulu

Southern California Coastal Water Research Project, Costa Mesa

Research Coordination Network, San Francisco, California

Ken Smith
Deep-Sea Biology Symposium, Aveiro, Portugal

Woods Hole Oceanographic Institution, Massachusetts

Susan von Thun
Moss Landing Marine Laboratories, California

Robert Vrijenhoek
Moss Landing Marine Laboratories, California

Susanne Wilken
European Phycological Congress, London, United Kingdom

University of Southern California, Los Angeles

Institute of Marine Sciences Spanish National Research Council, Barcelona, Spain

Alexandra Z. Worden
American Geophysical Union, San Francisco, California

European Molecular Biology Organization Exploring the Genomic Complexity and Diversity of Eukaryotes Conference, Sant Feliu de Guixols, Spain

Max Planck Institute for Marine Microbiology, Bremen, Germany

Jacques Monod Conference on Ecosystems Biology, Roscoff, France

Alfred Wegener Institute for Polar and Marine Research, Bremerhaven, Germany

University of Oldenburg, Germany

American Association for the Advancement of Science, San Jose, California

Yanwu Zhang
International Conference on Underwater Sciences, Technology, and Education, City University of Hong Kong, China

Shenyang Institute of Automation, Chinese Academy of Sciences, China

Amy Zimmerman
Gordon Research Conference on Marine Molecular Ecology, Hong Kong, China

Monterey Bay Aquarium, Monterey, California

Mentorships

David Anderson, Francisco Chavez
Alice Ren, graduate summer intern, University of Maine, Orono (declining oxygen concentrations in the California Current)

James Barry
Will Fennie, M.S. student, Moss Landing Marine Laboratories (effects of ocean acidification on California rockfishes)

James Barry, Charles Boch
Madison Heard, undergraduate summer intern, California State University, Monterey Bay (effects of multiple climate-change-related stressors on larval development of red abalone)

James Barry, Linda Kuhnz
Natalya Gallo, Ph.D. student, Scripps Institution of Oceanography (fish diversity and abundance in the Gulf of California)

Beatriz Mejia-Mercado, graduate summer intern (the characterization of deep-sea benthic megafaunal communities observed in the Gulf of California)

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

Peter Brewer
Kennedy McCone, undergraduate summer intern, Stanford University (quantitative laser Raman of mixed gases)

David Caress
Giancarlo Troni, postdoctoral fellow (low-cost underwater vehicle navigation and low-altitude, high-resolution seafloor mapping)

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

Lisa Zicarelli, summer intern (methods for quantifying phytoplankton biodiversity)

David Clague
Sami Chen, undergraduate student, University of California, Santa Cruz, (paleoclimate during the last glacial maxima recorded in a core from Axial Seamount)

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

Christina Maschmeyer, M.S. student, University of South Carolina, Columbia (automated lava flow classifier using high-resolution bathymetry and side-scan data)

Morgane Le Saout, postdoctoral fellow (tectonomagmatic evolution of mid-ocean ridges)

Danelle Cline, John Ryan
Prateek Murgai, undergraduate summer intern, Delhi Technological University (automated detection and classification of marine mammal vocalizations)

Kim Fulton-Bennett
Leigh Cooper, graduate student intern, University of California at Santa Cruz (prepared articles and video for MBARI's website)

Steven Haddock
Katie Beittenmiller, undergraduate summer intern, Carnegie Mellon University (geometry of Phaeodarian colonial spheres)

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

Séverine Martini, postdoctoral fellow (bioluminescence: from biological surveys to organism detection)

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

Rich Henthorn
Drew Burrier, graduate summer intern, Moss Landing Marine Laboratories (heading-correcting algorithm for a bottom-crawling AUV)

Ken Johnson
Wiley Wolfe, undergraduate summer intern, Oregon State University (measuring ocean respiration: validation of a low-cost CO_2 sensor)

Kakani Katija
Alexa Baumer, undergraduate summer intern, George Washington University (biomechanics of giant larvaceans using the Video Annotation and Reference System database)

Amanda Fay, undergraduate student, California State University, Monterey Bay (novel swimming behaviors in the Humboldt squid)

Kakani Katija, Alana Sherman
Sarah Black, undergraduate summer intern, Florida Atlantic University (jelly counter and orientation using AUV video footage)

Chad Kecy

Amy Chen, graduate summer intern, California Polytechnic State University, San Luis Obispo (oceanographic instrument simulator)

William Kirkwood

Johan Altamirano, M.S. student, Santa Clara University (building a real-time laser scanner)

Todd Chun-Van Osdol, M.S. student, Santa Clara University University (building a real-time laser scanner)

Jim Cochran, M.S. student, Santa Clara University University (building a remotely operated water sampler)

Brian Gamp, M.S. student, Santa Clara University University (building a remotely operated water sampler)

Hung Ngo, M.S. student, Santa Clara University University (building a real-time laser scanner)

Sylvee Proehl, M.S. student, Santa Clara University University (building a real-time laser scanner)

Eric Stockpile, M.S. student, Santa Clara University University (building a remotely operated water sampler)

Harsha Vemuluru, M.S. student, Santa Clara University University (building a real-time laser scanner)

Shying Wu, M.S. student, Santa Clara University University (building a remotely operated water sampler)

Linda Kuhnz

All students in the Watsonville Area Teens Conserving Habitats program, Aptos High School, Pajaro Valley High School, and Watsonville High School

George Matsumoto

Valeria Chavez-Aguilar, high school student, Watsonville High School, (how does *Ulva* affect species diversity within the pickleweed at Elkhorn Slough?)

