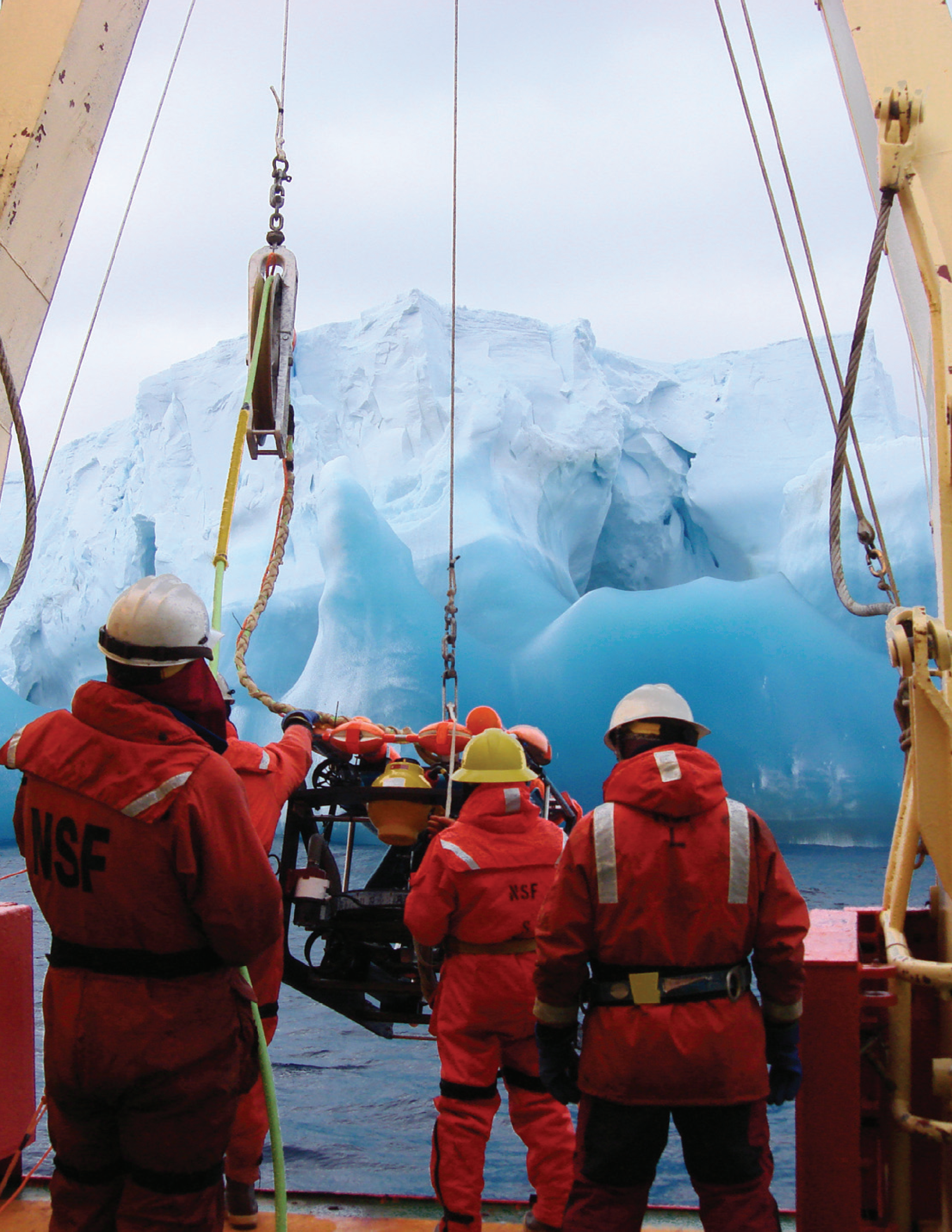
MBARI

Monterey Bay Aquarium Research Institute

ANNUAL REPORT

2009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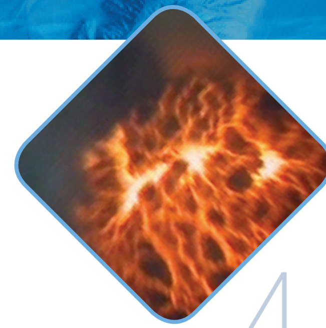

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View From the Masthead

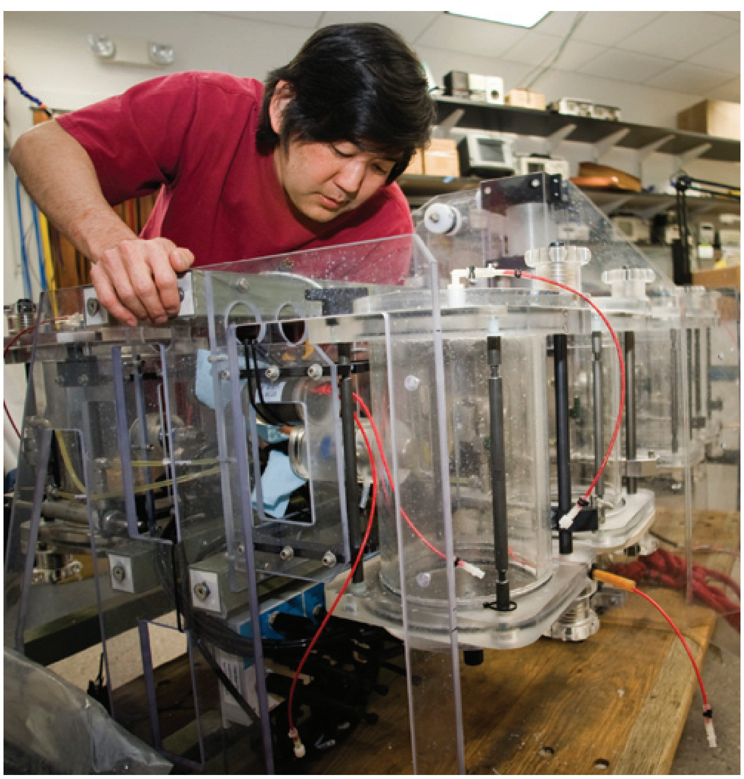
Looking back on 2009, change was the common theme that came to mind. The new administration in Washington galvanized new ocean policy directives. The changing global climate raised many questions for future generations and the economic decline touched the lives of nearly everyone on the planet. These were but a few of the changes many of us witnessed this past year. MBARI experienced our share of change, too, with a reallocation of resources in response to budget reductions, the departure of President and Chief Executive Officer Marcia McNutt to lead the U.S. Geological Survey, and my appointment by our Board of Directors as her replacement.

Reflecting these changing times, this Annual Report highlights how the institute is reaching out beyond our local waters in more collaborative partnerships and how those working behind the scenes bring science and technology to light. In addition, we showcase Monterey Bay as a window to the world of ocean science and technology and provide a glimpse of what programs and developments we see on the horizon.

Expeditionary science reigns as a fundamental cornerstone of our research and development programs. A series of investigations involving the chemistry of ocean greenhouse gases, oxygen minimum zones, seafloor processes, an erupting seafloor volcano, and studies of icebergs off Antarctica herald that fact. The success of these research programs rests on the shoulders of many. In that regard, this year we pay special tribute to the Support Engineering and Manufacturing Groups—the teams that keep the sensors, platforms, and data systems running, and help get essential research equipment out to sea and back again.

Local waters also remain central to many projects we endeavor at MBARI. Few regions of the world ocean have been studied as intensely or for as long duration as Monterey Bay and adjacent waters. This provides us a rare window to the larger ocean, where observed changes in surface water chemistry and biology can be intimately tied to the deep sea.

In keeping with the "Monterey Bay as a window to the world" theme, and the unique opportunities it offers, we recognize the value of MBARI's Summer Internship Program. Over the years the program has grown ever more popular, drawing a diverse group of



Engineer Craig Okuda works on the new midwater respirometer system that has eight individual chambers to measure rates of oxygen consumption for the animals placed in each chamber. A similar respirometer is also being built for deployment on the seafloor. See related stories on pages 28 and 36.

MBARI Research Specialist Bill Ussler and collaborator Mary McGann, of the U.S. Geological Survey, collect high-purity water samples from Niskin bottles mounted on the ROV *Doc Ricketts* during the northern expedition. The water will be used for five types of high-precision analyses to learn more about the sources of organic matter in the deep ocean adjacent to methane venting sites and the flow of methane-derived carbon through the complex bacterial communities near the seafloor. See story on page 7.

students and teachers. Summer interns experience ocean science firsthand by working with MBARI staff in many capacities, learning about what oceanographic research and engineering development entail and the varied career paths they foster.

Looking to the future, the development of new tools and technologies for studying the ocean continues unabated. Initiatives that concentrate on the carbon cycle and its relation to changes in oceanic chemistry and function, development and use of autonomous systems for tracking ephemeral biological phenomena, and efforts to understand biological diversity as a function of ocean processes and geology are but a few of the projects to be emphasized. Everything we have seen in the past year and foresee doing in the future reminds us that we inhabit a dynamic and changing Earth. MBARI remains an agile and vibrant organization capable of responding to that change.

Chris Scholin
President and Chief Executive Officer

Expeditions

Expeditionary voyages beyond Monterey Bay provide important opportunities to extend the reach of MBARI's locally developed technologies to new sites and new users. Journeys away from our home port enable comparative studies, often with colleagues from other institutions and other regions. MBARI researchers also take advantage of externally funded opportunities and collaborations that may allow them to visit a different part of the world ocean to explore, observe, and collect samples and data that would not be possible with Packard Foundation support alone.

Northern expedition

In the summer of 2009 MBARI sent both the R/V *Western Flyer* and the R/V *Zephyr* on a coordinated expedition northward to investigate specific targets along the Cascadia Margin and the Juan de Fuca mid-ocean ridge to the west of it (Figure 1). The series of field programs focused on the methane gas hydrates, midwater biology within the strong oxygen-minimum zone associated with Astoria Submarine Canyon, methane seepage and venting on the seafloor along the Cascadia Margin, and recent submarine volcanic eruptions on the Juan de Fuca ridge. Ship schedules were coordinated so that autonomous underwater vehicle (AUV) mapping surveys conducted from the R/V *Zephyr* could be used to guide subsequent remotely operated vehicle (ROV) dives launched from the R/V *Western Flyer*.

The potential and hazards of methane hydrates

MBARI researchers visited two remarkable seafloor sites where methane hydrates are easily accessible. Methane hydrates are an icy form of methane and other gases in which the gas molecules are trapped in a soccer-ball-like cage of "frozen" water molecules. They are made stable on the seafloor by the combination of pressure and temperature well above the normal freezing point of water. Hydrates are considered to be both a potential large-scale source of energy and a possible geologic hazard—decomposing hydrates could release a potent greenhouse gas into the atmosphere or a buildup of the gases within the sediment could cause an eruption creating an underwater landslide or a tsunami. MBARI research was devoted to exploring both of these issues.

Hydrate Ridge

The research vessels first visited Hydrate Ridge, offshore Newport, Oregon, where methane venting from the seafloor at a depth of about 850 meters had resulted in the accu-

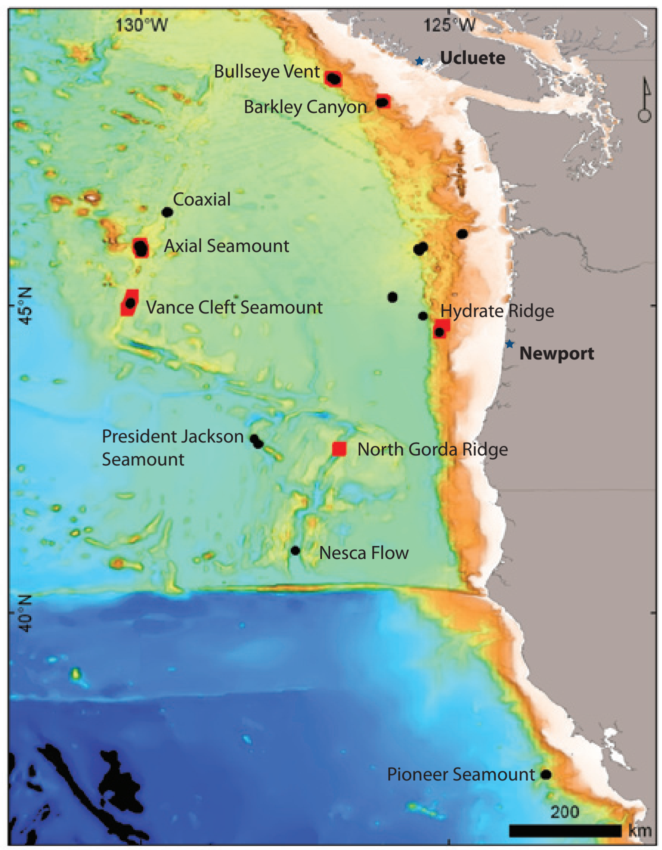


Figure 1: Map showing the areas where operations were conducted during MBARI's 2009 northern expedition. Areas where AUV mapping surveys were conducted are indicated by red squares. Areas where ROV dives occurred are indicated with black circles.

mulation of several deposits of hydrate readily accessible for ROV-based experiments.

Turning solid hydrate into gas—Scientists have long been intrigued by the question of how this solid form of methane might be efficiently converted to usable gas. It is in some ways analogous to the challenge of obtaining fresh water from icebergs, where vast quantities of potable water are plainly visible, but the cost of obtaining that water could be prohibitive.

The standard approach, now being explored through industry-government partnerships, is to depressurize the hydrate, thereby separating gas and water, as direct injection of heat would be far too expensive. Other methods have been proposed, and one scheme currently of interest is to inject carbon dioxide into the hydrate formation. This could, in theory, dispose of a greenhouse gas, carbon dioxide, which has the chemical potential to compete with the frozen methane for the water molecules in which it is trapped. One could "freeze" the carbon dioxide, and get back the liberated methane as an energy benefit which would cover the cost of the work. There are many impediments to this, however, including the slowness of the reaction and the very high solubility of carbon dioxide.

MBARI chemist Peter Brewer and his group considered a simpler approach using the chemical potential of nitrogen gas to produce a similar effect. Injection of that simple atmospheric gas would displace the surrounding pore-water and the solid hydrate would quickly break down into its gas and water components (Figure 2).

Their experiment showed how simple theory combined with the unique experimental opportunities at MBARI can rapidly change an important field. Their calculations showed that hydrate would no longer break down into gas and water at an injection ratio of about 47 percent nitrogen to 53 percent methane. This opened the door to a more efficient process for energy recovery and provided new insights into hydrate stability in nature.

Finding the real methane signal of sediments—Continental shelf sediments often contain large quantities of dissolved methane, which have important consequences for geochemistry and climate. When sediment cores are collected from the seafloor and brought to the surface, much of the methane is lost in bubbles formed due to compression, so geochemists have had a distorted view of this important

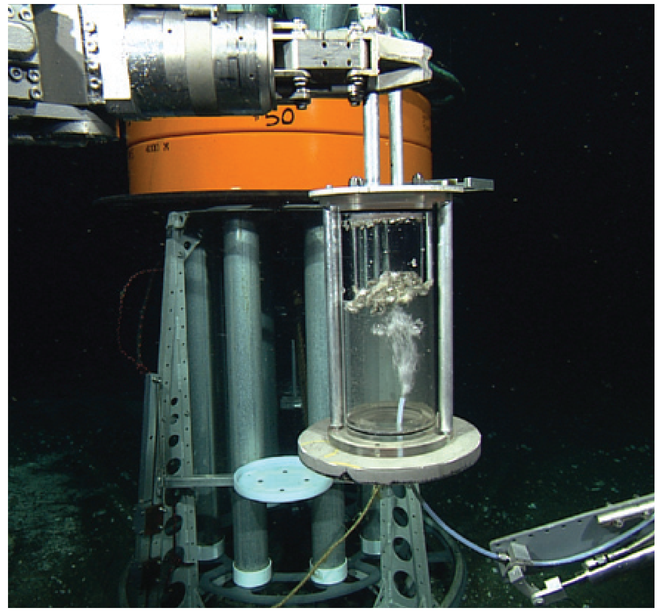


Figure 2: A seafloor experiment at 850-meters depth in which ice-like methane hydrate (seen in the glass container) recovered from the seafloor was exposed to nitrogen gas. The solid hydrate quickly broke down and the liberated methane was measured in place by laser Raman spectroscopy.

compound. Brewer's research team devised a novel way to solve this problem through in situ measurement.

The group's laser Raman techniques were incorporated into a pore-water probe—a pencil-thin device inserted into the sediments—which draws pore-water into a micro-cavity illuminated by the laser. From the frequency shift of the light scattered back, scientists can detect the dissolved methane and other chemical species (such as sulfate and sulfide species) that are characteristic of the fundamental reactions taking place without needing to bring a sample to the surface.

The results showed up to 10 times greater dissolved methane than the amount detected using standard procedures. The profiles correlated with sampling depth show a beautiful progression of change that elegantly fits geochemical models (Figure 3).

Barkley Canyon

The Barkley Canyon site offshore Vancouver Island offers a radically different geochemical picture. While the hydrates at Hydrate Ridge are almost pure methane, those found at Barkley Canyon are a complex mixture with substantial amounts of higher hydrocarbons, such as ethane and propane. This mixture, which is not well understood, results in large "icebergs" of hydrate pushing up through

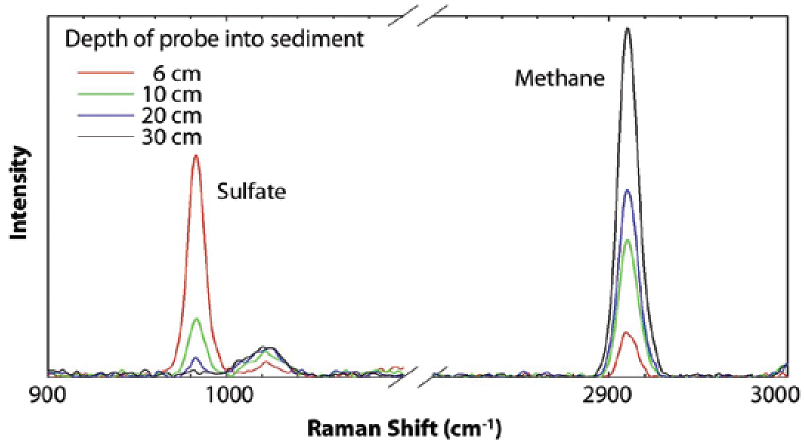


Figure 3: Results from measurements of the chemistry of pore waters. On the left, sulfate declines with depth into the sediment; on the right methane rises. The quantity of dissolved methane exceeds by a factor of 10 that observed if a sediment core is brought to the surface.

the sediments and forming spectacular mounds on the seafloor. Natural oil seepage was also evident at this site; droplets of oil were seen escaping from the seafloor when the ROV touched bottom.

Most dramatic was the change in appearance of these mounds in the 35 months since our first visit in August 2006, even though the change had been predicted. In 2006, the researchers took hydrate samples from an exposed cliff face and carried out a dissolution-rate experiment by simply transferring the samples to a small cage and imaging their change over time as water flowed by. The publication describing that experiment led to a prediction that the exposed hydrate faces would recede at the astonishing rate of about 70 centimeters or more per year. Until recently, hydrates exposed to seawater were expected to be stable, and that prediction of rapid change was controversial. Comparable images of the same site from 2006 and 2009 are shown in Figure 4.

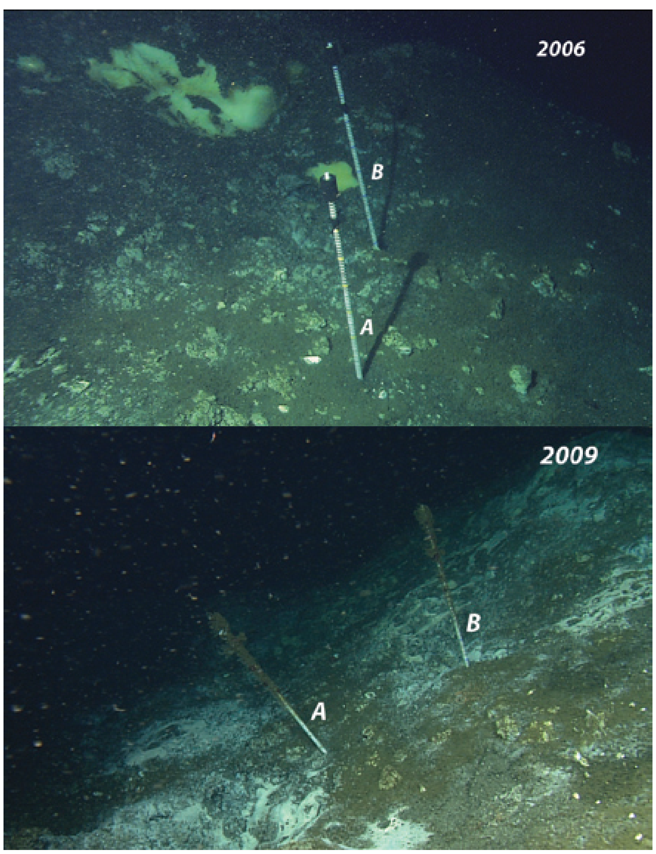


Figure 4: Images of the seafloor at Barkley Canyon taken in 2006 (upper panel) and 2009 (lower panel) show a significant retreat in the seafloor due to dissolution of gas hydrates at the site.