Rigo Collazo, high school student, Pajaro Valley High School, (how do shrimp abundance and diversity differ in regions with different water flow?)

Antonio Hernandez, high school student, Pajaro Valley High School, (how do shrimp abundance and diversity differ in regions with different water flow?)

Sergio Hernandez, high school student, Watsonville High School, (how do *Ulva* affect species diversity within the pickleweed at Elkhorn Slough?)

Maria Martinez, high school student, Watsonville High School, (how does *Ulva* affect species diversity within the pickleweed at Elkhorn Slough?)

Sofia Renteria, high school student, Pajaro Valley High School, (how do shrimp abundance and diversity differ in regions with different water flow?)

Lillian Uribe, high school student, Pajaro Valley High School, (how do shrimp abundance and diversity differ in regions with different water flow?)

Melinda Nakagawa

Alberto Amezcua, high school student, Pajaro Valley High School (do oak woodland game trails have more mammal diversity than grassland game trails?)

Elsie Escutia, high school student, Pajaro Valley High School (do oak woodland game trails have more mammal diversity than grassland game trails?)

Liszette Gonzalez, high school student, Pajaro Valley High School (do oak woodland game trails have more mammal diversity than grassland game trails?)

Jessica Mendoza, high school student, Pajaro Valley High School (do oak woodland game trails have more mammal diversity than grassland game trails?)

Charles Paull

Zachary Sickman, Ph.D. student, Stanford University (detrital zircon geochronology of grains found within Monterey Canyon)

Paris Smalls, undergraduate summer intern, California State University, Monterey Bay (benthic gouge marks in the Canadian Beaufort Sea: associations between whales and methane seeps)

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

William Symons, Ph.D. student, University of Southampton (how well do sediment traps reflect the deposits on the canyon flanks?)

Charles Paull, Robert Vrijenhoek

Magdalena Georgieva, Ph.D. student, University of Leeds (data/sample collection off Southern California)

Bruce Robison

Alicia Bitondo, M.S. student, Moss Landing Marine Laboratories (developmental and ecological changes in juvenile and subadult *Chiroteuthis calyx*)

Ben Burford, Ph.D. student, Stanford University (the use of chromatophore displays by the Humboldt squid for intraspecific communication)

Stephanie Bush, postdoctoral fellow (cephalopod biology, ecology, and behavior related to Monterey Bay Aquarium's *Tentacles* exhibit)

Anela Choy, postdoctoral fellow (pelagic food web structure using stable isotopes and amino acids; mercury and plastics as pelagic pollutants)

Diana Li, Ph.D. student, Stanford University (squid swimming behaviors across environmental variation)

Katie Thomas, Ph.D. student, Duke University (eyes and vision of the mesopelagic squid *Histioteuthis heteropsis*)

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)

Aditya Mahajan, Ph.D. student, Stanford University (feature-based navigation)

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

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

John Ryan

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

Alanna Lecher, Ph.D. student, University of California, Santa Cruz (groundwater as a nutrient source for phytoplankton blooms in Monterey Bay)

Alana Sherman

Kakani Katija, postdoctoral fellow (deep particle image velocimetry, soft-bodied invertebrate tagging)

Ken Smith

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

Samantha Peart, undergraduate summer intern, North Carolina State University (error and precision of photogrammetry in the deep sea)

Jessica Whelpley, summer intern, Smithsonian Institution (population and natural history of deep-sea enteropneust, *Tergivelum baldwinae*, with time-lapse photography)

Susan von Thun

Sonia Vargas, undergraduate intern, Colby College (video production"SeeStar: A simple, open-source camera system for underwater monitoring of marine ecosystems")

Robert Vrijenhoek

Corinna Breusing, Ph.D. student, Kiel University (identifying species of *Bathymodiolus brevior* complex)

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

Alexandra Z. Worden

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

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

Magdalena Gutowska, postdoctoral fellow (vitamin synthesis and utilization networks in marine microbial communities)

Maria Hamilton, Ph.D. student, University of California, Santa Cruz (ecology and physiology of polar eukaryotes)

Rachel Harbeitner, Ph.D. student, University of California, Santa Cruz (deep-sea eukaryotic life)

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)

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

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

Publications

Aylward, F.O., J.M. Eppley, **J.M. Smith**, **F.P. Chavez**, **C.A. Scholin**, and E.F. DeLong (2015). Microbial community transcriptional networks are conserved in three domains at ocean basin scales. *Proceedings of the National Academy of Sciences*, **112**: 5443-5448, doi: 10.1073/pnas.1502883112.

Bradley, C.J., N.J. Wallsgrove, **C.A. Choy**, J.C. Drazen, E.D. Hetherington, D.K. Hoen, and B.N. Popp (2015). Trophic position estimates of marine teleosts using amino acid compound specific isotopic analysis. *Limnology and Oceanography: Methods*, **13**: 476-493, doi: 10.1002/lom3.10041.

Breusing, C., **S.B. Johnson**, V. Tunnicliffe, and **R.C. Vrijenhoek** (2015). Population structure and connectivity in Indo-Pacific deep-sea mussels of the *Bathymodiolus septemdierum* complex. *Conservation Genetics,* **16**: 1415-1430, doi: 10.1007/s10592-015-0750-0.

Brewer, P.G., **E.T. Peltzer**, **J. Ryan**, **W.J. Kirkwood**, and A.F. Hofmann (2015). Ocean chemistry and the speed of sound in seawater. *Marine Chemistry*, **177**: 591-606, doi: 10.1016/j.marchem.2015.09.009.

Brothers, D.S., J.E. Conrad, K.L. Maier, **C.K. Paull**, M. McGann, and **D.W. Caress** (2015). The Palos Verdes Fault offshore Southern California: Late Pleistocene to present tectonic geomorphology, seascape evolution, and slip rate estimate based on AUV and ROV surveys. *Journal of Geophysical Research: Solid Earth*, **120**: 4734-4758, doi: 10.1002/2015jb011938.

Caron, D.A., A.G. Gellene, J. Smith, E.L. Seubert, V. Campbell, G.S. Sukhatme, B. Seegers, B.H. Jones, A.A.Y. Lie, R. Terrado, M.D.A. Howard, R.M. Kudela, K. Hayashi, **J. Ryan**, **J. Birch**, **E. Demir-Hilton**, **K. Yamahara**, **C. Scholin**, M. Mengel, and G. Robertson (2015). Response of phytoplankton and bacterial biomass during a wastewater effluent diversion into nearshore coastal waters. *Estuarine, Coastal and Shelf Science*, doi: 10.1016/j.ecss.2015.09.013.

Caress, D.W. and D.N. Chayes (2015). MB-System Version 5. Open source software distributed from the MBARI and L-DEO web sites, 2000-2015, www.mbari.org/products/research-software/mb-system/.

Choy, C.A., B.N. Popp, C.C.S. Hannides, and J.C. Drazen (2015). Trophic structure and food resources of epipelagic and mesopelagic fishes in the North Pacific Subtropical Gyre ecosystem inferred from nitrogen isotopic compositions. *Limnology and Oceanography*, **60**: 1156-1171, doi: 10.1002/lno.10085.

Coumans, J.P., J. Stix, **D.A. Clague**, and W.G. Minarik (2015). The magmatic architecture of Taney Seamount-A, NE Pacific Ocean. *Journal of Petrology*, **56**: 1037-1067, doi: 10.1093/petrology/egv027.

Cousens, B.L. and **D.A. Clague** (2015). Shield to rejuvenated stage volcanism on Kauai and Niihau, Hawaiian Islands. *Journal of Petrology*, **56**: 1547-1584, doi: 10.1093/petrology/egv045.

Dallimore, S.R., **C.K. Paull**, M. Riedel, Y.K. Jin, A.E. Taylor, H. Melling, A. Kopf, H. Villinger, and M.M.Côté (2015). Geohazard investigations of permafrost and permafrost gas hydrates in the outer shelf and upper slope of the Beaufort Sea, *Canadian Permafrost Conference, Canadian Geotechnical Conference*, Quebec City, Quebec.

Das, J., F. Py, **J.B.J. Harvey**, **J.P. Ryan**, A. Gellene, R. Graham, D.A. Caron, K. Rajan, and G.S. Sukhatme (2015). Data-driven robotic sampling for marine ecosystem monitoring. *The International Journal of Robotics Research*, **34**: 1435-1452, doi: 10.1177/0278364915587723.

Derelle, E., A. Monier, R. Cooke, **A.Z. Worden**, N.H. Grimsley, and H. Moreau (2015). Diversity of viruses infecting the green microalga *Ostreococcus lucimarinus*. *Journal of Virology*, **89**: 5812-5821, doi: 10.1128/JVI.00246-15.

Dunlop, K.M., **L.A. Kuhnz**, H.A. Ruhl, **C.L. Huffard**, **D.W. Caress**, **R.G. Henthorn**, **B.W. Hobson**, **P. McGill**, and **K.L. Smith Jr.** (2015). An evaluation of deep-sea benthic megafauna length measurements obtained with laser and stereo camera methods. *Deep Sea Research I*, **96**: 38-48, doi: 10.1016/j.dsr.2014.11.003.

Dunn, C.W., S.P. Leys, and **S.H.D. Haddock** (2015). The hidden biology of sponges and ctenophores. *Trends in Ecology & Evolution*, **30**: 282-291, doi: 10.1016/j.tree.2015.03.003.

Francis, W.R., N.C. Shaner, **L.M. Christianson**, M.L. Powers, and **S.H.D. Haddock** (2015). Occurrence of isopenicillin-N-synthase homologs in bioluminescent ctenophores and implications for coelenterazine biosynthesis. *PLoS One*, **10**: e0128742, doi: 10.1371/journal.pone.0128742.

Fries, D. and **W.J. Kirkwood** (2015). Non-Acoustic Sensors (Part B, Chapter 8), In: *Springer Handbook of Ocean Engineering*, edited by M.R. Dhanak and N.I. Xiros.

Gasca, R., E. Suárez-Morales, and **S.H.D. Haddock** (2015). Sapphirina irisDana, 1849 and S. sinuicaudaBrady, 1883 (Copepoda, Cyclopoida): predators of salps in Monterey Bay and the Gulf of

California. *Crustaceana*, **88**: 689-699, doi: 10.1163/15685403-00003438.