It was clear that the impressive cliff face seen earlier had collapsed as anticipated. The hydrate exposed to open seawater had simply dissolved. The ocean chemistry group showed that hydrates exposed to seawater will not last long, and that the seafloor at the Barkley Canyon site is constantly changing as mounds erupt, then dissolve away.

The pore-water probe mentioned previously was also used at this site. The oil droplets did not penetrate through the filter system—they would have caused horrible fouling of the optics—and data on the pore waters bathing these massive slabs of hydrate were obtained. These data showed that the sediment pore waters were not at strict equilibrium with the solid hydrate, but were poised at about 50 percent of that value. This provides testimony for the highly dynamic nature of these sites and their potential for rapid geochemical changes.

Ocean Chemistry of the Greenhouse Gases

Project leads: Peter Brewer, William Kirkwood
Project manager: Edward Peltzer
Project team: Keith Hester, Peter Walz
Collaborators: Baijin Chen, Heriot-Watt University, United Kingdom; Xin Zhang, Ocean University of China, Qingdao

New tools reveal discoveries at gas-venting sites

During the northern expedition Charlie Paull's group focused its efforts on the north and south summits of Hydrate Ridge off Oregon, and on Bullseye Vent and Barkley Canyon off Canada. The goal was to better elucidate the nature and origin of the small scale (1 to 10 meters high) topography associated with gas-rich seafloor environments. Historically, it has been difficult to resolve features of this scale using surface-ship bathymetric surveys. The combination of high resolution mapping survey data collected by *D. Allan B.*, MBARI's mapping AUV (Figure 5), followed by sampling from the remotely operated vehicle *Doc Ricketts* provided new insights about the impact that gas venting exerts on seafloor morphology.

The seafloor surrounding Bullseye Vent and Hydrate Ridge have been the focus of scientific ocean drilling, numerous ROV and HOV dives, sediment coring, seismic reflection surveys, and surface-ship multibeam bathymetric surveys. Previous observations from human-occupied vehicles (HOVs), ROVs, and towed camera sleds had shown that chemosynthetic biological communities, methane gas hydrates in the near subsurface, and methane gas vents occur in these areas. However, it has been difficult to assess the impact of the gas venting on the seafloor topography. For example, data from the surface-ship surveys gave the impression that Bullseye Vent was a broad subtle (approximately two meters) topographic high. However, the significantly improved resolution of the bathymetry obtained using MBARI's state-of-the-art mapping AUV showed the seafloor shape in unprecedented detail and clearly demonstrated that Bullseye Vent is a distinct, 350-meter-long, 50-meter-wide, and approximately 6-meter-deep topographic depression (Figure 6). The new high-resolution multibeam maps and the realizations that come from seeing the seafloor in such unprecedented detail have fundamentally changed the perception of what processes shape the seafloor. Instead of considering processes that produce local topographic highs, processes that excavate the seafloor are required. Thus, simple discoveries can still be made that radically change our point of view, even in some of the best-studied seafloor environments.

The bathymetric maps and subsurface data collected during the mapping AUV surveys provided a road map that enabled focused observations and ground-truth sampling to be conducted during the *Doc Ricketts* diving program. Of particular value was MBARI's unique ROV-deployed vibracoring technology that allows as many as five sediment cores up to 1.5 meters long to be collected on a single dive. This capability enables detailed sampling of subtle seafloor features, like Bullseye Vent, with enough precision to establish the detailed structure and stratigraphy of these features and to understand the development of this topography.

Notable features revealed by the mapping AUV data and sampled with the *Doc Ricketts* included widespread areas where methane-derived carbonates are exposed on the seafloor, circular seafloor depressions with diameters of three to 50 meters excavated into the seafloor, and smaller mound-like features one-to-three-meters higher than the surrounding seafloor. Thin lenses of solid gas hydrate exposed along fractures on the sides of the mounds suggest that these mounds are push-up features created by gas hydrate growth in the sediments just below the seafloor.

The youngest appearing mounds occur in a gulch approximately one kilometer northeast of Bullseye Vent. They are more subtle features (two to three meters in diameter and about half a meter high) than mounds seen at other localities. Their crests are crisscrossed by narrow polygonal cracks lined with white bacterial mat. Exposures of methane-derived carbonates and the larger animals characteristic of chemosynthetic biological communities were not observed. ROV-collected vibracores obtained from these mounds characteristically encountered a hard layer 30 to 60 centimeters below the seafloor. When this layer was penetrated, methane bubbles spontaneously gushed out

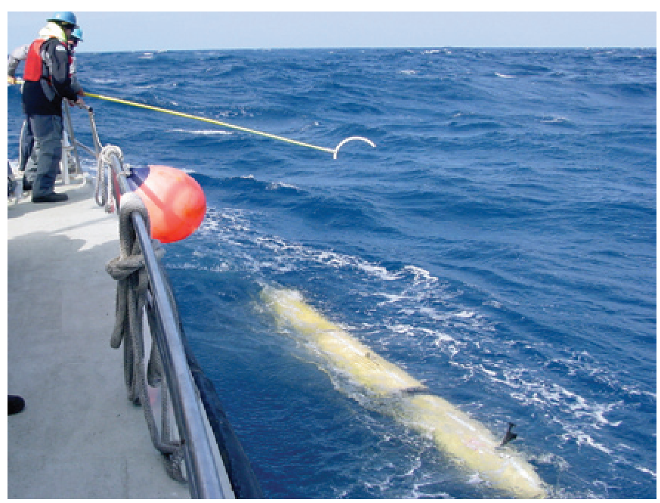
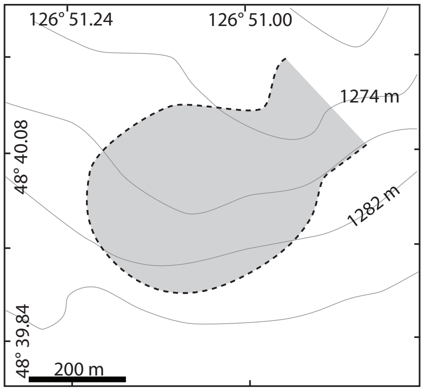


Figure 5: R/V *Zephyr* crew members Matt Noyes, in the foreground, and Olin Jordan prepare to attach a line to the mapping AUV, the *D. Allan B.*, for recovery following a survey of the Cleft Segment of Juan de Fuca Ridge.



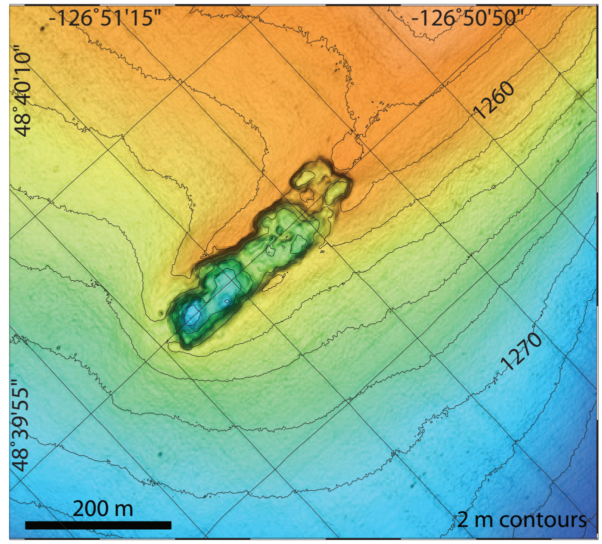


Figure 6: Map showing the previously available bathymetry around Bullseye Vent (left) and the bathymetry associated with Bullseye Vent provided by the AUV survey (right). Map on left was created with the best data previously available (after Riedel et al., 2006) and the gray shaded area outlines the area identified in seismic reflection profiler data as Bullseye Vent. AUV surveys show details less than one meter in size, making it possible to identify the seafloor depression overlying the Bullseye Vent area that could not be resolved using lower-resolution ship surveys.

of the hole and continued to flow for more than an hour. These observations suggest that these small mounds are young features that have trapped considerable amounts of methane gas just beneath the seafloor. These observations also indicate that slightly over-pressured gas pockets may occur within a meter of the seafloor surrounding gas vents. Together, the high-resolution seafloor maps, ROV observations, and carefully located seafloor samples have revealed the integrated effects shallow gas accumulations and gas hydrate can have on seafloor morphology. These tools allow us to recognize different stages in the development and evolution of carbonate mounds.

The installation of a seafloor observatory to monitor natural variations in the rates of gas venting and gas hydrate dynamics, and conducting perturbation experiments remain important concepts for the ocean observing initiatives supported by Canada and the U.S. Gas hydrate observatories are planned for installation at Bullseye Vent and Barkley Canyon, as part of the NEPTUNE Canada project to install a cabled submarine network. Hydrate Ridge in the U.S. is the other candidate for a submarine cable-connected borehole observatory to study gas-hydrate dynamics. The high-resolution maps collected in 2009 will facilitate detailed planning of such seafloor gas venting and gas hydrate observatories.

Continental Margin and Submarine Canyon Processes

Project lead: Charles Paull
Project manager: William Ussler
Project team: Larry Bird, David Caress, Brett Hobson, Eve Lundsten, Gene Massion, Melissa Meiner, Brian Schlining
Collaborators: Clarke Alexander, Skidaway Institute of Oceanography, Savannah, Georgia; Jim Bauer, Virginia Institute of Marine Sciences; Ross Chapman, University of Victoria, British Columbia, Canada; Mary McGann, U.S. Geological Survey, Menlo Park, California; John Pohlman, U.S. Geologic Survey, Woods Hole, Massachusetts; Michael Riedel, Natural Resources Canada; Thomas Stevens, University of London, Surry, United Kingdom

Seafloor Mapping Data Support and MB-System

Project lead/manager: David Caress
Project team: David Clague, Doug Conlin, Eve Lundsten, Jenny Paduan, Charlie Paull, Hans Thomas, Duane Thompson
Collaborators: Dale Chayes, Lamont-Doherty Earth Observatory of Columbia University, Palisades, New York; Val Schmidt, University of New Hampshire, Durham

Submarine volcanism

Oceanic spreading ridges, arguably the simplest of tectonic regimes, account for more than 75 percent of Earth's annual magmatic output. The ridge systems have an essential role in defining or controlling global energy and material fluxes, and also have important implications for marine ecosystems. Reconstructing the geologic and volcanic record of mid-ocean ridges can establish eruption recurrence, crustal spreading and accretion rates, magma and hydrothermal

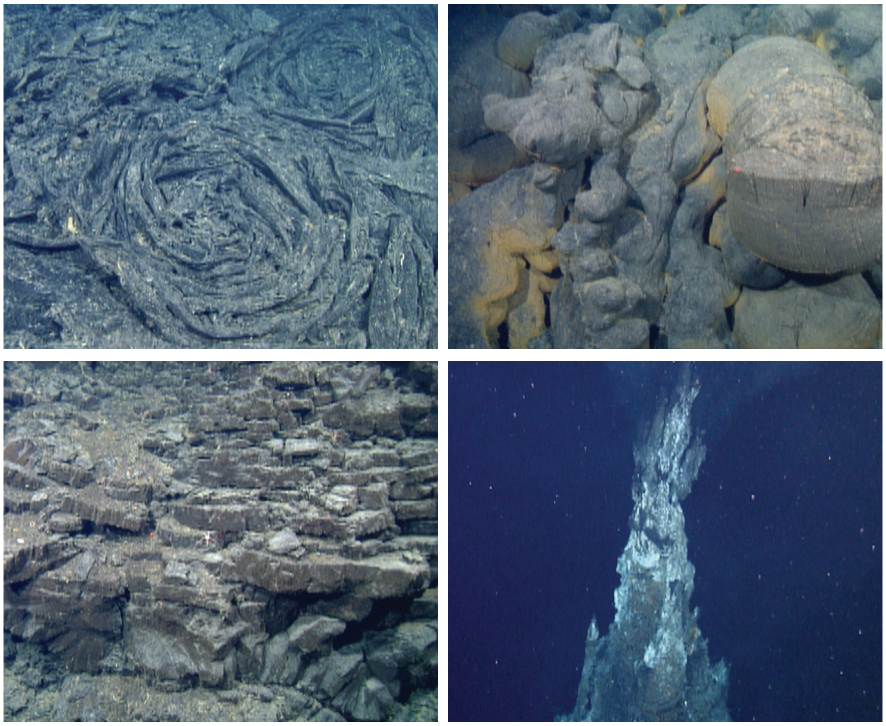


Figure 7: Clockwise from top left, 1) Ropy whorls of lava were eddies in the surface of a rapidly-advancing sheet flow. These vigorous eruptions are mildly explosive and produce abundant volcanic glass particles known as "limu o Pele". 2) Rust-colored hydrothermal stains in cracks of a lava pillow mound are just one indication that this is a recent flow. 3) Very top of the hydrothermal vent "El Guapo" at Axial Volcano, to which MBARI researchers returned with the ROV *Doc Ricketts*. The vent was discovered in 2006 on an ROV dive to explore terrain newly mapped with the MBARI AUV. Axial's vents have been studied for years, but this one had been missed. It stands 13 meters tall and vents water hotter than 330°C, both new records at Axial. 4) Shelves of lava were flow surfaces in a three-meter-wide lava tube now exposed in the wall of Axial Caldera. The margin of the tube is visible in the extreme right. Tube-fed flows are better insulated against the cold sea water so the lava can travel great distances. Dating flows at the base of the caldera wall will give an idea of how fast the volcano grows.

production rates and pathways, and timescales of biological colonization and evolution at spreading centers. For the first time, using AUV maps and ROV observations, submarine mid-ocean ridge segments can be mapped in sufficient detail and their eruptive history can be reconstructed in a manner comparable to that done at many volcanoes on land. Absolute ages for select flows can be determined using a combination of radiocarbon dating of foraminifera (small shelled organisms) from the overlying sediment, and the magnetic and isotopic characteristics of volcanic glass from the flows themselves (Figure 7).

The 2009 northern expedition allowed MBARI volcanologist David Clague and his group to add important data and samples to those collected at several eruption sites on expeditions over the previous four years: Axial Seamount (1998 eruption), the CoAxial (1993 and 1982-91 eruptions) and North Cleft (1986 eruption) segments of the Juan de Fuca Ridge, and the northern Gorda Ridge (1996 eruption). Two key elements of these sites are the presence of a historic lava flow and the geochemical similarities of all the flows erupted at each site.

Figure 8 shows part of the AUV map produced at the CoAxial site in 2009. Superimposed on the map are dive tracks for three dives, T882 in 2006 using ROV *Tiburon*, and D77 and D78 in 2009 using ROV *Doc Ricketts*. Tectonically fractured and fissured flows and pillow mounds are older than unfractured flows that are covered lightly with sediment. The pillowed margins of flows can be identified in the one-meter-resolution data, and in most cases, their superposition can be determined based on which flow overruns other flows. The volumes of the mapped flows, particularly pillow flows, can be calculated from the map data. Pillow flows from slow eruptions are easily distinguished from rapid-eruption sheet flows. Radiocarbon ages of foraminifera from sediment on three prehistoric flows under the historic flows are roughly 1,000, 4,000, and 6,500 years old and suggest a surprisingly long eruptive history in the more recent volcanic zone, despite the presence of two historic lava flows separated by less than 11 years.

Similar work is underway for three locations at Axial Seamount, around the 1986 North Cleft eruption, and around the 1996 North Gorda site. Over the next five years, eruptive histories should be constructed for each of these sites, as well as a few additional sites in the Gulf of California and the southernmost Gorda Ridge, which will allow Clague's group to critically determine temporal changes in lava chemistry, hydrothermal activity, and eruptive volumes, rates, and styles.

Several biologists participated in the expedition, including former MBARI postdoctoral fellow Craig McClain. Discerning the processes that influence geographic distributions of species remains one of the central goals of

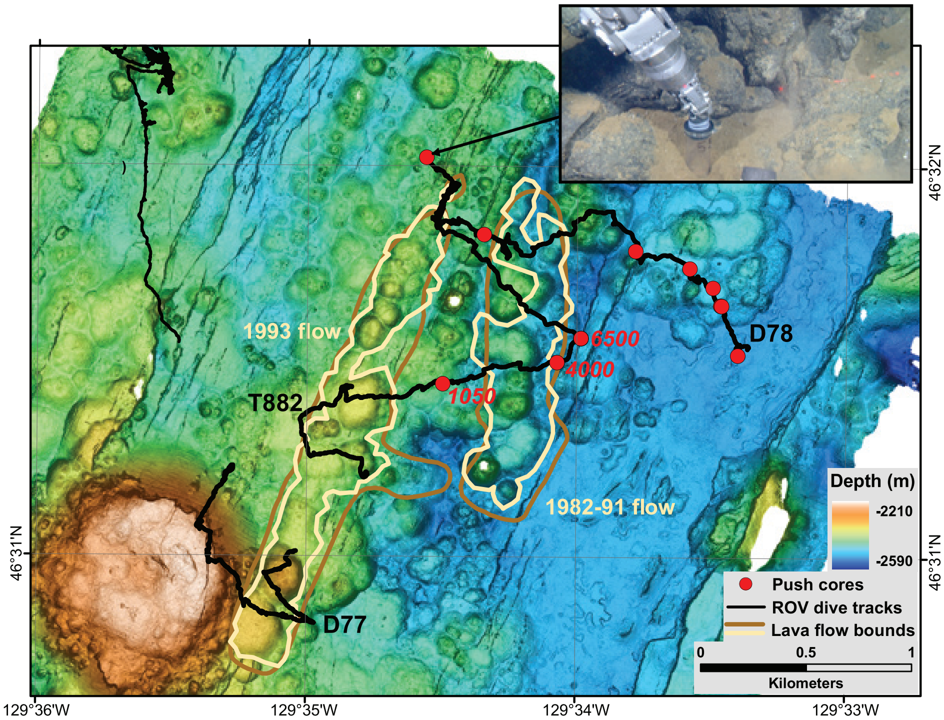


Figure 8: MBARI AUV map of the historic eruption site on the CoAxial segment of the Juan de Fuca Ridge. The resolution of the map is 1 meter. Tracks of one ROV *Tiburon* and two ROV *Doc Ricketts* dives are in black, and the locations of pushcore samples with forams at the bottom are red dots. ^{14}C dates of analyzed samples are indicated in red italics and are minimum ages in years-before-present of the underlying flows. The boundaries of lava flows that erupted in 1993 and between 1982 and 1991 as interpreted from the AUV-map data (in beige) are compared to those based only on previous camera and dive observations (in brown). The frame grab in the upper right shows a pushcore being collected in a small sediment pond between lava pillows.

ecology, directly speaking to the conservation of biodiversity. Little is known about the fauna that inhabit newly created seafloor lava flows, one of the few ways new unoccupied habitat is created in the deep ocean. Submarine lava flows literally wipe the slate clean so that subsequent recruitment occurs on pristine substrate devoid of animals. As the volcanic substrate ages and accumulates sediments, biological colonization and succession continue. How quickly species can colonize newly erupted seafloor and the order and timing of ecological succession remain unknown in the deep sea.

Transects conducted in 2005 on the historic lava flows indicated significant change in the fauna as lava flows aged, even on flows, that were observed seven to 19 years after they erupted. Additional transects in 2009, including some on the same flows, allow comparison of fauna from recent lava flows with fauna

Submarine Volcanism

Project lead: David Clague
Project manager: Jennifer Paduan
Project team: Alicé Davis, Brian Dreyer
Collaborators: Michael Bizimis, University of South Carolina, Columbia; Julie Bowles, University of Minnesota, Twin Cities; Juan Carlos Braga, University of Granada, Spain; Pat Castillo, David Hilton, Peter Lonsdale, and Jerry Winterer, Scripps Institution of Oceanography, La Jolla, California; William Chadwick, Robert Duncan, and John Huard, Oregon State University, Corvallis; Brian Cousens, Carleton University, Ottawa, Canada; Jackie Dixon, University of Miami, Florida; Robert Embley, Pacific Marine Environmental Laboratory, Newport, Oregon; Fred Frey and Guangping Xu, Massachusetts Institute of Technology, Cambridge; Paul Fullagar, University of North Carolina; Christina Gallup, University of Michigan, Dearborn; James Gill, Donald Potts, and Christina Ravelo, University of California, Santa Cruz; James Hein, Jim Moore, and Stephanie Ross, U.S. Geological Survey, Menlo Park, California; Tessa Hill, Jim McClain, Peter Schiffman, and Rob Zierenberg, University of California, Davis; Sichun Huang, Harvard University, Cambridge, Massachusetts; Deborah Kelley, University of Washington, Seattle; Chris Mah, Smithsonian Institution, Washington, D.C.; Craig McClain, National Evolutionary Synthesis Center, Durham, North Carolina; Kathie Marsaglia, California State University, Northridge; Michael Perfit, Florida State University, Tallahassee; Willem Renema, Leiden University, the Netherlands; John Stix, McGill University, Montreal, Canada; Jody Webster, University of Sydney, Australia

from nearby and remote seamounts. The researchers collected 46 different sea stars from a variety of habitats for collaborator Chris Mah, of which 21 are new to science and 15 more remain to be identified and may also be novel finds. Tissue from these specimens have been included in two major efforts addressing sea star evolution. Genetic studies of the new species suggest that some of them are much older than coastal sea stars. So, in addition to being newly discovered, several represent an earlier sea star lineage, their antiquity hidden by their location in the deep North Pacific.

An additional objective of this leg of the expedition was to sample vent clams at several sites discovered during a dive in 2006 in the northern Escanaba Trough. The vent clam, *Ectenagena extenta* is only known from two localities along the western U.S. margin—Monterey Canyon and Escanaba Trough. MBARI molecular ecologist Bob Vrijenhoek's team plans to compare the two populations and their associated bacteria.

Studying the zone of depleted oxygen

The midwater leg of the northern expedition comprised five ROV dives in the Astoria Canyon region off the Oregon coast. The objective of the dives was to produce vertical profiles of oxygen concentrations and animal distributions for comparison with profiles from Monterey Canyon. The characteristic oxygen minimum zone (OMZ) of the eastern North Pacific is expanding in Monterey Bay; the OMZ in Astoria Canyon has already expanded. Because the midwater fauna of the two regions are similar, a natural experiment has been created that gives a glimpse of what the future holds for Monterey Bay.

In addition to mapping the vertical distribution of midwater animals, specimens of selected Astoria species were collected for oxygen consumption measurements. Lab-based respirometry provided a measure of the animals' metabolism, and their physiological responses to environmental stressors like low oxygen. By comparing these measurements with those of species from Monterey Bay, physiological thresholds may be detected. When combined with the profile data, they may help explain how these animals respond to a changing habitat.

The ROV dives typically lasted 12 hours and provided data to supplement several ongoing Monterey Canyon studies of the same species. Dive profiles ranged from 1,100 meters to 2,800 meters deep, encompassing the water column from 200 meters depth to the seafloor at the selected locations. Four of the dives were made at sites occupied during the 2006 MBARI expedition. Bruce Robison's midwater team is statistically comparing the data from the 2006 and 2009 Astoria dives with a comparable set of seven dives made to 3,500 meters depth off Monterey in 2006.

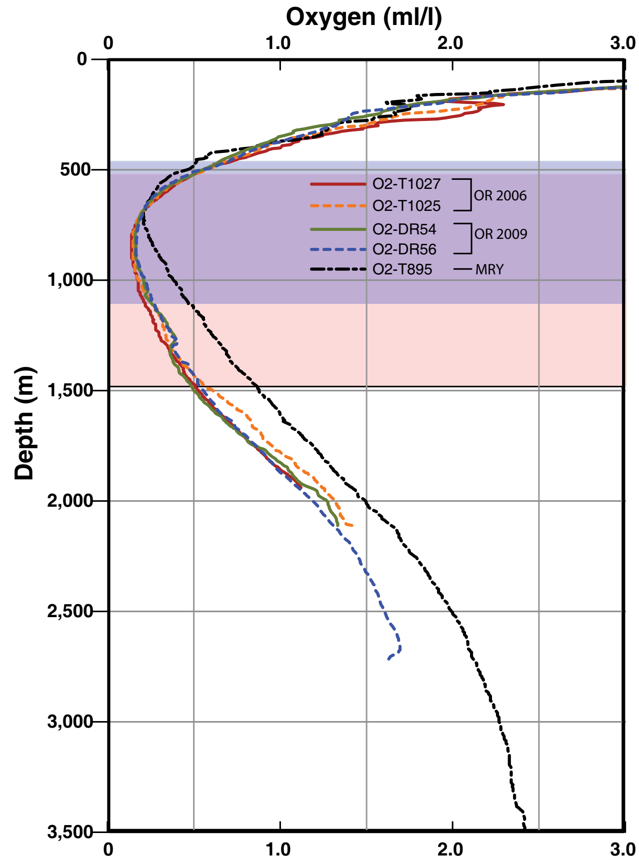


Figure 9: Oxygen profiles of the water column off the Oregon coast compared with Monterey Bay. The broad oxygen minimum zone (OMZ), where oxygen values are less than 0.5 milliliters per liter, extends approximately 500 meters deeper in waters off Oregon. Dive sites are focused along the Astoria Canyon. Data codes: OR = Oregon, MRY = Monterey, T = ROV *Tiburon*, DR = ROV *Doc Ricketts*.

Astoria's OMZ is more vertically extensive than the one in Monterey Bay. While the top of the OMZ (with 0.5 milliliters of oxygen per liter of seawater) occurs at about 500 meters in both regions, the core (with even lower oxygen levels) is deeper by 110 meters in Astoria, and the lower limit (also 0.5 milliliters of oxygen per liter) was 370 meters deeper than in Monterey Bay (Figure 9). One expectation is that the principal effects of an expanded OMZ would be observed in deeper-living species.

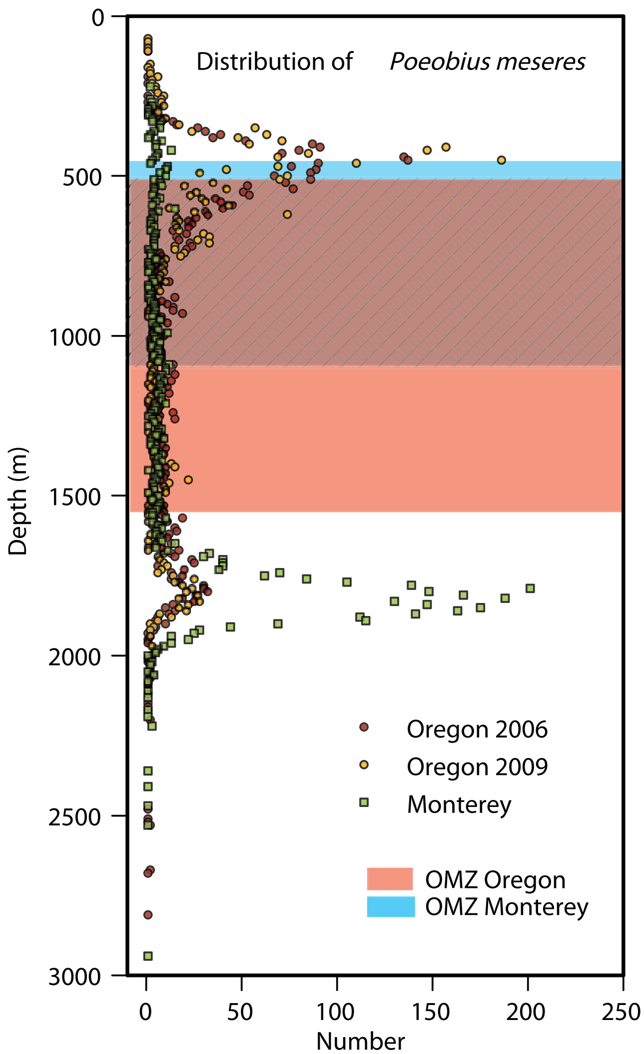


Figure 10: The depth distribution of the polychaete, *Poeobius meseres* during dives made off Oregon in 2006 and 2009, and off Monterey in 2006. Off Oregon, *P. meseres* were more numerous above the oxygen minimum zone (OMZ). In the Monterey dive series the worms were centered at 1,800 meters, well below the OMZ. The broader OMZ off Oregon may be a more effective barrier limiting the distribution of most *Poeobius* there. Data are meant to show the vertical distribution of *P. meseres* and have not been normalized for time spent at depth.

Midwater Ecology Expedition

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Rob Sherlock
Collaborators: Stephanie Bush, University of California, Berkeley; George I. Matsumoto, MBARI

Some interesting patterns are emerging from the comparisons of the two regions; several species show deeper centers of abundance, and deeper overall ranges in Monterey Bay than off Astoria. Conversely, and predictably, fewer species range as deeply where the OMZ is broader. For example, the polychaete worm *Poeobius meseres* was most abundant at about 450 meters deep in Astoria Canyon, just above the top of the OMZ. In the Monterey Canyon dives, *Poeobius* abundance peaked at 1,800 meters, well below the OMZ's lower extent (Figure 10).

Significant differences are evident in the vertical distributions and abundance patterns of some species common to both regions, but the underlying links to specific environmental factors remain unclear. Other discoveries during the expedition included confirmation that a new, undescribed family of nudibranchs deposit eggs on the seafloor, evidence of undescribed chromatophores and radical changes in the pigmentation of bathylagid fishes (deep-sea smelts), and noteworthy squid behavior.

How icebergs feed Antarctic ocean life

No areas of the world are more influenced by climate change than the polar regions. In Antarctica, there have been substantial losses in ice mass over the past decade particularly around the Antarctic Peninsula, which represents the most northward extension of the continent. Regional warming around the Antarctic Peninsula has resulted in retreating glaciers and the breakup of large ice shelves generating more icebergs.

Floating islands of ice range in size from "growlers" and "bergy bits" (less than 15 meters in their largest dimension) up to very large tabular icebergs that can exceed 300 kilometers in length. The majority of icebergs have been estimated to range from 60 to 2,200 meters in length, with thicknesses that vary between 150 and 550 meters. Icebergs fragment and become smaller with age due to evaporation, melting, wave-induced erosion, and fracturing. The highest concentration of icebergs occurs in the Weddell Sea (Figure 11) and travel in a clockwise, northerly route, dubbed "Iceberg Alley", that parallels the Antarctic Peninsula. The Coriolis force entrains icebergs from many geographic sources in the counterclockwise flow of the coastal current around Antarctica, although this flow is diverted by topographic features such as those along the eastern side of the Antarctic Peninsula. The movement of icebergs depends on topography and seasonal pack ice: grounded

Figure 11: Satellite tracks of icebergs around the Antarctic continent and reaching the northwest Weddell Sea and "Iceberg Alley".

icebergs are geographically stationary because they are in contact with the seafloor, constrained icebergs are generally free-floating but surrounded by seasonal pack ice, and free-drifting icebergs are unrestrained. Studies presented here were restricted to free-drifting icebergs in open water since they can most effectively be sampled without the added complications of the pack ice or the seafloor.

Little was known about the impact of free-drifting icebergs on the surrounding pelagic environment until several years ago. Increased concentrations of iron and chlorophyll-a were measured in the wake of a drifting iceberg. The density of acoustically-reflective targets, believed to be zooplankton and micronekton, were twice as high under a free-drifting iceberg compared to the surrounding open water. Aggregations of top predators such as seabirds and fur seals were commonly observed associated with Antarctic icebergs.

Given the increasing frequency of icebergs in the Southern Ocean and the paucity of data concerning their impact on the surrounding water, three MBARI engineers and 10 scientists from MBARI and other institutions across the U.S. undertook a National Science Foundation project to study the impact of free-drifting icebergs on the local pelagic communities. Preliminary field studies showed that icebergs could substantially influence the pelagic ecosystem of the Southern Ocean, serving as hot spots of chemical and biological enrichment (Figure 12). The study was expanded to examine the importance of iceberg hotspots as natural sources of iron fertilization and pelagic ecosystem alteration. This second field study was conducted on two cruises, the last in March and April 2009, to measure the influence of the nutrient concentrations on the pelagic community production and export of organic carbon to the deep ocean. The reasoning was that proliferation of icebergs could be very important in promoting the drawdown of carbon dioxide by enhanced primary production. This enhanced production would promote higher pelagic fauna abundance leading to organic carbon export and sequestration in the deep ocean.

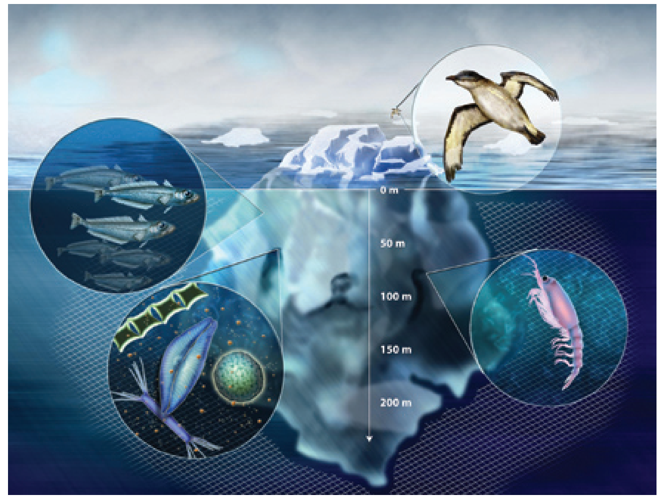


Figure 12: Icebergs hold trapped terrestrial material, which they release far out at sea as they melt. Scientists have discovered that this process produces a "halo effect" with significantly increased nutrients, chlorophyll and krill out to a radius of more than 3 kilometers (2 miles) from the iceberg.

A variety of instruments were employed to study these icebergs. A small ROV with a 600-meter tether was deployed to survey the submerged sides of each iceberg. Video cameras on the ROV provided images of the pelagic fauna in close proximity to the iceberg and the algal community attached to the underside of the ice. The ROV was also equipped with a conductivity-temperature-density (CTD) sensor, a fluorometer, a sequential plankton sampler, a water sampler, and sonar. It had the additional capability of pumping large volumes of water back to the ship for lab studies on trace elements, radioisotopes, and microorganisms. A collection net was fastened to the ROV to sample algal communities attached to the ice. A sonar system mounted on a rigid pole from the side of the ship was used to map the underside of the iceberg. A small remotely controlled airplane was

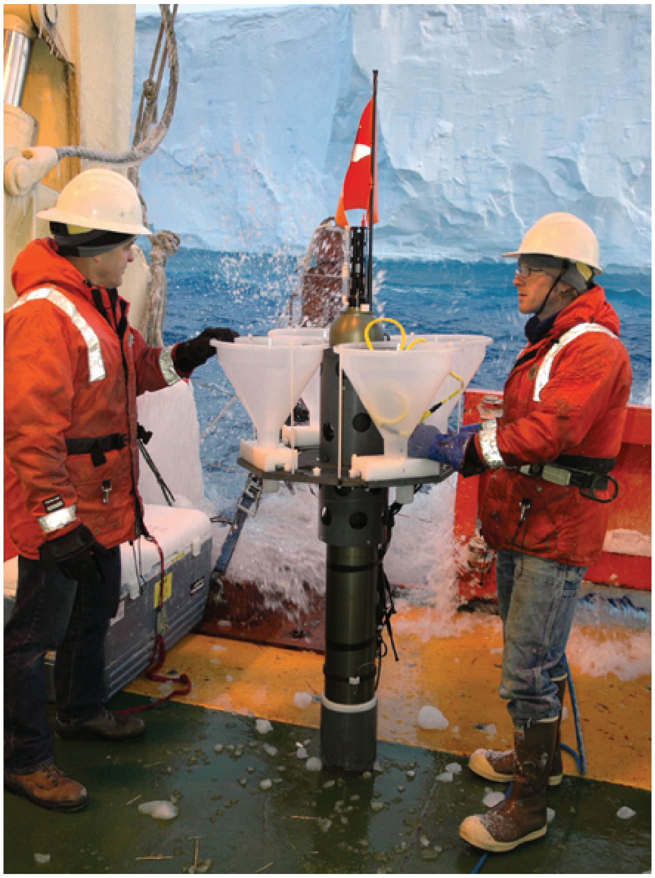


Figure 13: MBARI engineer Brett Hobson, left, and Raytheon Polar Services marine technician Joe Talbert ready the Lagrangian sediment trap for deployment off the Icebreaker *Nathaniel B. Palmer.*

deployed to conduct video surveys of the top of the tabular icebergs and to drop global positioning system (GPS) tags as navigational aids for tracking the icebergs. Lagrangian sediment traps, developed at MBARI, were deployed to depths of 600 meters and drifted under the iceberg to collect sinking particulate matter as a measure of carbon export (Figure 13). Other instrumentation used on this cruise included phytoplankton nets, a CTD rosette, and a large multiple opening-and-closing trawl system for the collection of zooplankton and micronekton.

The 2009 cruise began with the study of a large tabular iceberg, C-18A, which calved off the Ross Ice Shelf in 2003. The iceberg was tracked by satellite as it circumnavigated counterclockwise around the Antarctic continent in the coastal current, reaching the northwest Weddell Sea and drifting north through "Iceberg Alley" (Figure 11). C-18A was measured (32 kilometers long and 6 kilometers wide) as the ship circumnavigated it and was sampled intensively for 19 days.

The data from this cruise and the two earlier cruises are currently being analyzed and will be published in a special volume of *Deep-Sea Research* in 2010. This special iceberg volume will consist of 26 papers ranging in topics from the physical structure of icebergs and the pelagic community in the surrounding waters, to the export of organic carbon from the area of iceberg enhancement to the deep ocean. As always, research leads to more unanswered questions, and these studies of free-drifting Antarctic icebergs are no exception. The origin of icebergs either from glaciers or ice shelves, has a major impact on the land-derived deposits entrained in the ice and their ultimate influence on enriching the surrounding waters as the icebergs melt and drift on a final northward trajectory. Naturally, sunlight available for phytoplankton growth depends on the time of year when these studies were conducted. Even within the constraints of all these variables, there is a consistent pattern of increased concentrations of nutrients and pelagic fauna associated with icebergs. The chemical and biological enrichment around icebergs combined with their proliferation in the Southern Ocean must be considered in any predictive global models of the carbon cycle.

Antarctic Icebergs

Project lead: Ken Smith
Project managers: Bruce Robison, Alana Sherman, Ken Smith
Project team: Larry Bird, Craig Dawe, Jake Ellena, Steve Etchemendy, Brett Hobson, Paul McGill, Kim Reisenbichler, Steve Rock, Rob Sherlock
Collaborators: John Helly, University of California, San Diego; Ron Kaufmann, University of San Diego, California; David Long, Brigham Young University, Salt Lake City, Utah; Alison Murray, Desert Research Institute, Reno, Nevada; Tim Shaw, University of South Carolina, Columbia; Ben Twining, Bigelow Laboratory for Ocean Sciences, West Boothbay Harbor, Maine; Maria Vernet, Scripps Institution of Oceanography, La Jolla, California

Lagrangian Sediment Traps

Project leads: Brett Hobson, Alana Sherman, Ken Smith
Project manager: Brett Hobson
Project team: Paul McGill

A submarine eruption on the Northeast Lau Spreading Center: A rapid response effort

While most ocean expeditions are planned well in advance, scientists try to deploy rapidly when an unusual event is detected in progress. In May 2009, MBARI volcanologist David Clague and his team were given the rare opportunity to observe a volcano erupting in the deep sea. This provided the chance for the researchers to confirm their ideas about how such eruptions behave. Until this expedition, most volcanologists had been limited to interpretations based on lava flows and deposits that sometimes erupted thousands to millions of years ago. Deep submarine eruptions have only been detected a few times, and only Northwest Rota-1, a volcano in the Marianas Arc, had been observed in action, so this opportunity was highly unusual and very exciting.

Chemical signatures were detected in the water column in November 2008 that indicated active eruptions at two places in the Lau Basin, at West Mata Volcano and at a site 65 kilometers away at the Northeast Lau Spreading Center (NELSC). This Lau rapid response expedition was primarily funded by the National Science Foundation and the National Oceanic and Atmospheric Administration. The cruise combined ROV *Jason II*, MBARI mapping AUV *D. Allan B.*, and conductivity-temperature-depth (CTD) measurements. The field program was highly multidisciplinary, focusing primarily on water chemistry and microbiology, but included experts in biology, geology, petrology, and volcanology.