Gaylord, B., K.J. Kroeker, J.M. Sunday, K.M. Anderson, **J.P. Barry**, N.E. Brown, S.D. Connell, S. Dupont, K.E. Fabricius, J.M. Hall-Spencer, T. Klinger, M. Milazzo, P.L. Munday, B.D. Russell, E. Sanford, S.J. Schreiber, V. Thiyagarajan, M.L.H. Vaughan, S. Widdicombe, and C.D.G. Harley (2015). Ocean acidification through the lens of ecological theory. *Ecology*, **96**: 3-15, doi: 10.1890/14-0802.1.

Gwiazda, R., **C.K. Paull**, **W. Ussler III**, and C.R. Alexander (2015). Evidence of modern fine-grained sediment accumulation in the Monterey Fan from measurements of the pesticide DDT and its metabolites. *Marine Geology*, **363**: 125-133, doi: 10.1016/j.margeo.2015.02.006.

Haddock, S.H.D. and C.W. Dunn (2015). Fluorescent proteins function as a prey attractant: Experimental evidence from the hydromedusa *Olindias formosus* and other marine organisms. *Biology Open*, doi: 10.1242/bio.012138.

Helz, R.T., **D.A. Clague**, L.G. Mastin, and T.R. Rose (2015). Evidence for large compositional ranges in coeval melts erupted from Kilauea's summit reservoir. In: *Hawaiian Volcanoes: From Source to Surface*, edited by R. Carey, V. Cayol, M. Poland, and D. Weis. American Geophysical Union Monograph, Hoboken, NJ, pp. 125-145.

Herfort, L., C. Seaton, M. Wilkin, **B. Roman**, **C.M. Preston**, **R. Marin III**, K. Seitz, M.W. Smith, V. Haynes, **C.A. Scholin**, A.M. Baptista, and H.M. Simon (2015). Use of continuous, real-time observations and model simulations to achieve autonomous, adaptive sampling of microbial processes with a robotic sampler. *Limnology and Oceanography: Methods*, **14**: 50–67. doi:10.1002/lom3.10069

Hoving, H.J.T., V.V. Laptikhovsky, and **B.H. Robison** (2015). Vampire squid reproductive strategy is unique among coleoid cephalopods. *Current Biology*, **25**: R322-323, doi: 10.1016/j.cub.2015.02.018.

Hughes, B.B., M.D. Levey, M.C. Fountain, A.B. Carlisle, **F.P. Chavez**, and M.G. Gleason (2015). Climate mediates hypoxic stress on fish diversity and nursery function at the land-sea interface. *Proceedings of the National Academy of Sciences*, **112**: 8025-8030, doi: 10.1073/pnas.1505815112.

Johnson, K.S., **J.N. Plant**, S.C. Riser, and D. Gilbert (2015). Air oxygen calibration of oxygen optodes on a profiling float array. *Journal of Atmospheric and Oceanic Technology*, **32**: 2160-2172, doi: 10.1175/jtech-d-15-0101.1.

Katija, K. (2015). Morphology alters fluid transport and the ability of organisms to mix oceanic waters. *Integrative and Comparative Biology*, **55**: 698-705, doi: 10.1093/icb/icv075.

Katija, K., S.P. Colin, J.H. Costello, and H. Jiang (2015). Ontogenetic propulsive transitions by medusae *Sarsia tubulosa*. *Journal of Experimental Biology*, **218**: 2333-2343, doi: 10.1242/jeb.115832.

Kim, T.W., J. Taylor, **C. Lovera**, and **J.P. Barry** (2015). CO_2-driven decrease in pH disrupts olfactory behaviour and increases individual variation in deep-sea hermit crabs. *ICES Journal of Marine Science*, doi: 10.1093/icesjms/fsv019.

Kirkwood, W.J. (2015). FOCE: The evolution of in situ Free Ocean CO_2 Enrichment experiments. In: *Proceedings of Underwater Technology, 2015 IEEE*, Chennai, pp. 1-10, doi: 10.1109/UT.2015.7108322.

Kirkwood, W.J. (2015). Use of ocean related challenges in engineering education. In: *OCEANS 2015-Genova*, Genova, Italy, 1-6, doi: 10.1109/OCEANS-Genova.2015.7271416.

Kirkwood, W.J., **P.M. Walz**, **E.T. Peltzer**, **J.P. Barry**, **R.A. Herlien**, **K.L. Headley**, **C. Kecy**, **G.I. Matsumoto**, **T. Maughan**, **T.C. O'Reilly**, **K.A. Salamy**, **F. Shane**, and **P.G. Brewer** (2015). Design, construction, and operation of an actively controlled deep-sea CO_2 enrichment experiment using a cabled observatory system. *Deep Sea Research Part I: Oceanographic Research Papers*, **97**: 1-9, doi: 10.1016/j.dsr.2014.11.005.

Kuhnz, L.A., **K. Buck**, **C. Lovera**, **P.J. Whaling**, and **J.P. Barry** (2015). Potential impacts of the Monterey Accelerated Research System (MARS) Cable on the seabed and benthic faunal assemblages. Monterey Bay National Marine Sanctuary, The California Coastal Commission, and The California State Lands Commission: 71 pp.