The team set sail in May to the Lau Basin on the R/V *Thompson* to map, observe, and collect samples of the active eruptions. The NELSC eruption had ceased, but at West Mata Volcano, two active volcanic vents were found near the summit. MBARI's team deployed the mapping AUV to collect high-resolution seafloor mapping data to understand the geologic setting, and used the ROV to assess the physical volcanology of the active and recent eruptions.

A single 17-hour AUV mission along 77 kilometers of trackline mapped the NELSC. The NELSC spreading segment is about 10 kilometers long, and the depth of the axis ranges from about 1,500 meters to 1,800 meters. The segment consists of five distinct subsegments delineated by major changes in morphology and subtle changes in trend. The morphology varied from a narrow ridge in the north, to a wide flat plateau, to a line of discrete pillow mounds on a wide dome-shaped ridge, and finally to a nearly conical volcano in the south that shoals to 1,520 meters at the summit. This volcano had a pair of well-developed rift zones extending from the summit along the axis of spreading. Across the axis, the slope and texture was consistent with being a steep apron of loose sand and gravel of volcanic glass. A number of inward-facing fault scarps cut the flanks of the volcano parallel to the axis of spreading, suggesting recent extension or the early stages of caldera formation.

Two more 17-hour AUV missions surveyed the actively erupting West Mata Volcano, providing almost complete coverage of the summit region and the primary rift zones.

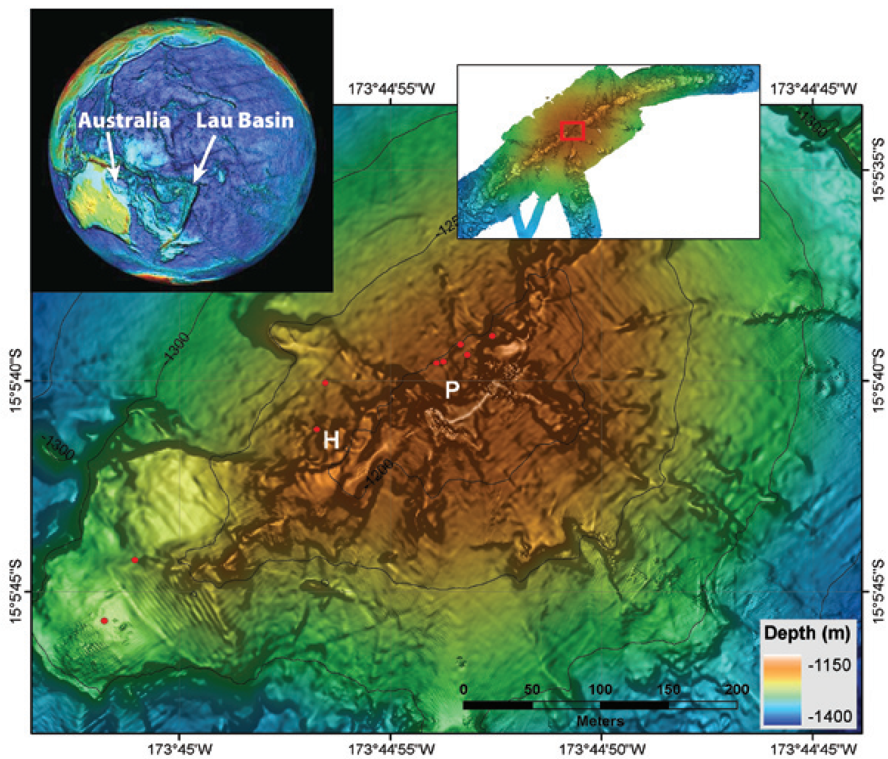


Figure 14: High-resolution bathymetry of the summit region of West Mata Volcano. The H and P mark the approximate locations of the Hades and Prometheus vents that were active in May 2009. The red dots indicate the sample locations of fragmental volcanic debris collected by the *Jason II*. Additional samples were collected outside the summit region, but still on the portions of the volcano mapped by the *D. Allan B.* shown in the inset. The red box shows the location of the enlarged summit map.

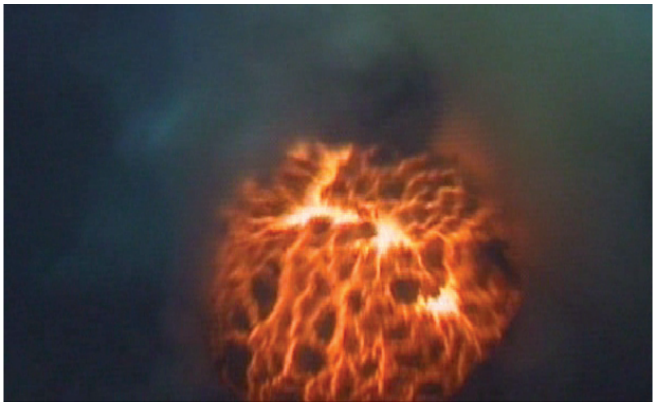


Figure 15: Video frame grab from ROV *Jason II* showing Strombolian bubble-burst activity at 1,194 meters depth on West Mata Volcano in the northern Lau Basin. The bubble has just stretched to the point that the lava skin was starting to split open to release the enclosed magmatic gas bubble. The bubble was roughly 0.5 meter in diameter.

West Mata is a nearly conical volcano that rises to a depth of 1,200 meters. The summit is a 60-meter-long, five-meter-wide ridge bounded by curved steep walls on both sides. The two active volcanic vents were on the upper rim of the northern wall, about five meters below the summit crest. The volcano's three rift zones were covered by thick lobate lava flows, a few of which had collapse features. The flanks of the volcano were mostly smooth slopes of loose volcanic sand and gravel debris, in a few places capped by lava flows cascading down from the rift zones.

The AUV maps provided the spatial framework for understanding the ROV observations of the volcanoes. Two active vents were found near the summit of West Mata. Clague's group named them Hades and Prometheus, and visited them several times with the ROV (Figure 14). The Prometheus vent erupted with fire fountains during each visit. A dense rain of glassy particles fell from the smoke-like plume of gas. Rock fragments (clasts) that fell near the vent were pulled back into the vent by water flowing in to replace that in the rising plume; these clasts were rounded like beach cobbles from being recycled numerous times. The Hades vent activity varied among passive degassing of fumes, low fire fountains, and Strombolian activity (vigorous expulsions of incandescent gas that blew large lava bubbles). When the bubbles burst, abundant spatter and thin, glassy, delicate, and intricately folded volcanic glass threads called "limu o Pele" and "Pele's hairs" were produced. This is the same type of material the MBARI team had found at other deep-sea eruption sites around the world, and confirmed their interpretation that the particles form from mildly explosive eruptions.

The eruptive behavior at these vents appears to be primarily related to magma supply or rise rates, with vigor probably varying due to depth in the conduit where fragmentation takes place. Passive degassing occurs when the eruption stagnates and gases escape from the magma deep in the conduit. Fire fountains result at higher lava rise rates, when degassing and magmatic gas bubble formation occur in the shallow part of the conduit, fragmenting the lava into pieces that are ejected during the eruption. Strombolian bubble-burst activity (Figure 15), generating spatter and accompanied by extrusion of pillow lavas, occurs at intermediate lava rise rates that allow some of the magmatic gas bubbles to coalesce in the shallow conduit.

Geochemical analysis of the volcanic glass fragments from the two active vents at West Mata indicates that the eruption consists of boninite lava, an unusual primitive type of lava that is high in silicon dioxide and erupts in the early stages of volcanic arc formation. Analysis of fragments more distant from the active vents indicates that much of the volcaniclastic debris mapped by the AUV on the surface is also boninite, although quite variable in composition. A sand sample from partway down the southwest rift contains a range of basalt compositions, derived from several eruptions. At the NELSC, the eruption in November 2008 produced a lava flow of fluid, bubble-rich basalt from the crest of the ridge axis that extends for about 1.9 kilometers. Much of the ridge and flanks are buried beneath deposits of glassy sands. Clague suspects these volcaniclastic deposits were produced, at least in part, during the November eruption, as the range of composition of the sands is small and close to that of the lava flow.

Collaborative Research: A Submarine Eruption on the Northeast Lau Spreading Center: A Rapid Response Effort

Project lead/manager: David Clague
Project team: David Caress, Doug Conlin, Hans Thomas, Duane Thompson
Collaborators: Robert Embley, Pacific Marine Environmental Laboratory, Newport, Oregon; Nicolle Keller and Adam Soule, Woods Hole Oceanographic Institution, Massachusetts; Peter Michael, University of Tulsa, Oklahoma; Joe Resing, University of Washington, Seattle; Ken Rubin, University of Hawaii at Manoa

Monterey Bay as a Window to the World

Local conditions provide insight to global changes. The ocean covers 71 percent of the earth and controls global climate and the biogeochemical cycling of materials. Within the world ocean there are a handful of sites, among them Monterey Bay, where scientists have developed detailed understanding of the connections between physical, chemical, biological, and geological processes. The study of these particular sites complements globally distributed observations made by satellites and in situ platforms which measure limited sets of variables. Monterey Bay's time-series sites, with focused instrumentation, observation, and experimentation, provide a natural laboratory where biogeochemical cycling and ecosystem processes can be examined in detail and technology development and teaching can be accelerated. The processes studied in Monterey Bay are also at work across the North Pacific and even globally so that what is learned at relatively small scales can be used to interpret and eventually predict larger scale dynamics. In a similar manner the dissemination of technology developed at MBARI and the education of young researchers here position Monterey Bay as a window to the world.

Monterey Bay and global climate

Combining observations from drifters, moorings, ships, submarines, satellites and computer models, MBARI's Biological Ocean Group, led by Francisco Chavez, has documented climate fluctuations and trends on seasonal, interannual, and multidecadal timescales.

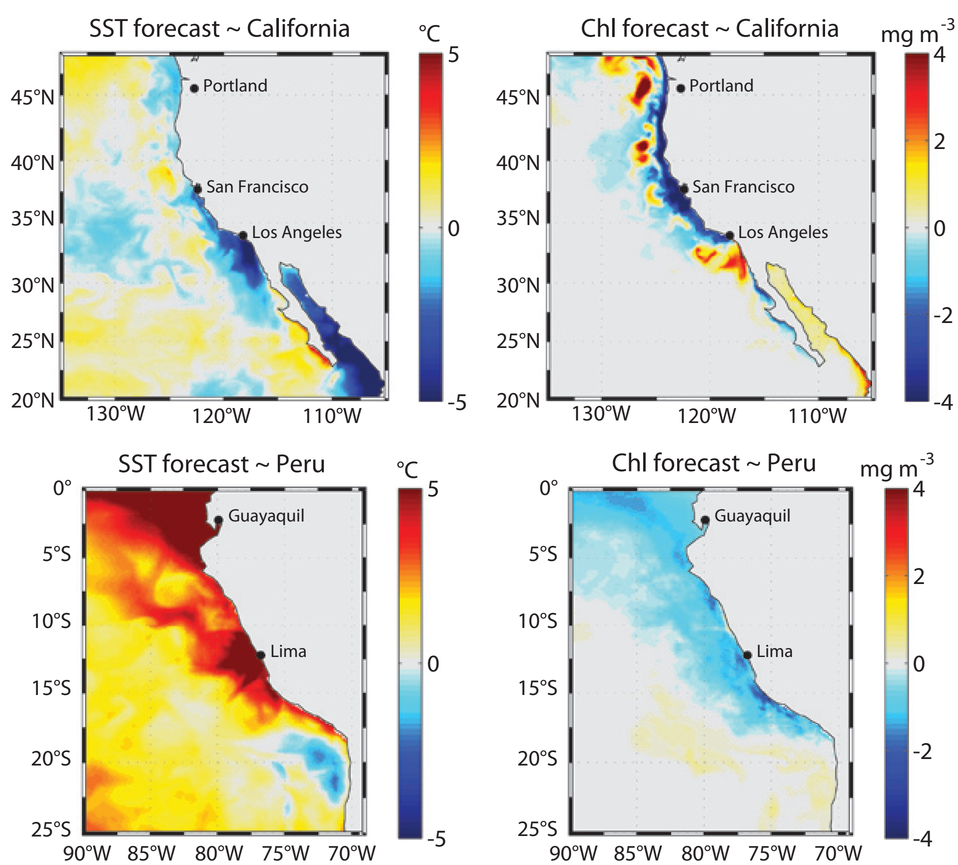


Figure 16: Recent advances in observing systems, computational power and understanding of ecosystem function offer credible evidence that the variability of the ocean ecosystem and its impact on fishery yield can be forecast accurately and with enough lead time to be useful to society. The images show forecasts for May 2010 made in December 2009 of sea surface temperature (SST) and chlorophyll (Chl) for California and Peru. The forecasts are made with a basin-scale 12.5 kilometer numerical physical model with an embedded nutrient-phytoplankton-zooplankton ecosystem. These forecasts are used by resource managers of the Peruvian anchoveta to assign quotas for the year.

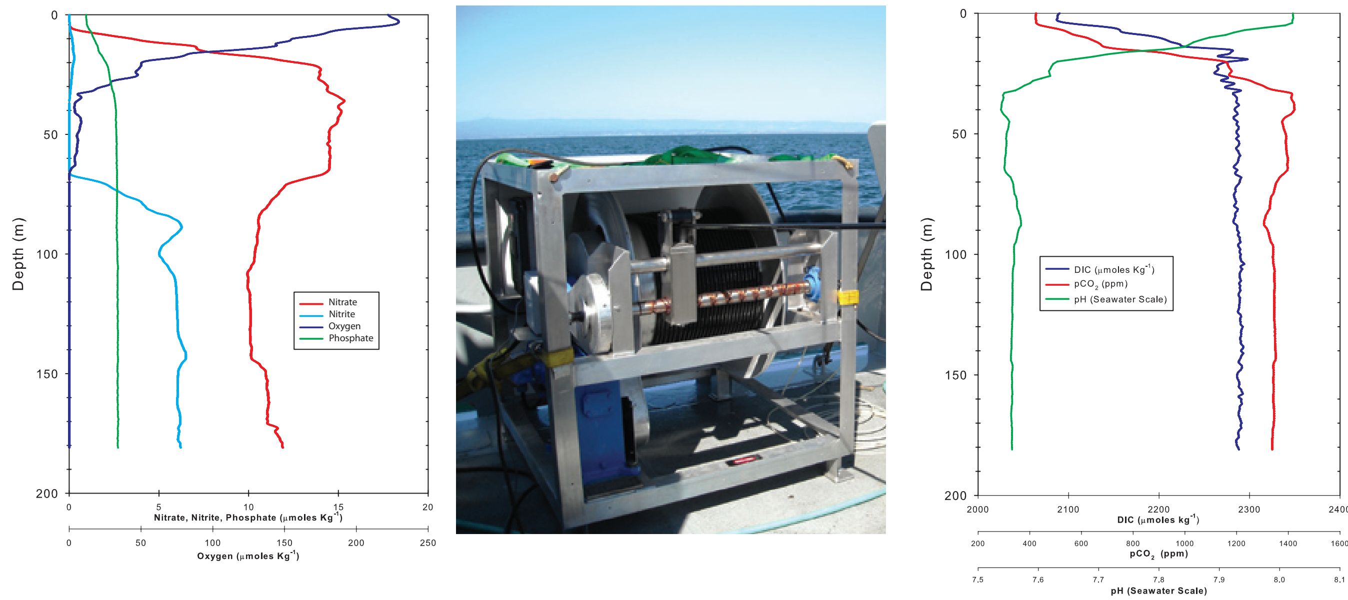


Figure 17: Anoxic zones of the eastern tropical Pacific contain a diverse and vibrant microbial community. A consortium of scientists from Chile, Denmark, and the United States are studying these communities and the chemical environment that they live in with the above profiling pumping system developed at MBARI. This system allows these communities to be studied at meter resolution, compared to the typical tens of meters possible with bottles on a rosette. High-resolution profiles of oxygen, nitrate, and nitrite collected with the pumping system off northern Chile are shown on the left. Similar profiles of pCO_2, total CO_2 (dissolved inorganic carbon, DIC), and pH are shown on the right.

Seasonal signals were fairly normal for Monterey Bay in 2009. Although local summer upwelling was weak, the thermocline layer separating the warmer surface from the cold depths remained shallow and sea surface temperature stayed fairly cool with high nutrient levels. Phytoplankton biomass and growth were close to normal in spite of the nutrient availability, until September when strong phytoplankton blooms developed.

During summer, the popular press reported a moderate-strength El Niño developing along the equator. However, its effects in Monterey Bay were not notable through December 2009, with near-normal seasonal rainfall totals and slightly warm sea temperatures mid-bay through the end of the year. This normalcy may end, however, if El Niño shifts the north Pacific storm track southward to produce a wet, late winter with delayed transition to spring upwelling, particularly in southern California. El Niño did not affect phytoplankton in Monterey Bay in 2009, but model results (Figure 16) predict a delayed transition to spring upwelling along much of western North America. The forecasting capability was developed as part of a collaborative project which uses National Aeronautics and Space Administration (NASA) satellite data and model solutions for practical projects, in this case for natural resource management of central California Chinook salmon and Peruvian anchoveta, the largest fishery in the world.

Monterey Bay and much of the California Current System has been strikingly cold, nutrient-rich, and biologically productive for the past 11 years, though this cool period has been interrupted by several weak-to-moderate strength El Niño events. The cool pattern is apparently driven by normal decade-scale climate fluctuations, and has a strong effect on fisheries species including sardines, rockfish, and salmon, perhaps due to its multiyear persistence and widespread occurrence. A cascade of effects associated with the cool period has been observed: increased phytoplankton production followed by sinking and decay, and consequent depletion of subsurface oxygen. Perhaps as part of this cascade, Monterey Bay has been invaded by the jumbo squid, *Dosidicus gigas*, a fish predator tolerant of low-oxygen waters and normally found in tropical to subtropical habitats.

Is the low oxygen driven by global warming? It is possible. Oxygen levels off the North American coast are not only reduced by local phytoplankton sinking and decay, as mentioned above, but also by low-oxygen waters carried northwards from the eastern tropical Pacific by way of the California Undercurrent. However there is tantalizing new

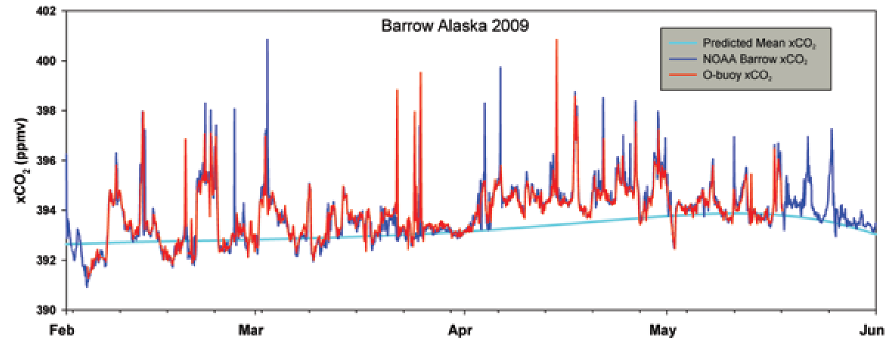


Figure 18: New developments in instrumentation, power management, and instrumentation control have now made long-term measurements possible in the harsh Arctic environment. This is one of a series of buoys deployed throughout the Arctic by scientists from Canada and the United States. The buoys contain MBARI-developed pCO_2 sensors that have been optimized to make very precise measurements in the atmosphere. The graph shows the excellent comparison of measurements made in one of these buoys with those made operationally by NOAA in a controlled laboratory environment in Barrow, Alaska.

evidence that subsurface oxygen levels across the entire north Pacific subtropical gyre are declining so that waters carried southward in the California Current are also lower in oxygen. If so, what is driving such a change—could it be global-warming-driven stratification that reduces atmospheric ventilation or a combination of natural changes in ocean circulation?

Regardless of the source of low-oxygen water, the consequences of this phenomenon are extremely important. The subsurface waters off Peru and northern Chile have been permanently anoxic for centuries and may reveal the prospects for other parts of the globe, including the U.S. west coast in the not so distant future. A vertical profiling system built by Gernot Friederich and Francisco Chavez has been used recently off northern Chile to provide the first-ever high resolution vertical profiles of microbes and total carbon dioxide (CO_2), pCO_2, and pH in those permanently anoxic zones (Figure 17). The system is able to collect water that is much lower in oxygen than that collected by conventional devices so that scientists can accurately assess biological dynamics in those regions.

Another consequence of phytoplankton decay and oxygen consumption is the increased remineralization of nutrients including carbon. This means that levels of nutrients and inorganic carbon in upwelled water off California are increasing and the upwelled waters are more acidic. A second source of surface acidification in California coastal waters is driven by the slow diffusion of atmospheric CO_2, a topic of increased concern. MBARI has been studying surface ocean acidification with CO_2 instruments developed by Friederich and Chavez off California for many years. A commercial partner is now marketing the pCO_2 system for large mooring deployments in the global ocean, while MBARI is developing smaller systems. MBARI pCO_2 sensors are now deployed on coastal moorings off Mexico and another MBARI system is sending accurate measurements from the frozen Arctic Ocean (Figure 18).

Natural and Human-Induced Change in Monterey Bay and the California Current System

Project lead: Francisco Chavez
Project manager: Tim Pennington
Project team: Luke Beatman, Gernot Friederich, Monique Messié, Reiko Michisaki, Chris Wahl
Collaborators: Marguerite Blum and Baldo Marinovic, University of California, Santa Cruz; Curtis Collins, Naval Postgraduate School, Monterey, California

Forecasting Anchovy and Sardine Transitions

Project lead/manager: Francisco Chavez
Project team: Dorota Kolber, Monique Messié, Reiko Michisaki
Collaborators: Richard Barber, Duke University, Durham, North Carolina; Fei Chai, University of Maine, Orono; Yi Chao, Jet Propulsion Laboratory, Pasadena, California; Sam McClatchie, National Marine Fisheries Service, San Diego, California; Miguel Niquen, Instituto del Mar del Peru, Callao

Climate, carbon cycling, and deep-ocean ecosystems

Long time-series studies are also important for interpreting the influence of climate change on oceanic processes in the deep-sea. Atmospheric and upper-ocean warming have been documented over the past four decades. Global warming has been predicted to increase stratification while reducing vertical mixing and nutrient exchange from deeper depths resulting in reduced photosynthesis (primary production) and particulate organic carbon export to the deep sea.

Oceanic regions extending more than 2,000 meters deep occupy approximately 60 percent of the Earth's surface, but only a very small fraction of this area has ever been explored or sampled. Organisms occupying the vast expanses of the deep seafloor covered by sediment are ultimately fueled by organic matter produced through photosynthesis in surface waters. The general trend is a decrease in food supply with increasing depth in the ocean—an estimated five percent or less reaches abyssal depths. This minimal food supply sustains diverse biological communities.

With this perspective in mind, a time-series station (Station M) was established 20 years ago on the Monterey Deep-Sea Fan at a depth of approximately 4,100 meters. This station was chosen because of its relatively flat topography, soft silty-clay sediment and logistical convenience to several major ports along the California coast. More importantly, Station M lies beneath an area influenced by seasonal shifts in surface water production that provides the sinking flux of particulate organic carbon (food supply) into the deep ocean.

Station M consists of a long-term mooring holding two funnel-shaped sediment traps at 3,500 and 4,050 meter depths and a time-lapse camera on the seafloor at 4,100 meters. MBARI benthic ecologist Ken Smith and his group use this station to make time-series collections of the particulate matter that sinks to the benthic boundary layer and to photograph biological pro-

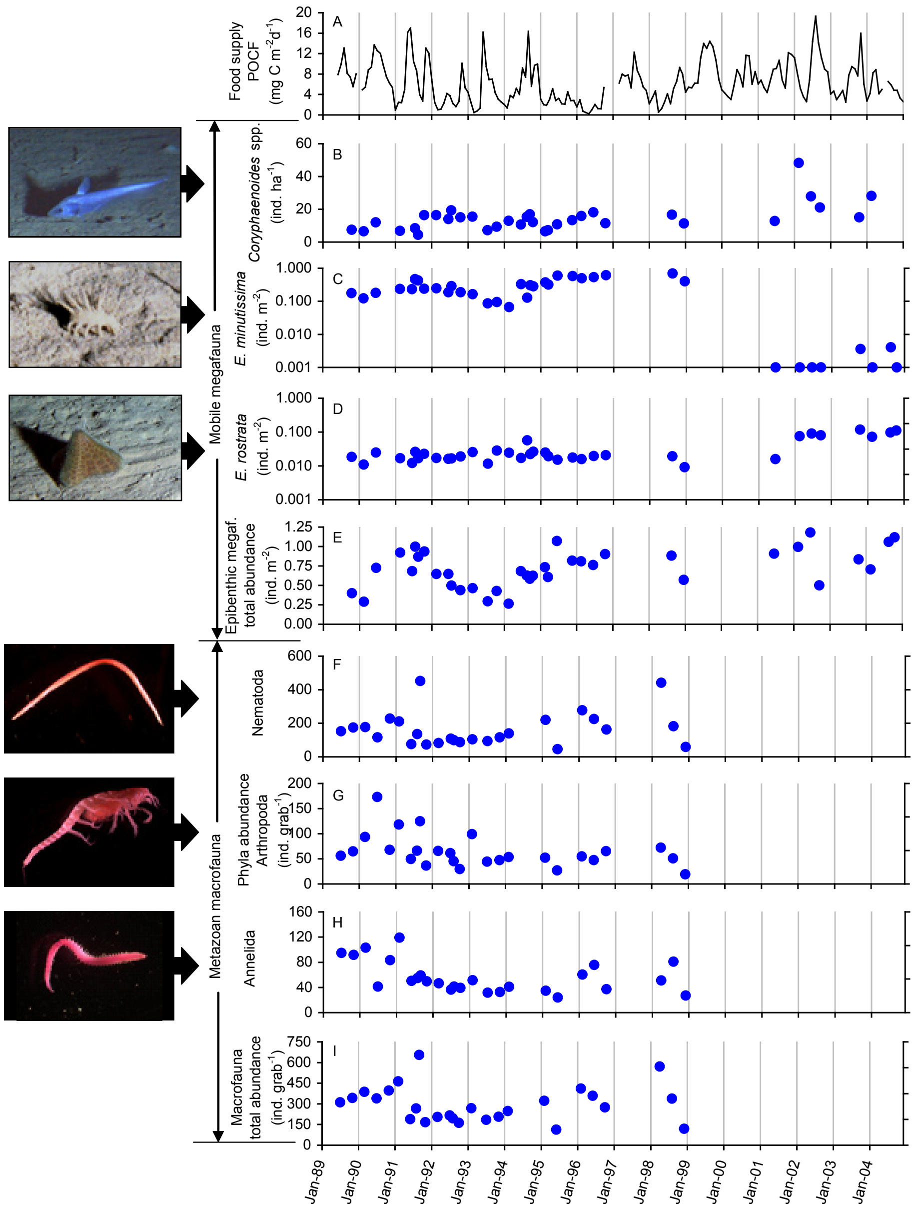


Figure 19: Variation in particulate organic carbon food supply (A) and changes in abundance and density of select mobile animals: grenadier fish (B), holothurians (C), echinoids (D), and total megafaunal abundance (E); and changes in abundance of smaller animals: nematodes (F), arthropods (G), annelid worms (H), and total macrofaunal abundance (I) at Station M in the Northeast Pacific between 1989 and 2004.

cesses on the seafloor. Estimates of food supply based on particulate organic carbon (POC) collected in the sediment traps significantly correlate to estimates of surface primary production from satellite data and to export flux of organic carbon from the sunlit zone. POC measured in the traps reflects the primary production detected at the surface one to two months earlier in the northeast Pacific. POC flux also significantly correlates with the Northern Oscillation index, a climate index for the Pacific Basin, which it follows by six months, and with the regional scale Bakun Upwelling index, which it follows by two to three months. These correlations indicate a strong relationship between the intensity of coastal upwelling that delivers nutrient-rich water for primary production and food supply to the abyss.

Smith's group determined that food supply sinking into the deep ocean is linked to the benthic community at Station M. The dominant fishes at Station M are two species of grenadiers, which feed on a combination of carrion from fishes from above and from seafloor animals. These fishes more than doubled in abundance over a period of 15 years. The large animals (megafauna) on the seafloor at Station M were dominated by echinoderms, particularly mobile holothurians (sea cucumbers) and echinoids (sea urchins). Two species of holothurians increased in abundance from 1989 through 1996 then decreased after 1998, by two to three orders of magnitude (Figure 19). In contrast, three other species of holothurians and one echinoid increased significantly in abundance after 2001. These shifts in megafauna abundance are significantly correlated to El Niño/La Niña events 14 to 18 months earlier.

Somewhat smaller animals (macrofauna) on the seafloor were dominated by nematode worms, crustaceans, and polychaete worms (Figure 19 F,G,H,I). Over a 10-year period, the macrofaunal abundance and biomass were significantly correlated to climate-related changes in food supply with lags of four months for abundance and eight months for biomass. The time lag from climate events to changes in abundance of these smaller animals was shorter than that found for the larger seafloor megafauna, suggesting a more rapid response by macrofauna.

Benthic communities respond readily to food supply with significant changes in community activity. The macrofauna in the sediment also showed changes in abundance and biomass that were significantly correlated to food supply. Using autonomous respiration chambers on the seafloor, Smith's group measured oxygen consumption by the sediment community as a way to estimate their food utilization. Seasonal fluctuation in the oxygen consumption is in relative synchrony with food supply (POC flux) at Station M, but a long-term discrepancy was recorded between food supply and utilization, with diminishing supply of particulate organic carbon to meet the consumption by the sediment community. Fluctuations in food supply driven by climate variation ultimately are linked to changes in benthic community structure and processes: higher food supply is significantly correlated with increased oxygen consumption on both seasonal and inter-annual time scales. The apparent discrepancy between food supply and benthic community utilization can possibly be reconciled by infrequent, episodic inputs of organic matter to the seafloor. Such events have been inadequately detected thus far but continuous measurements of oxygen consumption using the bottom transecting vehicle, Benthic Rover, recently developed at MBARI, will contribute significantly to resolving this discrepancy.

A similar influence of climate change on the deep-sea ecosystem such as that observed at Station M, is also apparent in the long time-series studies of the Porcupine Abyssal Plain in the northeast Atlantic Ocean. These two long-term sites in two major ocean basins show that deep-sea communities are strongly affected by climate variation. Station M has provided the first glimpse of how climate change will impact the vast deep-sea ecosystem, and, with the recent Atlantic corroboration a half-world away, serves as a "window to the world". One vision for the future is a worldwide network of long time-series observatories, including the polar regions, using a combination of government, private, and industry resources to monitor deep-sea community response to climate change on decadal scales.

Pelagic-Benthic Coupling and the Carbon Cycle

Project lead: Ken Smith
Project manager: Alana Sherman
Project team: Jake Ellena, Brett Hobson, Paul McGill, Mike Vardaro, Stephanie Wilson
Collaborators: Jeffrey Drazen, University of Hawaii, Honolulu; Ron Kaufmann, University of San Diego, California; Henry Ruhl, National Oceanography Centre, University of Southampton, United Kingdom; Ursula Witte, University of Aberdeen, United Kingdom

Cabled observatory put through the paces

In its first full year of operation the Monterey Accelerated Research System (MARS) has served as a successful test bed for seven ocean science and engineering projects. MARS is a deep-water cabled observatory test bed. Its unique capabilities have attracted interest from U.S. science and defense interests, as well as from international organizations. The observatory is managed by the MBARI Division of Marine Operations. With agreement from the National Science Foundation, which has funded MARS, the U.S. Defense Advanced Research Program Agency has listed MARS as a test bed for its Deep Sea Operations proposal program.

MARS is primarily a platform for testing equipment and control software, accelerating the development of software systems by providing real-time control of instruments deployed at depth. MARS also supports a long-term broadband seismometer providing data to the U.S. Geological Survey Northern California Seismic Network. Science and engineering projects that connected to the MARS cabled observatory during 2009 (and their sponsoring institutions) include:

- Conductivity, temperature, and depth sensors that test the efficacy of two MBARI technologies integral to development of a generic science instrument network interface—the Software Infrastructure and Applications for Monterey Ocean Observing System (SIAM) and PUCK, a plug-and-work protocol. (MBARI)
- The Eye-in-the-Sea (EITS), a deep-sea camera capable of producing images with extremely low ambient light. While deployed, links to EITS real-time video are available from the MARS website. EITS includes a novel jellyfish simulator that uses lights to mimic bioluminescence to attract predators to the site. (Ocean Research and Conservation Association)
- The Monterey Ocean Bottom Broadband (MOBB) seismometer, a three-component, broadband seismometer and the only permanent underwater seismometer west of the San Andreas Fault system. It is attached to MARS via a 3.5 kilometer cable laid by the MBARI remotely operated vehicle *Ventana* (Figure 20). (MBARI and the University of California, Berkeley)
- The Deep Echo-Integrating Marine Observatory System, an acoustic transmitter/receiver that quantifies fish and invertebrates from 900 meters to the sea surface. (University of Washington Fisheries Department)

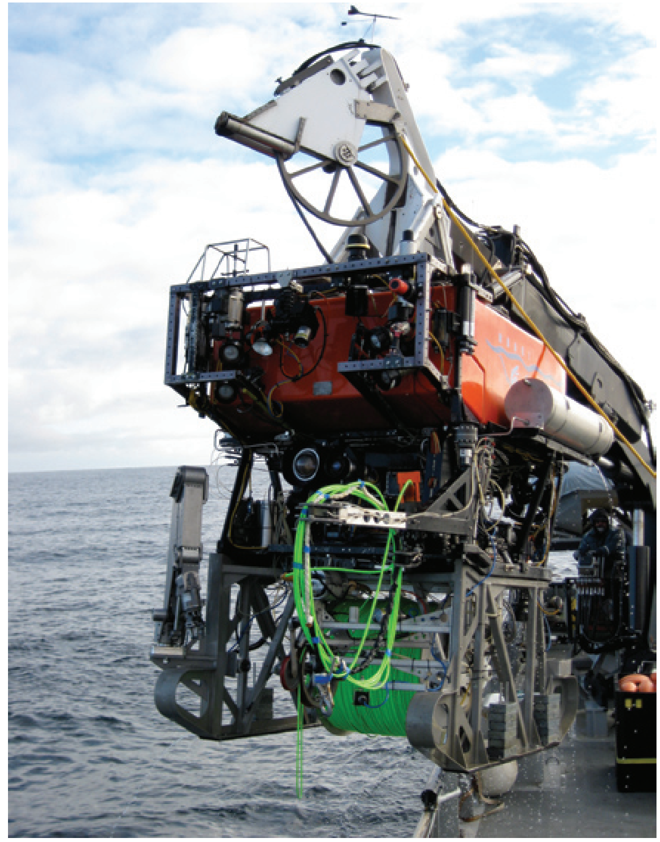


Figure 20: The ROV *Ventana* is launched carrying a reel that holds the 3.6 kilometer extension cable for the MOBB seismometer.

- The Free Ocean CO_2 Enrichment (FOCE) experiment, designed to study the effects of an increasingly acidic ocean on deep-sea biology. FOCE was perhaps the largest, but not the heaviest, instrument deployed on MARS. (MBARI)
- The Benthic Rover, an autonomous underwater vehicle that crawls across the seafloor. The Rover is outfitted with respirometers and cameras to study animals' oxygen consumption and seafloor ecology. (MBARI)
- The Deep Environmental Sample Processor, an autonomous molecular biology lab that can identify microbes and invertebrates in seawater. (MBARI/NASA)

Monterey Accelerated Research System Operations and Maintenance

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

Several new projects are scheduled for installation on MARS in 2010:

- The Acoustic Communications Base Station, a key component in the communications scheme for future observatories. It will be tested on MARS and is destined for use in the NSF-sponsored Ocean Observing Initiative. (Woods Hole Oceanographic Institution)
- A bottom pressure recorder (BPR) and precision tiltmeter, designed to monitor inflation or deflation in submarine volcanic areas caused by underground magma movements. The BPR's final destination is Axial Seamount, a tectonically active area on the margin of the Juan de Fuca plate. (National Oceanic and Atmospheric Administration)
- An ocean bottom seismometer, for the development of data management techniques. (OOI Cyberinfrastructure Group)

Opportunities for students and educators

Each summer MBARI invites a small group of teachers and college students from around the globe to Moss Landing for an intensive ten-week summer internship program exposing them to research, engineering, and science communication. For many of these student interns, the summer at MBARI has been a defining experience as they plan their careers.

"If it wasn't for the internship program, I wouldn't have the job that I have now and have had for the last 13 years," said Jenny de la Hoz, a member of the first intern class who now works at the Monterey Bay Aquarium. "I would have never thought of being an educator or coming to Monterey."

The focus of the MBARI internship is on the student intern's professional development and career options, learning research techniques, and improving communication and collaboration skills. For the educators who spend the summer as interns, the goal is to bring new information and perspectives to their classrooms. Each intern works with a designated mentor—49 MBARIans have served as mentors over the years—in his or her field of interest. Support from MBARI staff has been critical to the success of the program. Every year staff members propose more than 20 different projects for the applicants to consider. In addition to the primary mentors, many more members of the MBARI staff act as secondary mentors and are invigorated with the arrival of excited, eager students and educators who bring countless ideas to share.

Figure 21: Shawn Meredyck, a 2006 undergraduate intern from the University of New Brunswick, works on a benchtop simulation of part of the Environmental Sample Processor as part of his project on sandwich hybridizations and microarrays.

Figure 22: Alejandra Ortiz, a Wellesley College student, checks on her cultures of the microscopic algae *Micromonas*, which she studied during her 2008 MBARI summer internship.

Access to the day-to-day workings of an oceanographic research institute as well as to the longer term strategic planning provides our interns with a glimpse of what life will be like after graduation. The primary outcome for the program is that the interns will leave with a better understanding of their future options—beyond the field they were considering on their arrival at MBARI.

"I actually came out of the internship more confused about where my path was headed. The reason: exposure to so many different aspects of marine science and engineering that I had no idea existed. This is a good thing," commented one intern in the anonymous end-of-summer survey. Said another, "After the internship I was much more confident about becoming a professional engineer after college graduation."

The summer projects range from solving a complex engineering challenge to studying the ecology of deep-sea animals to producing an educational website (Figures 21 and 22). Interns also participate in weekly meetings to learn about each other's progress, attend educational seminars, participate in and host staff social events, go to sea on research expeditions, take field trips, and have opportunities to interact with the MBARI staff. The projects are written up in final papers, some of which have later been revised for publications in peer-reviewed journals. The summer culminates with a public symposium at which the interns present their summer projects. The most common complaint at the end of the program is that "ten weeks isn't long enough".

The interns are encouraged to meet with seminar speakers, visiting researchers, and members of the MBARI Board of Directors. They often share what they have learned about MBARI with others, speaking to visiting school groups or presenting MBARI research to the public at the institute's open house.

Since the program's inception in 1997, MBARI has hosted 171 interns representing 103 different academic institutions from 33 states and nine countries. The program has included a total of 105 undergraduate students, 58 graduate students, and eight educators. While MBARI education and research specialist George Matsumoto strives to include as many educators in the program as possible, it is the rare educator willing and able to give up the valuable summer break to participate.

Despite the varied backgrounds, countries of origin, and majors, the MBARI interns work together during the program, learning firsthand about the power of an integrated approach to ocean research and engineering. Often, interns working in different disciplines will help troubleshoot each other's problems. Many of the relationships they developed during the program continue for years.

MBARI Summer Internship Program
Project managers: Linda Kuhnz, George I. Matsumoto

Figure 23: Former MBARI intern AnnMarie Polsenberg Thomas, takes her engineering students at the University of Saint Thomas to a local gym to learn about the physics of circus performances.

It is heartening to follow the paths our interns take after their MBARI experiences. Three completed their graduate studies, then returned to MBARI for postdoctoral fellowships, four went to work for our sister organization, the Monterey Bay Aquarium, and many continue to collaborate with MBARI staff on various projects. Many MBARI interns are working in academia and industry and some have secured employment at MBARI. A sampling of the interns who are now scattered around the world include a staff geophysicist for Murphy Exploration and Production in Colorado, a geochemist at the University of Florida, an independent contractor for the National Oceanic and Atmospheric Administration, an assistant professor at the University of St. Thomas in Minnesota (Figure 23), a postdoctoral scholar at the Santa Barbara Coastal Long Term Ecological Research Network, the director of education at the Crichton Carbon Center in England, a program director for the Wildlife Conservation Society in Fiji, a professor at the University of Ulster (Ireland), and a chemistry teacher in Missouri. One intern went on to earn a law degree and is now practicing environmental law.

The outcome of MBARI's commitment of funds, time, and effort is valuable experience for the interns who go off to careers around the world, not only with fond memories and new friends, but with a better understanding of ocean research and engineering. And summers leave MBARI richer for the experience of working with enthusiastic and energetic interns.