Laguionie-Marchais, C., **L.A. Kuhnz**, **C.L. Huffard**, H.A. Ruhl, and **K.L. Smith Jr.** (2015). Spatial and temporal variation in sponge spicule patches at Station M, northeast Pacific. *Marine Biology*, **162**: 617-624, doi: 10.1007/s00227-014-2609-1.

Laguionie-Marchais, C., G.L.J. Paterson, B.J. Bett, **K.L. Smith Jr.**, and H.A. Ruhl (2015). Inter-annual species-level variations in an abyssal polychaete assemblage (Sta. M, NE Pacific, 4000m). *Progress in Oceanography*, **140**: 43-53, doi: 10.1016/j.pocean.2015.10.006.

Lecher, A.L., K. Mackey, R. Kudela, **J. Ryan**, A. Fisher, J. Murray, and A. Paytan (2015). Nutrient loading through submarine groundwater discharge and phytoplankton growth in Monterey Bay, CA. *Environmental Science & Technology*, **49**: 6665-6673, doi: 10.1021/acs.est.5b00909.

Limardo, A.J. and **A.Z. Worden** (2015). Microbiology: Exclusive networks in the sea. *Nature*, **522**: 36-37, doi: 10.1038/nature14530.

Liu, H., S. Cai, H. Zhang, and **R.C. Vrijenhoek** (2015). Complete mitochondrial genome of hydrothermal vent clam *Calyptogena magnifica. Mitochondrial DNA*: 1-3, doi: 10.3109/19401736.2015.1089488.

Lopez, P., **T.C. O'Reilly**, and **D. Klimov** (2015). Cytometers set sail with sea-going mobile robots. *Marine Technology Society Journal*, **49**: 17-26, doi: 10.4031/mtsj.49.3.9.

Mah, C., K. Linse, J. Copley, L. Marsh, A. Rogers, **D. Clague**, and D. Foltz (2015). Description of a new family, new genus, and two new species of deep-sea Forcipulatacea (Asteroidea), including the first known sea star from hydrothermal vent habitats. *Zoological Journal of the Linnean Society*, **174**: 93-113, doi: 10.1111/zoj.12229.

Matsumoto, G.I. (2015). A different approach to the research internship. *Marine Technology Society Journal*, **49**: 35-44, doi: 10.4031/mtsj.49.4.1.

Miljutin, D., M. Miljutina, and **M. Messié** (2015). Changes in abundance and community structure of nematodes from the abyssal polymetallic nodule field, Tropical Northeast Pacific. *Deep Sea Research Part I: Oceanographic Research Papers*, **106**: 126-135, doi.org/10.1016/j.dsr.2015.10.009.

Mooney, T.A.*, **K. Katija**,* K.A. Shorter, T. Hurst, J. Fontes, and P. Afonso (2015). ITAG: An eco-sensor for fine-scale behavioral measurements of soft-bodied marine invertebrates. *Animal Biotelemetry*, **3**, doi: 10.1186/s40317-015-0076-1.

O'Reilly, T., **B. Kieft**, and **M. Chaffey** (2015). Communications relay and autonomous tracking applications for Wave Glider. In: *OCEANS 2015-Genova*, Genova, Italy, 1-6, doi: 10.1109/OCEANS-Genova.2015.7271243.

Orsi, W.D., **J.M. Smith**, H.M. Wilcox, J.E. Swalwell, P. Carini, **A.Z. Worden**, and A.E. Santoro (2015). Ecophysiology of uncultivated marine euryarchaea is linked to particulate organic matter. *ISME Journal*, **9**: 1747-1763, doi: 10.1038/ismej.2014.260.

Pargett, D.M., **J.M. Birch**, **C.M. Preston**, **J.P. Ryan**, **Y. Zhang**, and **C.A. Scholin** (2015). Development of a mobile ecogenomic sensor. In: *Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference*, Washington, D.C., pp. 1-6.

Paull, C.K., **D.W. Caress**, **H. Thomas**, **E. Lundsten**, **K. Anderson**, **R. Gwiazda**, M. Riedel, M. McGann, and J.C. Herguera (2015). Seafloor geomorphic manifestations of gas venting and shallow subbottom gas hydrate occurrences. *Geosphere*, **11**: 491-513, doi: 10.1130/ges01012.1.

Paull, C.K., S.R. Dallimore, **D.W. Caress**, **R. Gwiazda**, H. Melling, M. Riedel, Y.K. Jin, J.K. Hong, Y.G. Kim, **D. Graves**, **A. Sherman**, **E. Lundsten**, **K. Anderson**, **L. Lundsten**, H. Villinger, A. Kopf, **S.B. Johnson**, J. Hughes Clarke, S. Blasco, K. Conway, P. Neelands, **H. Thomas**, and M. Côté (2015). Active mud volcanoes on the continental slope of the Canadian Beaufort Sea. *Geochemistry, Geophysics, Geosystems*, **16**: 3160-3181, doi: 10.1002/2015GC005928.

Pearse, J.S., W.T. Doyle, V.B. Pearce, M.M. Gowing, **J.T. Pennington**, E. Danner, and A. Wasser (2015). Long-term monitoring of surfgrass meadows in the Monterey Bay National Marine Sanctuary: Recovery followed by stability after the termination of a domestic sewage discharge. Marine Sanctuaries Conservation Series ONMS, 15-10: http://sanctuaries.noaa.gov/science/conservation/conservation_reports.html.