On the Horizon

Research and development projects at MBARI are founded on the basis of merging science, engineering, and marine operations. These programs are led by a principal investigator and a supporting team, and are typically funded in three-year increments. Institutional initiatives were created as vehicles for undertaking complex problems that lie well beyond the traditional project cycle, and that require a larger team exceeding that of a single research group. Multiple research groups combine forces to solve particularly difficult problems that MBARI is uniquely positioned to address. Each initiative includes elements of ocean chemistry, biology, and ecology, and demands technology development. Each brings a unique perspective for understanding the ocean's natural cycles and the impacts humans are having on them. The three initiatives currently in progress span habitats from the sea surface to the deep seafloor:

- *The Ocean in a High CO_2 World*—An interdisciplinary study of how marine ecosystems respond to elevated carbon dioxide levels and increased acidity in the ocean.
- *The Controlled, Agile, and Novel Observing Network (CANON)*—A program to develop technology and sampling methods to remotely monitor oceanic conditions and study how microorganisms at the core of the food web react to changing climate conditions.
- *Biodiversity*—Currently in a feasibility stage, the immediate objective of this initiative is to develop a biodiversity baseline for the deep waters of Monterey Bay.

The Ocean in a High CO_2 World

Continued burning of fossil fuels will result in elevated CO_2 levels and a more acidic ocean. How marine ecosystems will respond to this change is not well understood. To better inform scientists as well as policy makers of what may lie ahead, a team led by Peter Brewer and Jim Barry is developing systems and methods for small-scale perturbation experiments in the laboratory and at sea to expose marine animals to the conditions that will likely represent the ocean of the late 21st century.

By tackling this topic as an MBARI initiative, a team of scientists and engineers have begun to identify and explore issues from an interdisciplinary perspective. As the team studied the changing ocean chemistry, the group gained a profound sense of unease as a multitude of poorly understood consequences arose. They have already detected two previously unanticipated effects of ocean acidification: changes in the absorption of sound and physiological limits to the higher forms of marine life.

An ocean more transparent to sound

In the 1970s ocean physicists first recognized that the absorption of sound varied in the ocean. The Pacific was more transparent to low frequency sound than the Atlantic. The absorption of sound in seawater varies with changes in the chemistry of the water itself and is strongly controlled by the acidity of the seawater. As sound moves through seawater, it causes groups of atoms to vibrate, absorbing sounds at specific frequencies.

As ocean pH declines, chemical changes occur in seawater, including a critical change in dissolved borate which, together with the carbon dioxide system, absorbs sound. MBARI researchers estimate that the sound absorption properties of the upper ocean have changed by 15 percent or more since pre-industrial times.

As we look to the future we find that pH changes of 0.3 or more are widely predicted based upon several of the well-recognized scenarios published by the Intergovernmental Panel on Climate Change. The MBARI team explored this phenomenon and found that it could lead to a noisier ocean

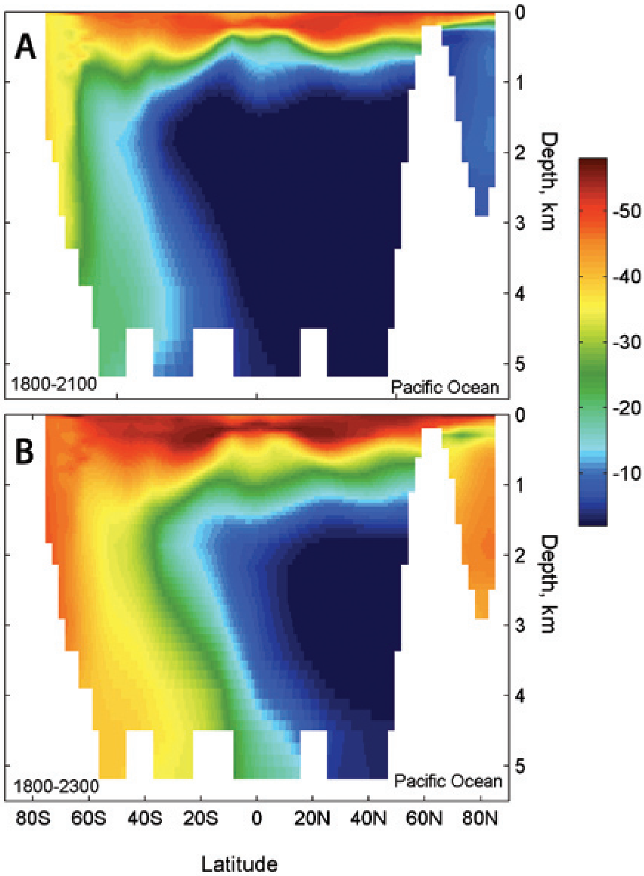


Figure 24: Changes in the spatial distribution of the sound absorption coefficient in the Pacific Ocean along 165 degrees West projected for the years 2100 (A) and 2300 (B).

with sound absorption changes of 40 percent or more by the end of this century. This range of sounds includes "low frequency" sounds used by marine mammals and underwater sounds generated by industrial and military activity, as well as by boats and ships.

Publication of these findings attracted worldwide interest. In subsequent work with colleagues at the University of Hawaii, the team used ocean numerical models to better predict the evolution of this unusual change in ocean properties in time and space (Figure 24).

Challenges to marine life

At the same time that ocean carbon dioxide is increasing, the oxygen content of seawater is decreasing due to climate change, reduced ventilation of the midwater, and eutrophication from excessive nutrients. The combined impact of these two trends is troubling. If for example humans were trapped in a submarine, they would begin to suffer significant stress if carbon dioxide levels rose to about two percent. Marine organisms—even deep-sea animals that are adapted to low-oxygen environments—have their limits as well, but what *are* those limits?

MBARI researchers Peter Brewer and Ed Peltzer developed a respiration index based on the log of the ratio of the partial pressures of oxygen and carbon dioxide. They explored the distribution of the index in the ocean and where the greatest challenges to marine life might occur in the future. At depths of a few hundred meters, a zone of low oxygen and high CO_2 waters occurs as a consequence of natural cycles, where changes can render these waters inhospitable to aerobic life. Their calculations indicate, and experiments confirm, that stress begins for a large number of animals when the ratio of oxygen to CO_2 is about ten to one, and at a ratio of about four to one, most higher animals cannot survive.

As ocean oxygen levels decline and CO_2 levels rise these conditions will be prevalent over very large areas of the Eastern Pacific and the Northern Indian Oceans. Areas where there is now abundant marine life will likely give way to dead zones in a region stretching from Chile to eastern Russia.

Figure 25 shows a sample calculation for an extreme station in the Pacific off Central America; at 500 meters depth the ratio of oxygen to CO_2 is already about one and considered a dead zone. Their projections for the future show that these conditions will greatly expand with troubling consequences for marine life.

Experiments on the seafloor

This research on the physiological limits to marine life showed that a critical property is the partial pressure of CO_2. While the partial pressure of CO_2 in surface ocean waters is close to equilibrium with the atmosphere at around 390 parts per million (ppm) today, waters at depth have far higher values—close to 1,000 ppm in the oxygen minimum zone, with the likelihood of doubling to more than 2,000 ppm in the future. Deep-sea waters are far less buffered against change than surface waters, and these future levels will present a challenge to marine life.

MBARI engineers and scientists have tackled this problem through the building of a Free Ocean CO_2 Enrichment (FOCE) system designed to allow CO_2 enrichment experiments on the seafloor. FOCE is essentially a flume, a boxed water channel that is set on the seafloor and attached to the

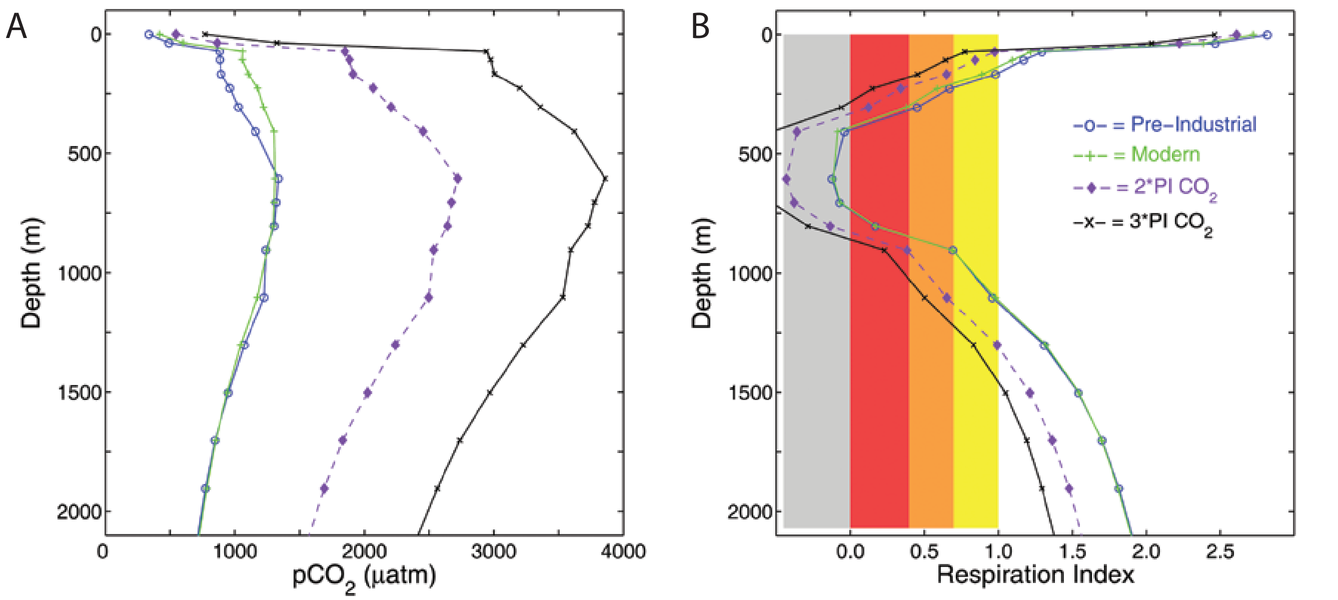


Figure 25: Rise in partial pressure predicted as the ocean equilibrates with the higher levels of atmospheric CO_2 and its predicted effect on marine organisms' aerobic respiration. A) Oceanic partial pressure of CO_2 in the eastern tropical Pacific as a function of depth at four levels: pre-industrial atmospheric CO_2 level; modern level (late 20th century); twice pre-industrial level, and three times pre-industrial level. B) Calculated respiration indices (RI) with depth show decline in marine aerobic respiration with increasing partial pressure of CO_2. Gray indicates dead zone for aerobic life (RI ≈ 0); red band (RI = 0.0 to 0.4) where aerobic respiration is generally not observed; orange band (RI = 0.4 to 0.7) the limit for bacterial respiration; and yellow band (RI = 1 or slightly less) tolerable level for some marine animals.

cable of the MARS observatory, which provides power and communications. The system allows a scientist to adjust the CO_2 in seawater flowing through the box so as to examine the impacts on marine life. As the world's first test of such a system, it may be replicated by others worldwide if proven successful. MBARI engineers have already taken part in a similar effort on the Great Barrier Reef.

CO_2 enrichment experiments on land have been deployed for over 20 years, but no equivalent ocean experiments have yet been attempted. The challenge is large. The MBARI team quickly recognized that it is impossible to do a perfect experiment, and that it is very easy to carry out a bad experiment. They needed to design an optimal system for such complexities as the slow reaction rate of CO_2 added to seawater and the variable flow through the experimental chamber. Also to be factored in were the challenges of an array of pH sensors, a cable/data system that is still very new, and the need to provide real-time feedback and control on a 24-hour basis to maintain the desired offset in CO_2 system conditions.

The engineering team created an elegant system of thrusters to control flow, matched to the pH signals received, thus allowing for feedback and maintenance of the desired chemical conditions. The experimental box has two long arms through which enriched water must flow before reaching the experimental chamber, allowing time for the essential chemical reactions to occur.

A major problem was the delivery of a sufficient quantity of CO_2 to allow experiments of reasonable duration. On land scientists have large tanker trucks deliver many tons of material but that option was not available for ocean

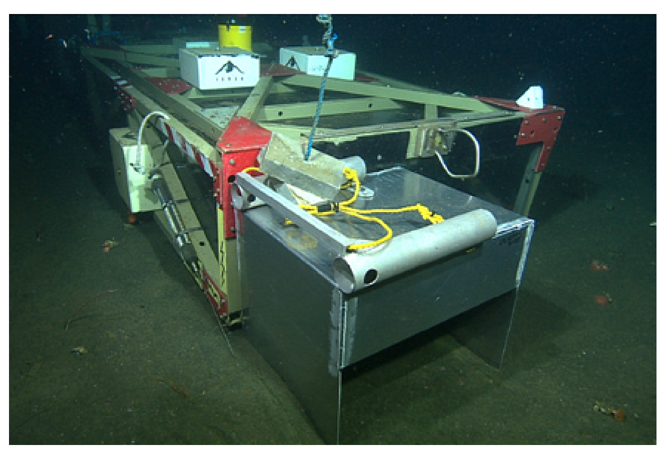


Figure 26: Aluminum box at end of FOCE flume for enriching seawater with CO_2.

studies. The researchers re-used a technique they first published five years ago in which a simple upside-down box traps liquid CO_2 delivered by MBARI's remotely operated vehicle *Ventana* (Figure 26). The exposed liquid CO_2-seawater interface then slowly dissolves, delivering low pH-high CO_2 water to the FOCE system.

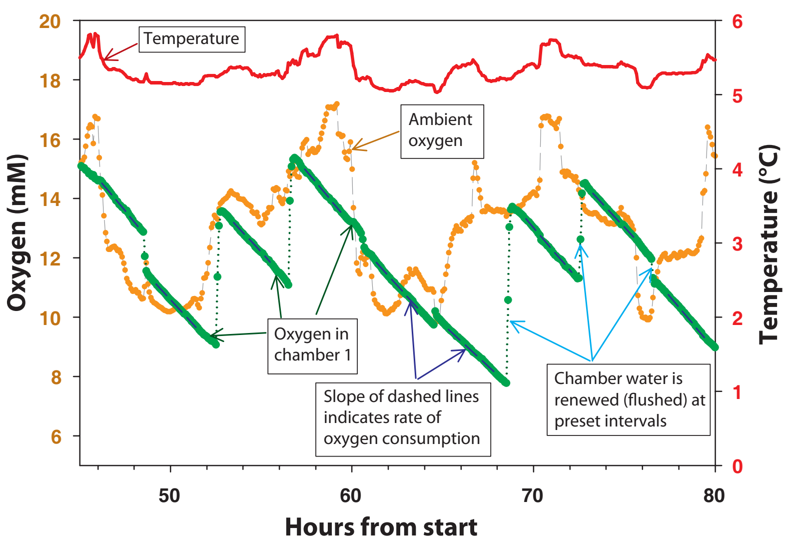
Their first efforts showed that realistic week-long experiments could be carried out efficiently, but that better control was required on the leakage rate of the CO_2. That final step is now being undertaken.

In situ CO_2 enrichment experiments

To test the impact of increased ocean acidity on deep-sea animals, the benthic and midwater research labs headed by Jim Barry and Bruce Robison, in conjunction with a team of engineers, are developing in situ respiration chamber systems for studies of animal metabolism. The metabolic rates of an animal, particularly any changes in response to environmental stress, are often indicative of the organism's general health. The benthic respirometer system (BRS) will be used for studies of animals living on the seabed, while the midwater respirometer system (MRS) will target midwater animals. Together, these systems allow researchers to make detailed measurements of animal physiology in response to environmental changes caused by ocean acidification (Figure 27).

The two systems are nearly identical in electronics and software, but differ in their configuration for more efficient operation in their respective areas of study. Eight individual chambers on each system allow measurement of rates of oxygen consumption for animals placed inside. By conducting several replicate measurements simultaneously on each species of interest, ship time is minimized. Metabolic rates are determined from the rate of oxygen consumption in the chamber over time. Future ocean acidification is simulated by injecting a small amount of carbon-dioxide-saturated seawater into the chambers. Ultimately, these systems will help broaden our understanding of the effects of changing ocean conditions on a wide variety of marine animals.

These systems complement studies by the benthic and midwater groups of the physiological response of deep-sea animals to high CO_2 levels under laboratory conditions where more detailed examination of animal physiology is possible. Acid-base balance, respiration rates, and various metabolic processes (e.g. protein synthesis) are often affected strongly by environmental stress, including ocean acidification, warming, and hypoxia. Facilities developed at MBARI to simultaneously control the pH, temperature, and oxygen levels in aquarium tanks have enabled comprehensive studies of the effects of multiple climate-related stresses on animals.



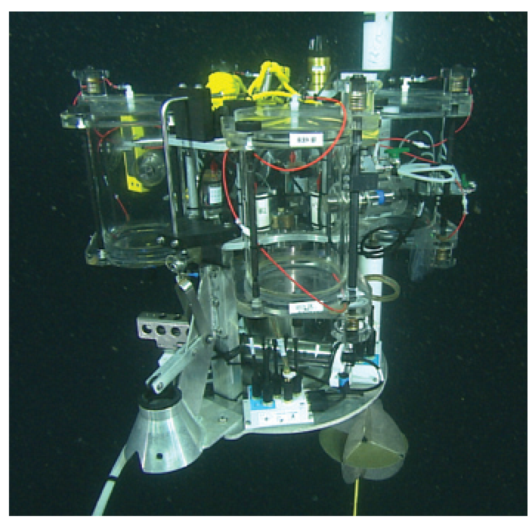


Figure 27: Rates of oxygen consumption calculated from the rate of change in oxygen concentrations in respiration chambers with a known volume. Each chamber is flushed with new water at a set interval to prevent oxygen from dropping to stressful levels. Animals held in chambers are weighed after the measurements to determine oxygen consumption on a per weight basis to allow comparisons among animals. The data shown here are from a single benthic respiration chamber (green), as well as the ambient oxygen (orange) and temperature (red) at the deployment site at 600 meters depth in Monterey Canyon. (Right, the early midwater respirometer mooring deployed at a depth of 800 meters.)

The Controlled, Agile, and Novel Observing Network (CANON)

Growth and death of microorganisms in the sea occur as ephemeral features that move over time in many directions. These "booms and busts" reflect the interplay between physics, chemistry, and biology, and represent the core of the oceanic food web. But not all of this activity is benign. Some blooms can be harmful to humans and wildlife, and can bring negative economic consequences. The ability to achieve mechanistic understanding of these phenomena has eluded us because of technical difficulties tracking water masses and the rapidly changing life they carry. The CANON team aims to overcome that limitation by creating new ways to remotely interrogate oceanic conditions and collect samples of microorganisms for in situ analysis as well as for return to shoreside laboratories.

How does the pelagic food web respond to changes in the natural environment? Our ability to answer this question is central to predicting how the oceans will respond to human perturbations such as increasing atmospheric CO_2 levels, nutrient runoff from agricultural and aquacultural activities, dispersal of various pollutants, and climate change. Yet present-day models are not capable of accurately predicting future consequences because very basic questions about the food web are still unanswered. Further, unexpected but significant events will continue to appear requiring an observing system capable of rapidly responding to these new challenges as well as investigating the basic processes required for accurate environmental prediction.

The food web of interest is much more complex than it might initially appear. Take the marine microorganisms at its core—not composed of one entity, but rather they span a tremendous range of physiological capabilities and mediate many different biogeochemical processes as functionally diverse as that of the full biota on land. Thus, changes such as increased atmospheric CO_2 levels, which will reduce ocean pH, will have different consequences for the many organisms in the marine environment, and these in turn will propagate through the food web. While the last decade has seen a revolution in understanding of the diversity and importance of microbial populations in the ocean, our understanding of how those populations respond to changes in their environment—and to other microbes—is rudimentary at best. Developing a better understanding of microbial dynamics through the development of new ocean observation capabilities is the initial thrust of the CANON program.