Pennington, J.T., **M. Blum**, and **F.P. Chavez** (2015). Seawater sampling by an autonomous underwater vehicle: "Gulper" sample validation for nitrate, chlorophyll, phytoplankton, and primary production. *Limnology and Oceanography: Methods*, **14**: 14-23, doi: 10.1002/lom3.10065.

Plesch, A. and **M. McCann** (2015). The X3D geospatial component: X3DOM implementation of GeoOrigin, GeoLocation, GeoViewpoint, and GeoPositionInterpolator nodes. In: *Proceedings of the 20th International Conference on 3D Web Technology*, New York, NY, pp.31-37. doi: 10.1145/2775292.2775315.

Pomponi, S.A., D.W. Titley, E. Boyle, M. Briscoe, R.E. Davis, M. Edwards, M.H. Feeley, D. Forsyth, P. Liss, S. Lozier, R. Marinelli, J.J. McCarthy, A. Mix, S.A. Murawski, R.T. Paine, **C. Paull**, D. Walsh, B.B. Ward, J.A. Yoder, and W.R. Young (2015). *Sea Change: 2015-2025 Decadal Survey of Ocean Sciences.* National Academy Press, Washington, D.C., 146 pp., doi: 10.17226/21655.

Portner, R.A., **D.A. Clague**, C. Helo, **B.M. Dreyer**, and **J.B. Paduan** (2015). Contrasting styles of deep-marine pyroclastic eruptions revealed from Axial Seamount push core records. *Earth and Planetary Science Letters*, **423**: 219-231, doi: 10.1016/j.epsl.2015.03.043.

Puga-Bernabéu, Á., J.M. Webster, J.C. Braga, **D.A. Clague**, A. Dutton, S. Eggins, S. Fallon, G. Jacobsen, **J.B. Paduan**, and D.C. Potts (2015). Morphology and evolution of drowned carbonate terraces during the last two interglacial cycles, off Hilo, NE Hawaii. *Marine Geology*, **371**: 57-81, doi: 10.1016/j.margeo.2015.10.016.

Raanan, B.Y., J. Bellingham, **Y. Zhang**, **B. Kieft**, **M.J. Stanway**, **R. McEwen**, and **B. Hobson** (2015). A real-time vertical plane flight anomaly detection system for a long range autonomous underwater vehicle. In: *Proceedings of the Marine Technology Society/Institute of Electrical and Electronics Engineers Oceans Conference*, Washington, D.C., 1-6.

Raskoff, K.A. and **G.I. Matsumoto** (2015). Caveat lector: The perils of critical thinking for today's students. *California Classroom Science*, **27**.

Ribalet, F., J. Swalwell, S. Clayton, **V. Jimenez**, **S. Sudek**, Y. Lin, Z. Johnson, **A.Z. Worden**, and E.V. Armbrust (2015). Light-driven synchrony of *Prochlorococcus* growth and mortality in the subtropical Pacific gyre. *Proceedings of the National Academy of Sci-*

*Shared first authorship

ences of the United States of America, **112**: 8008-8012, doi: 10.1073/pnas.1424279112.

Rouse, G.W., N.G. Wilson, K. Worsaae, and **R.C. Vrijenhoek** (2015). A dwarf male reversal in bone-eating worms. *Current Biology*, **25**: 236-241, doi: 10.1016/j.cub.2014.11.032.

Sackett, D.K., J.C. Drazen, **C.A. Choy**, B. Popp, and G.L. Pitz (2015). Mercury sources and trophic ecology for Hawaiian bottomfish. *Environmental Science & Technology*, **49**: 6909-6918, doi: 10.1021/acs.est.5b01009.

Sanamyan, N.P., K.E. Sanamyan, and **L. Lundsten** (2015). Two new deepwater sea anemones (Cnidaria: Anthozoa: Actiniaria) *Sicyonis heliodiscus* sp.n. (Actinostolidae) and *Hormathia pacifica* sp.n. (Hormathiidae) from Pacific. *Invertebrate Zoology*, **12**: 131-149, doi: 10.15298/invertzool.12.2.02

Sassoubre, L.M., **K.M. Yamahara**, and A.B. Boehm (2015). Temporal stability of the microbial community in sewage-polluted seawater exposed to natural sunlight cycles and marine microbiota. *Applied and Environmental Microbiology*, **81**: 2107-2116, doi: 10.1128/AEM.03950-14.

Seegers, B.N., **J.M. Birch**, **R. Marin**, **C.A. Scholin**, D.A. Caron, E.L. Seubert, M.D.A. Howard, G.L. Robertson, and B.H. Jones (2015). Subsurface seeding of surface harmful algal blooms observed through the integration of autonomous gliders, moored environmental sample processors, and satellite remote sensing in southern California. *Limnology and Oceanography*, **60**: 754-764, doi: 10.1002/lno.10082.

Sevadjian, J.C., E.E. McPhee-Shaw, **B.Y. Raanan**, O.M. Cheriton, and C.D. Storlazzi (2015). Vertical convergence of resuspended sediment and subducted phytoplankton to a persistent detached layer over the southern shelf of Monterey Bay, California. *Journal of Geophysical Research: Oceans*, **120**: 3462-3483, doi: 10.1002/2015jc010785.