A key initial premise of CANON is to provide a new class of observation systems that will be able to follow and facilitate the study of organism assemblages and the transitions they undergo in the ocean environment. This is a critical development. The spatial and temporal sampling resolutions currently possible are not relevant to the spatial and temporal scales on which microbial processes occur. A fundamental principle for the initiative, and further technology development, is that processes and microbes must be studied at scales relevant to the organisms' adaptive strategies to determine how metabolism influences larger-

The Ocean in a High CO_2 World

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

Free Ocean CO_2 Enrichment

Project leads: James Barry, Peter Brewer, William Kirkwood
Project manager: William Kirkwood
Project team: Kent Headley, Bob Herlien, Chad Kecy, Thom Maughan, Tom O'Reilly, Ed Peltzer, Karen Salamy, Jim Scholfield, Farley Shane, Peter Walz
Collaborator: David Kline, University of Queensland, Australia

Benthic Biology and Ecology

Project lead/manager: James Barry
Project team: Kurt Buck, Chris Lovera, Craig Okuda, Eric Pane, Patrick Whaling
Collaborators: Joan Bernhard, Woods Hole Oceanographic Institution, Massachusetts; Jackie Grebmeier, University of Maryland, College Park; Ulf Reibesell, The Leibniz Institute of Marine Sciences, Kiel, Germany; David Thistle, Florida State University, Tallahassee

Modification of In Situ Respirometers for Ocean Acidification Studies

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

scale ecosystem dynamics. The initiative builds on lessons learned from previous multi-platform, multi-institutional field programs of the Autonomous Ocean Sampling Network (AOSN). In contrast to the earlier field programs, which addressed observing and predicting the physical ocean, the AOSN team is further developing the Collaborative Ocean Observatory Portal and other tools and methods to observe marine microorganism populations.

The CANON team aims to merge observation, modeling, and prediction to cast projections of biological, chemical, and physical gradients within a defined region. By directing small fleets of mobile sensors within that domain, they will detect specific phenomena remotely, collect physical samples of microbes, algae, and small invertebrates autonomously, and track the evolution of biological patches over time. The system in its final form will be able to provide scientists and managers with the information required to interpret the mechanisms detected and make decisions as to how to proceed.

Environmental Sample Processor

From a technological perspective, CANON has its roots in a convergence of sensing and autonomous platform technologies developed at MBARI over the last decade. New "ecogenomic sensors", like the Environmental Sample Processor (ESP), provide an unprecedented possibility for in situ molecular detection of organisms such as harmful algal species.

The ESP employs molecular probe techniques to autonomously assess the abundance of microorganisms, their genes, and metabolites in near real-time. Coupled with sustained environmental measurements provided by ocean observatories, assessment of microbial community structure and function will soon be possible in situ on spatial and temporal scales not previously achievable. To date, tests proving the feasibility of this approach were largely limited to coastal waters. In 2009, the MBARI team proved for the first time that the ESP could also be operated for extended periods at depth (Figure 28). Deployed to 900 meters, the instrument successfully used the same DNA probe array and sample archival functionality as that proven to work in shallow waters, revealing time-varying alterations in microbial community structure as a function of changing environmental conditions. The instrument ran as a stand-alone system as well as networked via the MARS cabled observatory.

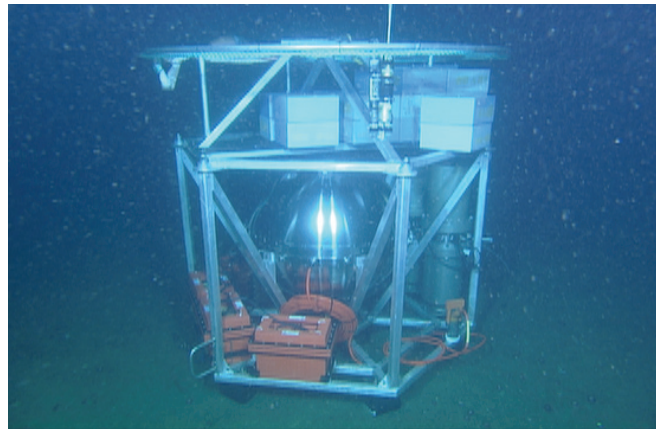


Figure 28: The Deep Environmental Sample Processor at 643 meters in Monterey Bay during its first test deployment.

Long-range autonomous underwater vehicle

Over the last three years MBARI engineers have developed a new class of autonomous underwater vehicles (AUVs) to support chemical and biological sensing missions covering ranges of 1,000 kilometers or more. The size and power consumption of desired chemical and biological sensors precluded the use of existing long-range gliders, and the endurance requirement precluded the use of more traditional propeller-driven AUVs. The concept for the new vehicle was a highly energy efficient propeller-driven AUV capable of operating at speeds between 0.5 and 1.0 meter per second. The new vehicle, named *Tethys*, conducted its first brief autonomous missions in December 2009, just offshore of Moss Landing (Figure 29).

The range and endurance of the new long-range AUV greatly expands the types of observations and experiments possible with autonomous platforms. For example, one of the institute's AUVs carries a comprehensive suite of sensors out to MBARI's M2 mooring and back. *Tethys* will carry a smaller, but still impressive suite of sensors 10 times farther, extending the reach of MBARI's shore-launched AUVs into the California Current system. This will expand researchers' non-ship observational capability beyond the upwelling shadow, well into the oligotrophic (nutrient poor) ocean. The capability also provides a foundation for studying phytoplankton blooms from boom to bust, by providing a mobile platform which can survey a bloom continuously through the two weeks to month-long lifetime of a bloom.

Figure 29: Thomas Hoover (front) and Chris Wahl launch the long range autonomous underwater vehicle, *Tethys*, during early field tests in Moss Landing Harbor.

Improving autonomous water sample collection

The development of novel water samplers for autonomous platforms is another focus of CANON. In 2009, major advances were made in sampling intensity and screening of biodiversity from water samples obtained with MBARI's AUV "gulper" water sampling system. Previously, only tens of samples were collected and processed, but during 2009, nearly 100 were obtained and processed, thanks to a shift in project collection priorities and the success of AUV missions. New molecular probes were designed to assay a greater diversity of zooplankton, including copepods, to complement those already available for microorganisms. Together, these improvements are yielding data with sufficient resolution to reveal patterns in the distribution of plankton across oceanographic fronts, layers, and other features identified in the AUV surveys. A national workshop is being organized at MBARI in 2010 to develop a detailed understanding of sampling needs, including requirements for sample size; spatial and temporal scales of sample intake; sample container sterility; management of ambient and container pressure differentials before, during, and after sample acquisition; onboard sample processing or preservation methods appropriate for specific target species; and subsequent sample analyses.

Decision support system

One principal problem continues to be where to position the AUVs and where they should sample to resolve key ecological questions. This also involves deriving an optimal path for sampling at the right place and time based on science requirements. To solve this problem the team envisions the capability to capture data from diverse sources to target AUV deployment as well as to provide situational awareness to the scientist on shore. Current efforts take a number of complementary approaches. One approach will use a wide range of data sources including satellite observations, mooring data, and high-frequency radar to statistically project patch advection. Another will build decision-making capability using artificial intelligence techniques onboard AUVs to adaptively sample dynamic coastal phenomenon. CANON proposes to systematically use these capabilities to provide a shore-side decision support system tool (Figure 30) for scientists to target the placement of AUVs close to and within bloom patches. Such a tool will enable scientists on shore to generate "what if" scenarios for potential changes to AUV transects, changes to environmental conditions, or alternative sample sites for hypothesis testing. The aim will be to encapsulate predictive capabilities in one tool that generates advice for scientists on shore.

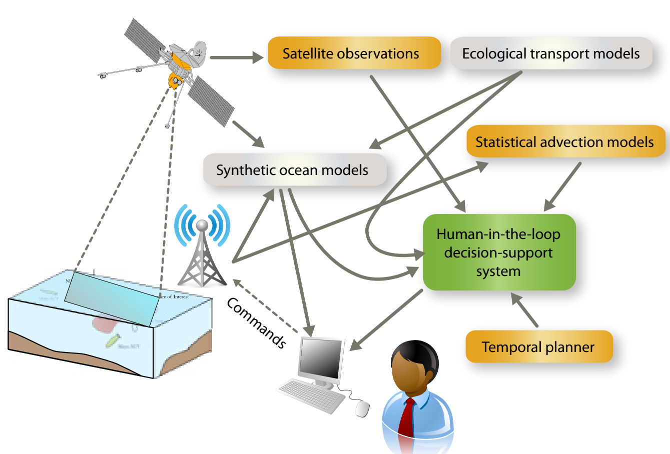


Figure 30: Proposed architecture of the shore-side decision support system for coordination and adaptation of mobile platforms for CANON.

Data and information management

In the first year of the CANON initiative, one goal was to integrate data and information management systems to provide uniform access to data from various sources. The ongoing efforts at MBARI include:

- a project to organize and visualize MBARI upper-water-column oceanographic data;
- data systems and collaborative tools developed initially for multi-platform experiments in Monterey Bay;
- development of the decision support system described previously;
- data management and communications systems developed by our close partner, the Central and Northern California Coastal Ocean Observing System, a regional association that is part of the U.S. Integrated Ocean Observing Systems;
- emerging genomic data management systems.

Figure 31 shows a conceptual diagram of how these efforts might be integrated so that as the initiative progresses, its information management needs will be met.

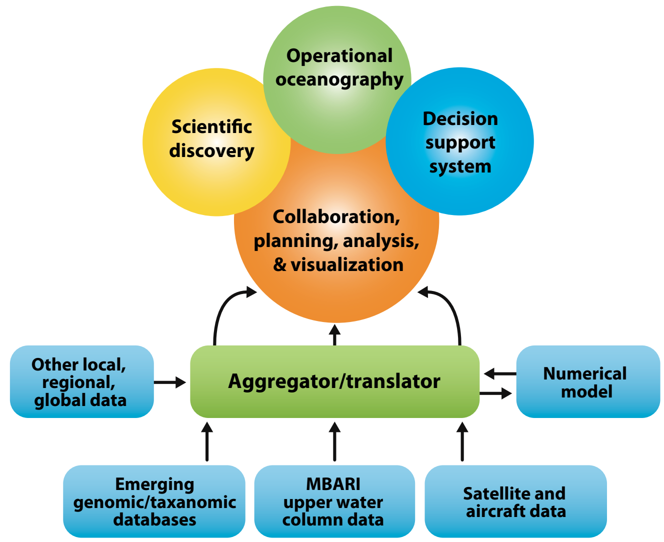


Figure 31:Conceptual model of how environmental information from diverse sources is combined and fed to researchers, operational applications, and decision support systems. The decision support systems from CANON will integrate this information to allow assets in the water to autonomously follow their target over long periods.

The initial focus

CANON will bring the biological insights to the requirements of new sensor development, based on cutting-edge approaches to genomics, transcriptomics, and physiology studies, and the technological innovations necessary to access the environment in unprecedented resolution, letting environmental conditions guide sampling decisions in real time and in situ.

Field work in 2010 will tackle two fundamentally different ocean biomes—the coastal environment, which is highly dynamic in terms of physical and chemical properties—and more oligotrophic waters representative of the open ocean environments that cover much of the planet. Each environment provides a different set of challenges. Coastal systems harbor the majority of ocean life, are in direct contact with human populations, and are easier to access but highly dynamic, triggering resolution and time response issues for instrumentation and adaptive sampling processes. The coastal experiments will center on observing and following harmful algal blooms. The primary coastal microorganisms are diatoms and dinoflagellates, part of the microphytoplankton.

Open ocean waters tend to be more stable and drive global biogeochemical budgets but provide intense technological challenges, requiring long-range autonomous devices and sample preservation techniques for samples that may be collected weeks or months prior to analysis. Organisms in these environments are very different from coastal communities and are dominated by very tiny phytoplankton (picophytoplankton). We still have limited understanding of which picophytoplankton are the key players in photo-

Controlled, Agile, and Novel Observing Network

Project lead: Chris Scholin
Project manager: Francisco Chavez
Project team: James Bellingham, Sergey Frolov, Kanna Rajan, Steve Ramp, John Ryan, Bob Vrijenhoek, Alexandra Worden

Long-Range Autonomous Underwater Vehicle

Project lead: James Bellingham
Project manager: Brett Hobson
Project team: Jon Erickson, Mike Godin, Thomas Hoover, Chad Kecy, Brian Kieft, Rob McEwen, Ed Mellinger, Yanwu Zhang

Autonomous Ocean Sampling Network

Project lead/manager: James Bellingham
Project team: Mike Godin, Thomas Hoover, Yanwu Zhang

synthetic uptake of carbon in open ocean environments. Progress will require measuring not only abundance of individual groups, but also measuring their activities, growth and mortality.

By contrasting field work in these two systems we hope to tease apart rules of community assembly for each system, which can then be applied to more predictive modeling of how communities might transition under variable conditions.

Biodiversity Initiative

This initiative seeks to generate new means of assessing deep-ocean health in response to both natural and human activities. Previous efforts at creating baselines for deep-sea biota have been rare and were focused on particular habitats, with narrow taxonomic scope and short time scales. MBARI is uniquely positioned to overcome these limitations and to develop a broader and more realistic assessment. A more comprehensive view will provide the means to assess the influence of anthropogenic forces such as climate change on the deep-water biota of the region. The short-term objective of this initiative is to develop a baseline of the diversity of animals in the deep waters of Monterey Bay. The long-term goals are to integrate studies of animals on the seafloor and in the water column, to understand their natural patterns of variability, and to gain a predictive capability to support the needs of ocean management and conservation (Figure 32).

The project team of six biologists, an engineer, and a geologist has been working to define the best way to address these issues. While the group is in agreement on ultimate goals, the individuals do not share a uniform approach to the challenge of creating a biodiversity baseline. Each of the biologists has been building a Monterey database on a specific component of the biota, in some cases for more than a decade. Because each of these efforts has evolved independently, the most common problem for the initiative was finding a way to integrate data from these different efforts.

This problem stems from the diversity of the methodologies of the separate research groups. The differences in data can be as simple as the need to use area for computing the abundance of seafloor animals, and using volume for counting species in the water column. Other differences are as distinct as measuring sediment dynamics and molecular sequencing, while data streams range from video to physiological rates. Sampling is done with different kinds of equipment at vastly different rates and scales across the spectrum of these assessments.

Thus, the biggest problem is not acquiring data, which are already being generated by ongoing research projects; the problem lies with integrating the data from these diverse streams. In 2009 the focus of the initiative shifted to a search for ways to coordinate data from disparate sources. It has become clear that using biodiversity informatics to develop a common language for the expression of the existing data sets is more practical than trying to re-configure seven pre-existing research programs to fit a common standard of data collection. Instead, post-processing will be neces-

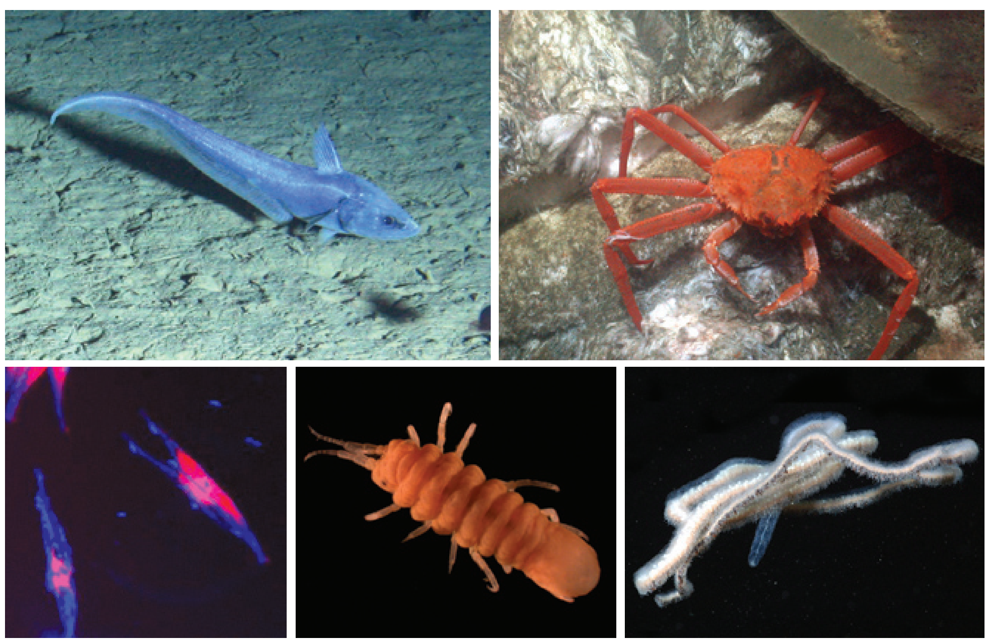


Figure 32: The Biodiversity Initiative aims to document species diversity and genetic connectivity of organisms from fish to microbes in order to establish a solid baseline and to better understand the structure and function of Monterey Bay's deep-sea ecosystem. A sampling of the diversity of marine organisms includes, clockwise from top left, a deep-sea grenadier fish, a Tanner crab feeding on a whale carcass, a midwater siphonophore, a microscopic sediment-dwelling isopod, and marine bacteria (small blue dots) interacting with a diatom (large cells with red chlorophyll fluorescence).

sary to achieve data compatibility. The critical effort will be to reconcile the genetic, species, environmental, and functional aspects of biodiversity measurements to build a coherent database from existing sources.

Likewise, the project's initial concept of joint, time-linked cruises for integrated and synoptic data collection appears to be impractical, given the constraints on ship and ROV/AUV operations. As a consequence, data for the first iteration of the biodiversity baseline will have to come from existing data sets. This approach also circumvents the initiative's second principal problem—that of finding a cruise track and station grid that would meet the projected needs of all the participants. Collecting data for all elements of the initiative, at the same place and time, is not feasible in the short term.

Several engineering and technology developments needed to support the initiative are already underway.

Benthic imaging autonomous underwater vehicle (BIAUV)

This autonomous system collects high-resolution color images that allow identification of animals to the species level and visual records of significant seafloor features. Using the successful, Dorado-class AUV as its starting point, the BIAUV is comprised of a high-resolution still camera, two xenon strobe lights, an obstacle-avoidance sonar, an acoustic modem and a navigation sonar. The BIAUV can conduct benthic animal time-series surveys in one third the amount of time it takes to run them with the ROV. The BIAUV will also be used for exploratory investigations in tandem with the mapping AUV.

Typically programmed to fly three meters off the seafloor at one meter per second, the BIAUV's camera fires every 1.6 seconds and produces overlapping images four meters wide that can be merged into one continuous mosaic. The resolution of each image at that altitude is sharp enough to resolve even the tiniest of crab antennae (Figure 33). The light from the twin strobes is carefully controlled to evenly illuminate the seafloor beneath the AUV. The high resolution images and illumination greatly enhance the manual animal identification tasks as well as the accuracy of the computer-based Automated Visual Event Detection system.

Future plans include improving the BIAUV's capacity to collect images over complex seafloor terrain as well as in the midwater, where there is a wealth of animal life. To further expand the BIAUV's breadth of capabilities, the team is exploring new terrain-based navigation techniques, cameras that take pictures from farther away, AUV hovering, and automated data processing.

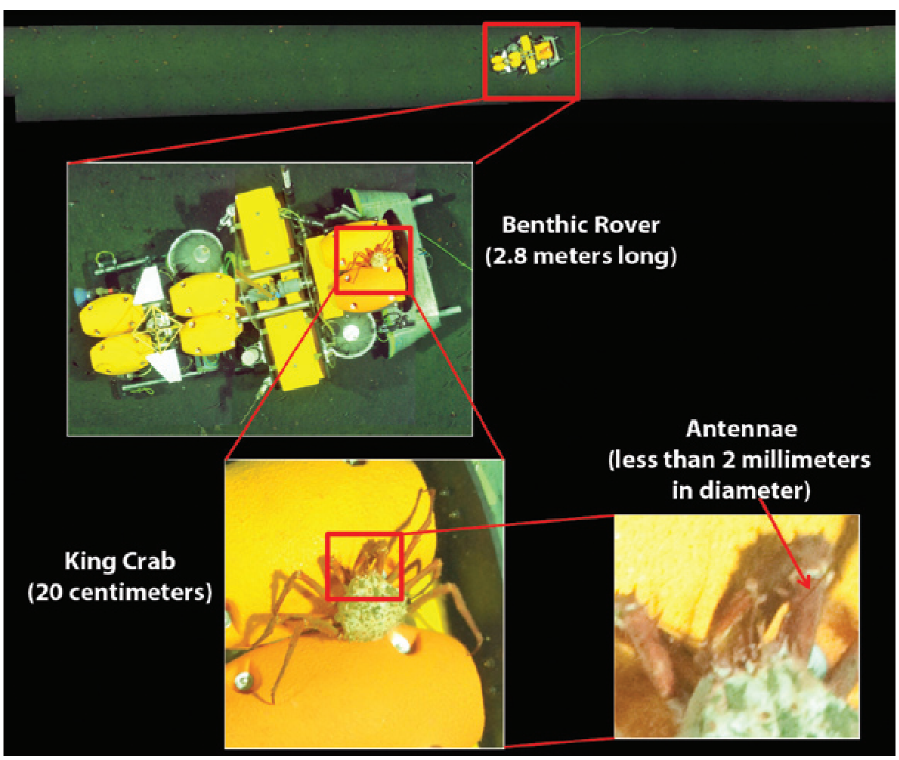


Figure 33: The Benthic Imaging AUV flew over the Benthic Rover which was at a depth of approximately 900 meters. The close-up shots taken by the AUV's camera show that it can zoom in close enough to see the antennae on a crab resting on the Benthic Rover.