Ševčíková, T., A. Horák, V. Klimeš , V. Zbránková, **E. Demir-Hilton**, **S. Sudek**, J. Jenkins, J. Schmutz, P. Přibyl , J. Fousek, C. Vlček , B.F. Lang, M. Oborník, **A.Z. Worden**, and M. Eliáš (2015). Updating algal evolutionary relationships through plastid genome sequencing: Did alveolate plastids emerge through endosymbiosis of an ochrophyte? *Scientific Reports*, **5 (10134)**, doi: 10.1038/srep10134.

Siebert, S., F.E. Goetz, S.H. Church, P. Bhattacharyya, F. Zapata, **S.H.D. Haddock**, and C.W. Dunn (2015). Stem cells in *Nanomia bijuga* (Siphonophora), a colonial animal with localized growth zones. *EvoDevo*, **6**: 22, doi: 10.1186/s13227-015-0018-2.

Simmons, M.P., **C. Bachy**, **S. Sudek**, M.J. van Baren, **L. Sudek**, M. Ares Jr., and **A.Z. Worden** (2015). Intron invasions trace algal speciation and reveal nearly identical Arctic and Antarctic *Micromonas populations. Molecular Biology and Evolution*, **32**: 2219-2235, doi: 10.1093/molbev/msv122.

Smith, J.M., J. Damashek, **F.P. Chavez**, and C.A. Francis (2015). Factors influencing nitrification rates and the abundance and transcriptional activity of ammonia-oxidizing microorganisms in the dark northeast Pacific Ocean. *Limnology and Oceanography*, **61**:596-609, doi: 10.1002/lno.10235.

Smith Jr., K.L., **M. Messié**, **A.D. Sherman**, **C.L. Huffard**, **B.W. Hobson**, H.A. Ruhl, and A. Boetius (2015). Navigating the uncertain future of global oceanic time series. *EOS*, **96**, doi: 10.1029/2015eo038095.

Stanway, M.J. (2015). Biangunilateration using azimuth, elevation, and depth difference to localize submerged assets. In: *Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference*, Washington, D.C., 1-5.

Stanway, M.J., **B. Kieft**, T. Hoover, **B. Hobson**, **D. Klimov**, **J. Erickson**, **B.Y. Raanan**, D.A. Ebert, and J. Bellingham (2015). White shark strike on a long-range AUV in Monterey Bay. In: *OCEANS 2015-Genova*, Genova, Italy, 7 pp. 1-6, doi: 10.1109/OCEANS-Genova.2015.7271726

Thompson, D., **D. Caress**, **H. Thomas**, and **D. Conlin** (2015). MBARI mapping AUV operations in the Gulf of California 2015, In: *Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference*, Washington, D.C., pp 1-7.

Thys, T.M., **J.P. Ryan**, H. Dewar, C.R. Perle, K. Lyons, J. O'Sullivan, C. Farwell, M.J. Howard, K.C. Weng, B.E. Lavaniegos, G. Gaxiola-Castro, L.E. Miranda Bojorquez, E.L. Hazen, and S.J. Bograd (2015). Ecology of the ocean sunfish, *Mola mola*, in the southern California Current System. *Journal of Experimental Marine Biology and Ecology*, **471**: 64-76, doi: 10.1016/j.jembe.2015.05.005.

Trueblood, L.A., S. Zylinski, **B.H. Robison**, and B.A. Seibel. (2015). An ethogram of the Humboldt squid *Dosidicus gigas* Orbigny (1835) as observed from remotely operated vehicles. *Behaviour*, **152**: 1911-1932, doi: 10.1163/1568539x-00003324.

Tubau, X., **C.K. Paull**, G. Lastras, **D.W. Caress**, M. Canals, **E. Lundsten**, **K. Anderson**, **R. Gwiazda**, and D. Amblas (2015). Submarine canyons of Santa Monica Bay, Southern California: Variability in morphology and sedimentary processes. *Marine Geology*, **365**: 61-79, doi: 10.1016/j.margeo.2015.04.004.

Varaljay, V.A., J. Robidart, **C.M. Preston**, S.M. Gifford, B.P. Durham, A.S. Burns, **J.P. Ryan**, **R. Marin III**, R.P. Kiene, J.P. Zehr, **C.A. Scholin**, and M.A. Moran (2015). Single-taxon field measurements of bacterial gene regulation controlling DMSP fate. *ISME Journal*, **9**: 1677-1686, doi: 10.1038/ismej.2015.23 and *ISME Journal*, **9**: 1692: doi: 10.1038/ismej.2015.94.

Wasson, K., B. Suarez, A. Akhavan, E. McCarthy, J. Kildow, **K.S. Johnson**, M.C. Fountain, A. Woolfolk, M. Silberstein, L. Pendleton, and D. Feliz (2015). Lessons learned from an ecosystem-based management approach to restoration of a California estuary. *Marine Policy*, **58**: 60-70, doi: 10.1016/j.marpol.2015.04.002.

Wicksten, M. and **L.A. Kuhnz** (2015). A swimming deep-sea peneaoid shrimp photographed off California. *California Fish and Game*, **101**: 146-148.

Worden, A.Z., M.J. Follows, S.J. Giovannoni, **S. Wilken**, **A.E. Zimmerman**, and P.J. Keeling (2015). Rethinking the marine carbon cycle: Factoring in the multifarious lifestyles of microbes. *Science*, **347**, doi: 10.1126/science.1257594.

Xu, Y., K.A. Rose, F. Chai, **F.P. Chavez**, and P. Ayón (2015). Does spatial variation in environmental conditions affect recruitment? A study using a 3-D model of Peruvian anchovy. *Progress in Oceanography*, **138**: 417-430, doi: 10.1016/j.pocean.2015.04.002.

Yamahara, K.M., **E. Demir-Hilton**, **C.M. Preston**, **R. Marin III**, **D. Pargett**, **B. Roman**, **S. Jensen**, **J.M. Birch**, A.B. Boehm, and **C.A. Scholin** (2015). Simultaneous monitoring of faecal indicators and harmful algae using an in-situ autonomous sensor. *Letters in Applied Microbiology*, **61**: 130-138, doi: 10.1111/lam.12432.

Young, J.W., B.P.V. Hunt, T.R. Cook, J.K. Llopiz, E.L. Hazen, H.R. Pethybridge, D. Ceccarelli, A. Lorrain, R.J. Olson, V. Allain, C. Menkes, T. Patterson, S. Nicol, P. Lehodey, R.J. Kloser, H. Arrizabalaga, and **C.A. Choy** (2015). The trophodynamics of marine top predators: Current knowledge, recent advances and challenges. *Deep Sea Research Part II: Topical Studies in Oceanography*, **113**: 170-187, doi: 10.1016/j.dsr2.2014.05.015.

Zapata, F., F.E. Goetz, S.A. Smith, M. Howison, S. Siebert, S.H. Church, S.M. Sanders, C.L. Ames, C.S. McFadden, S.C. France, M. Daly, A.G. Collins, **S.H.D. Haddock**, C.W. Dunn, and P. Cartwright (2015). Phylogenomic analyses support traditional relationships within Cnidaria. *PLoS One*, **10**: e0139068, doi: 10.1371/journal.pone.0139068.

Zhang, H., **S.B. Johnson**, V.R. Flores, and **R.C. Vrijenhoek** (2015). Intergradation between discrete lineages of *Tevnia jerichonana*, a deep-sea hydrothermal vent tubeworm. *Deep-Sea Research Part II: Topical Studies in Oceanography*, **121**: 53-61, doi: 10.1016/j.dsr2.2015.04.028.

Zhang, Y., J.G. Bellingham, **J.P. Ryan**, and M.A. Godin (2015). Evolution of a physical and biological front from upwelling to relaxation. *Continental Shelf Research*, **108**: 55-64, doi: 10.1016/j.csr.2015.08.005.

Zhang, Y., J.G. Bellingham, **J.P. Ryan**, **B. Kieft**, and **M.J. Stanway** (2015). Autonomous four-dimensional mapping and tracking of a coastal upwelling front by an autonomous underwater vehicle. *Journal of Field Robotics*, **33**: 67-81, doi: 10.1002/rob.21617.

Zhang, Y., **B. Kieft**, **R. McEwen**, **M.J. Stanway**, J. Bellingham, **J. Ryan**, **B. Hobson**, **D. Pargett**, **J. Birch**, and **C. Scholin** (2015). Tracking and sampling of a phytoplankton patch by an autonomous underwater vehicle in drifting mode. In: *Proceedings of the Marine Technology Society / Institute of Electrical and Electronics Engineers Oceans Conference*, Washington, D.C., 1-5.

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Cover: One of the stunning formations discovered by researchers exploring hydrothermal vents and associated lava fields in the Gulf of California. This is a view looking up at the underside of a large protruding rim, with hot vent fluid ponding underneath, high on a chimney at the newly discovered Pescadero Basin vent field in the south Gulf. See page 24.

Back cover: This long-legged squat lobster was encountered on a bubblegum coral during a remotely operated vehicle dive in the Gulf of California. See page 20.

Inside front cover: An underwater view of the remotely operated vehicle *Doc Ricketts* being launched from the research vessel *Western Flyer*. Photo by Andrew McKee.

Above: Engineer Brett Hobson, aboard the research vessel *Paragon*, prepares to retrieve a long-range autonomous vehicle following a successful mission in Monterey Bay. Photo courtesy of Kip Evans.

Image credits, by page: 2: Photo taken by drone operated by Ben Erwin; 3: Todd Walsh; 4: Courtesy of the Monterey Bay Aquarium; 6 (left): Kim Fulton-Bennett, (right): Holly Bowers; 8: Todd Walsh; 11 (top left): Kakani Katija, (top center and right): Paul McGill; 13: Lynne Talley, Scripps Institution of Oceanography; 15 (both): Courtesy of the Monterey Bay Aquarium; 17: David Caress; 18: Steve Etchemendy; Foldout facing page 18: Illustration by David Fierstein; 21 (top): Jim Barry, (bottom): Octavio Aburto; 35: Illustration by Kelly Lance; 41: Krystle Anderson; 44: Todd Walsh; 45 (top two): Todd Walsh, (bottom): MBARI archives; 47: Todd Walsh; 49 (left): Shana Goffredi, (right): George Matsumoto; 51 (jelly tag): Kakani Katija, (right top): Todd Walsh; 52 (left): François Cazenave, (right): Peter Walz; 57: Andrew McKee. Deep-sea photos are frame grabs from MBARI ROV video.

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