Seafloor imaging of marine protected areas image analysis tool

Area-based surveys of patches of the seafloor provide new and potentially valuable information over that provided by more conventional linear transect surveys, and offer a means of monitoring specific habitats—and even individual organisms—within that habitat over time. In contrast, linear transect surveys typically yield only statistical characterizations of a region. However, area-based surveys are expensive. To assess the merits of an area-based survey, this project proposed to generate baseline surveys of selected areas within two newly established Marine Protected Areas in the Monterey Bay: Soquel Canyon and Portuguese Ledge. Repeated surveys have been conducted at a 95-meters-deep site just outside Soquel Canyon that is populated with numerous sea pens. These survey data are now being evaluated in MBARI's Video Lab.

These surveys required precise navigation of the ROV to guarantee complete coverage of an area. To achieve this, a vision-augmented system was developed and deployed (on both *Ventana* and *Tiburon*). This novel system yields accuracies of several centimeters using instrumentation typically mounted on the ROV, without an acoustic array, which makes it possible to perform surveys any time the ROV is deployed. A tool was also developed to allow annotation of the video data as they are collected during a survey. Because images overlap in an area-based survey, research technicians needed to eliminate the possibility of counting an organism multiple times. This in turn required the new capability of logging the precise location of organisms within a video frame. To achieve this, this prototype tool was developed.

Video annotation analysis and presentation

The video annotation analysis and presentation (VAAP) system will provide the analytical toolset required for establishing baseline composition of the biological community and its functional relationships, which are fundamental to biodiversity research. A number of existing analytical techniques will be aggregated and systematically applied across the biological groups that have been observed to date using various MBARI research tools. The resulting quantitative and qualitative data sets will allow researchers to begin to understand the spatial, environmental, and historical context of organisms found in the Monterey Bay region. The VAAP toolset will also provide the means for evaluating data quality and robustness, resolving conflicts in the identification of organisms, as well as developing expanded, ad hoc analyses that will be needed as knowledge advances and new research techniques are employed. To enable access to the data products, a web-based interface, dubbed the *Deep Sea Guide* will be created. This presentation of the data is also expected to serve as an identification guide for researchers as well as an excellent tool for educational and public outreach that highlights MBARI's unique contributions to ocean research.

Other MBARI developments such as the Automated Visual Event Detection System, Self-Triggering Event Detector, Tissue Sampler, and Precision Controls for ROVs and AUVS also have potential to contribute to the Biodiversity Initiative.

Biodiversity Initiative

Project leads: Duane Edgington, Bruce Robison
Principal investigators: James Barry, Steven Haddock, Charles Paull, Bruce Robison, Ken Smith, Bob Vrijenhoek, Alexandra Worden

Benthic Imaging AUV

Project leads: James Barry, Brett Hobson
Project manager: Brett Hobson
Project team: Jon Erickson, Kent Headley, Lonny Lundsten, Rob McEwen, Steve Rock, Jim Scholfield, Alana Sherman, Hans Thomas

Seafloor Imaging of Marine Protected Areas

Project lead: Steve Rock
Project manager: James Barry
Project team: David Caress, Linda Kuhnz, Eve Lundsten, Lonny Lundsten, Charles Paull, Brian Schlining, Nancy Jacobsen Stout

Video Annotation Analysis and Presentation

Project leads: Steven Haddock, Charles Paull, Brian Schlining
Project manager: Nancy Jacobsen Stout
Project team: Lonny Lundsten

Behind the Scenes: Keeping Pace with Changing Ocean Technologies

A decade ago, MBARI faced a serious challenge of how to maintain and operate a broad array of science tools and provide ongoing support to scientists, even as engineers continued to develop new technologies. At the time engineers were focused on developing autonomous underwater vehicles and ocean observing systems for future science applications. The scope of projects in 1999 ranged from building vertical profilers and mooring controllers to the need to regulate biofouling of optical sensors on moorings. A benthic elevator was being designed to augment ROV capabilities such as carrying heavy equipment to the seafloor or bringing samples up to the sea surface. And there were data management issues, involving high-bandwidth video, sample archives, and a user-friendly expedition database.

The engineering staff was faced with growing demands to develop these new tools and to ensure that existing tools were fully functional for the science programs. MBARI met the challenge by designating a special group of engineers—the Support Engineering Group—specifically tasked with helping to smooth the transition of new technologies from the engineering development stage to robust scientific use in the ocean. These engineers would also work closely with the institute's Division of Marine Operations on a day-to-day basis to maintain essential equipment and systems on moorings, ships, and vehicles.

Changing science requirements continuously challenge the institute to improve the tools in use. Support engineers have redesigned mooring hardware and the respirometers used to study animal metabolism. As researchers adopted complex new systems such as the seafloor seismometer, laser Raman spectrometer, Benthic Rover, and Environmental Sample Processor for field studies, the Manufacturing Group contributed the talents of electronic, mechanical and software technicians, and machinists to make those systems robust and functional.

Software engineers Mike McCann and Rich Schramm have developed applications and systems for managing and

Figure 34: Software Engineer Rich Schramm programs a new instrument driver for the controller for MBARI's OASIS 3 moorings. Every new instrument type requires the creation of a new driver to sample the instrument and log its data. OASIS 3 now has drivers to handle data from more than 30 oceanographic instrument types commonly used on MBARI oceanographic moorings.

Figure 35: Electronics Technician Tom Marion works on the wiring system for the Monterey Sediment Transport Acoustic Receiver, which will be used to detect sediment transport events in Monterey Canyon.

visualizing the vast amounts of data collected (Figure 34). Other systems such as MBARI's Software Infrastructure and Applications for MOOS and the Shore-Side Data System have improved access to MBARI data and serve as a model to the research community using ocean observatories. In the past year, engineers have even been able to test and make improvements in real time to the software systems that control instruments connected to the MARS cabled observatory test bed offshore.

Individuals have moved back and forth between support engineering, development engineering, and marine operations as software, mechanical, and electrical engineering needs shifted. This exchange of staff has served to improve competence and communication around the institute. ROV pilots joined forces with Larry Bird on ROV toolsled designs and technicians and machinists helped turn designs into reality (Figures 35 and 36). Thom Maughan's practical engineering knowledge led to improvements to the pH sensors for the Free Ocean CO_2 Enrichment (FOCE) experiment and considerable interest from outside MBARI. Craig Okuda's redesign of the microwave communication system reaches beyond MBARI as the microwave system serves real-time video to visitors at the Monterey Bay Aquarium.

Figure 36: Mechanical Technician John Ferreira uses the lathe to conduct a materials test on acrylic that will be used in manufacturing equipment to be deployed in the ocean.

Both groups, Support Engineering and Manufacturing, now provide engineering support to the whole institute and have a big impact on MBARI's success. They share a "can do" attitude and a commitment for excellence. From design and development, to the fabrication of new gear and electronic devices, they prove their dedication and value in support of MBARI's research and development goals.

Support Engineering Group

Group Lead: Kevin Gomes
Team: Craig Okuda, Thom Maughan, Mike McCann, Karen Salamy, Rich Schramm

Manufacturing Group

Group Lead: Dale Graves
Electronics Technician Lead: Jose Rosal
Machine Shop Lead: Ray Thompson
Manufacturing Team: Jerry Allen, Larry Bird, Paul Coenen, John Ferreira, Tom Marion, Dean Martinez, Jim Montgomery, Mike Parker, Jim Scholfield

Project Teams

Application of Chemical Sensors and National Oceanographic Partners Program

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

Nitrate, oxygen, and bio-optical sensors have been deployed on profiling floats creating a global ocean chemical sensor network. At the end of 2009, floats were operating successfully in the Southern Ocean, in low-nutrient regions of the Pacific and Atlantic basins, and in the Subarctic North Pacific. The design of the profiling float and sensor package was revised to make integration of sensors easier, to provide additional floatation for the sensor payload, and to extend the package lifetime to five years. Forty additional floats will be deployed over the next three years. The chemical and biological sensors on these floats will serve as the nucleus for a global observing system that will revolutionize our capability to quantify shifts in biogeochemical cycles driven by changing climate and to understand the underlying processes that drive these shifts. Closer to home, the project team continued to support the chemical sensor network in Elkhorn Slough and the nearshore waters of Monterey Bay. This six-year-old network has allowed an unprecedented view of the impacts of land/ocean coupling on the nitrogen cycle. Results demonstrate that large amounts of nitrogen move from the Gabilan watershed into Elkhorn Slough via the Old Salinas River channel.

Aquarium-MBARI Partnership

Project leads: Chris Harrold, George I. Matsumoto
Project manager: George I. Matsumoto
Project team: Nancy Barr, James Barry, Lisa Borok, Lori Chaney, Judith Connor, Kim Fulton-Bennett, Steve Haddock, Linda Kuhnz, Lonny Lundsten, Craig Okuda, Josh Plant, Kyra Schlining, Nancy Jacobsen-Stout, Susan von Thun
Collaborators: Rita Bell, James Covel, Aimee David, Humberto Kam, Traci Reid, Kim Swan, Jaci Tomulonis, and Chad Widmer, Monterey Bay Aquarium, California

The Monterey Bay Aquarium and MBARI continue to work together on various education, public outreach, and research projects. Collaborative efforts have been renewed between the Aquarium husbandry group and MBARI researchers helping to plan *Hot Pink Flamingos*, an exhibit on climate change, and the upcoming renovation of the Outer Bay Wing. The Aquarium Education Department helped MBARI connect with educators at the National Marine Educators Association conference. The Aquarium benefitted from MBARI staff expertise via trainings, seminars, classes, workshops, and assistance with exhibits. The partnership is studying the feasibility of deploying a camera on the MARS observatory and a high-resolution camera with up to four times the current frame rate (for slow motion) onto the ROV.

Autonomous Underwater Vehicle (AUV) Upper Ocean Research and Applications

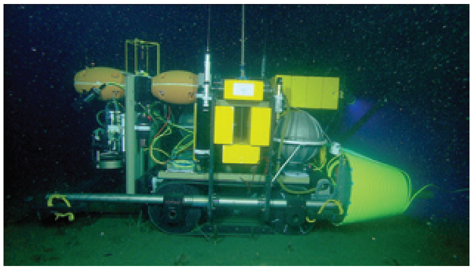
Project leads: Kanna Rajan, John Ryan
Project manager: John Ryan
Project team: Julio Harvey, Shannon Johnson, Mike McCann, Chris Scholin, Hans Thomas, Bob Vrijenhoek

Science and engineering collaborations were pursued on several fronts. This project helped advance autonomous research capabilities through experiments using two-way satellite communication between an AUV and a shore-side scientist to modify an AUV survey in real time. The project team also helped develop methods to optimize detection and sampling of biological layers. A second goal, to optimize AUV operations in multi-platform field programs and support resulting data synthesis, focused on plankton ecology research. A synthesis of the results was published describing the application of autonomous feature recognition and sampling to studies of marine and larval ecology. A third goal, to evaluate the use of AUV water sampling operations to reduce reliance upon ship operations, resulted in field tests conducted with parallel R/V *Zephyr* and R/V *Point Lobos* operations at one of MBARI's time-series stations.

Benthic Rover

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

Several features were added to the Benthic Rover, MBARI's autonomous bottom-transecting instrument for time-series studies on the deep seafloor. The new low-power hibernation mode will allow the Rover to "sleep" between measurements, significantly decreasing the vehicle's energy consumption and enabling longer deployments on a single set of batteries. A fluo-

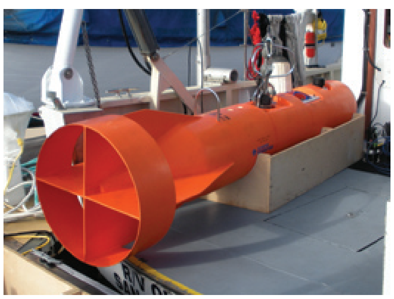


rescence imaging system was added to the front of the vehicle to capture the light emitted by chlorophyll fluorescence for quantifying fresh food supply from the upper water column. Components were added so that the Rover could be plugged into the MARS observatory, allowing for two successful deployments on the MARS node. During one deployment, the Rover traveled 290 meters, stopping every few meters to take fluorescence images and collect sediment community oxygen consumption measurements over a 24-hour period. Streaming video from the Benthic Rover cameras was available on the Internet. MBARI Video Lab technicians produced a mosaic of seafloor images taken with a still camera on the vehicle. In 2010, the Benthic Rover will be deployed for six months on its first long-term autonomous deployment at Station M at a depth of 4,000 meters.

Central and Northern California Ocean Observing System (CeNCOOS)

Project leads: Francisco Chavez, Steve Ramp
Project manager: Heather Kerkering
Project team: Fred Bahr
Collaborators: Tom Wadsworth, University of California, Santa Cruz; Over 50 throughout the State of California

CeNCOOS improved and stabilized its web services by integrating its hardware into the MBARI server network and launching a new dynamic website. Links to the CeNCOOS Data Management and Communications system under development will soon provide one-stop access to multiple data sets throughout California. Easy access is provided to computer models for model-to-model and model-to-data comparisons. Products for outreach and education were expanded. Key new products include a display of key ocean parameters for the five major bays in central and northern California, a map that shows where all ships are off the Central Coast in real time, and easy access to the latest satellite surface temperature and chlorophyll imagery side-by-side, with an overlay of surface currents. Other major activities included a pilot study for an observing system in the San Francisco Bay, a numerical modeling workshop, and leadership of a National Marine Educators Association workshop.



Chemical Sensor Program

Project lead/manager: Ken Johnson
Project team: Luke Coletti, Ginger Elrod, Steve Fitzwater, Hans Jannasch, Gene Massion, Josh Plant, Carole Sakamoto
Collaborator: Todd Martz, Scripps Institution of Oceanography, La Jolla, California

Further efforts were made to refine the ISUS optical nitrate sensor as well as adapting the Honeywell Ion Sensitive Field Effect Transistor pH sensor to operate at high pressure in the ocean. One such pH sensor was deployed for nearly eight months in the MBARI test tank with no perceptible drift. Other units were deployed on moorings in Monterey Bay and Elkhorn Slough to assess the impacts of biofouling on the sensor. Two prototype fluidic instruments have been developed for benchtop operation. The instruments were used to develop high sensitivity analyses for dissolved ammonium and phosphate, two key plankton nutrients, and showed promising results during sea trials. The next step, to be undertaken in 2010, will be conversion of the benchtop prototypes to units capable of operating in situ on ocean moorings for several months.

Core Conductivity-Temperature-Depth (CTD) Data

Project lead: David Caress
Project manager: Martin Suro
Project team: Reiko Michisaki, Bruce Robison, Richard Schramm

Support continued on the maintenance, calibration, and configuration of core CTD instruments, electronics, and related hardware. Overhaul of the user interface for real-time ROV data display was completed and integrated onto both vehicles. The control station for the profiler CTD aboard the R/V *Western Flyer* was upgraded to improve real-time interface between the operator and the science team.

Core Mooring Data

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

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

Core Navigation

Project leads: David Caress, Dale Graves
Project manager: David Caress
Project team: Lori Chaney, Craig Dawe, Linda Kuhnz, Dana Lacono, Mike McCann, Rich Schramm

The primary challenge faced by the project team in 2009 was the initial poor quality of navigation data from the new ROV *Doc Ricketts* during the early dive series. Both navigation-setting errors and hardware faults were addressed. The team also continued the operation and maintenance of the ROV and ship navigation hardware, maintained and improved software for automated processing and archiving of ship and ROV navigation, edited ROV navigation data, and monitored data quality.

Data Handling for Eye-in-the-Sea (EITS) on MARS

Project leads: Duane Edgington, Edith Widder
Project manager: Erika Raymond
Project team: Danelle Cline, Brian Schlining

The Eye-in-the-Sea ran nearly continuously for the last five months of 2009, generating a large data stream. The Automated Visual Event Detection (AVED) data can now be integrated into MBARI's Video Annotation and Referencing System (VARS), and significant improvements were made to the graphical tool to make it easier for the science user to analyze results. Overall, approximately 80 hours of Eye-in-the-Sea video were processed using the AVED software in 2009—the most ever processed at MBARI by an automated software tool. A simplified version of VARS was also created as an outreach tool that allows educators and students to annotate video.

Demonstration Study on Applying AVED to Still Image from Station M

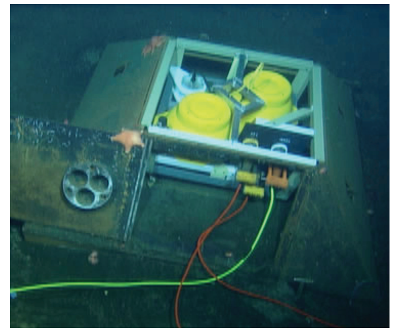
Project lead/manager: Danelle Cline
Project team: Duane Edgington, Jacob Ellena, Linda Kuhnz, Ken Smith, Michael Vardaro

The AVED system, originally developed for use with video images, was adapted for use with still-frame images. The team began creating 18 training libraries representing a variety of species and physical objects for testing with the AVED classifier. When these training libraries are fully developed, researchers will demonstrate the use of computer-aided vision software to analyze the thousands of still-frame images taken by time-lapse cameras at Station M since 1989.

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

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

The Monterey Ocean Bottom Broadband (MOBB) seismometer, the longest-running ocean-bottom broadband seismometer in the world, was installed on the MARS cabled observatory in February and immediately began to stream data to the Berkeley Seismological Laboratory. This connection required a redesign of MOBB's power and data-logging electronics, and the installation of a 3.6-kilometer extension cable on the MARS node. The extension cable has been caught by trawls twice, but despite being dragged, tangled, and damaged, it continued to operate through 2009. The damage, however, is likely corroding the cable's conductors and failure could occur at any time, so the cable will be replaced in 2010. To prevent trawling damage in the future, a cable-burying system is being developed for MBARI's remotely operated vehicles. Other work in the immediate future will focus on improving the stability and accuracy of MOBB's clocks, and publication of the system design to the wider research community so that it might serve as a prototype for other cabled ocean observatories.



Dissolved Oxygen Sensor and Improved Data Recovery for Pop-up Archival Tags

Project leads: Chris Harrold, Brett Hobson
Project manager: George I. Matsumoto
Project team: Paul McGill, Erika Raymond
Collaborators: William Gilly, Hopkins Marine Station of Stanford University, Pacific Grove, California; Laurent Giovangrandi, Stanford University, California; Melinda Holland, Wildlife Computers, Redmond, Washington; John O'Sullivan, Monterey Bay Aquarium, California

Researchers from the Monterey Bay Aquarium and MBARI investigated the feasibility of incorporating a sensor for dissolved oxygen into an existing commercially available pop-up archival tag package, which would be useful in several ongoing research projects at both institutions.

Ecology and Dynamics of Picophytoeukaryotes

Project lead/manager: Alexandra Worden
Project team: Elif Demir, Alyssa Gehman, Darcy McRose, Adam Monier, Melinda Simmons, Heather Wilcox
Collaborators: Francisco Chavez, Ken Johnson, and Zbigniew Kolber, MBARI; Marie Cuvelier, Rosenstiel School of Marine and Atmospheric Science, University of Miami, Florida; Matthew Sullivan, Arizona State University, Tempe; E. Virginia Armbrust, University of Washington, Seattle; George Weinstock, Washington University in St. Louis, Missouri; Andrew Allen, J. Craig Venter Institute, San Diego, California

An interdisciplinary team went on an R/V *Western Flyer* expedition following a transect from Moss Landing out to the low-nutrient open ocean waters. A highly integrated sampling pattern and experiments were performed involving measurements of chemical and photosynthetic properties, viral dynamics, and primary production. The research group measured organism abundance and complete transcriptomes (all the genes expressed by the community at a given point in time) as well as experiments on growth and mortality of different phytoplankton populations. Uncultivated eukaryotes were collected for sequencing genomes by separating cells using high-speed cell sorting at sea. By undertaking this integrated approach, knowledge regarding known organisms will be advanced and, concurrently, knowledge will be gained on unknown aspects of the natural community. Longer term goals focus on transitioning information in phytoplankton genomes into tools that can tell more about the experience of the population under study. Thus, the team will target unknown genes, in order to "mine" genomes for information about currently unrecognized factors affecting phytoplankton dynamics.

Education and Research: Testing Hypotheses (EARTH)

Project lead/manager: George I. Matsumoto
Project team: Heather Kerkering, Linda Kuhnz, Erika Raymond
Collaborators: Rita Bell, Monterey Bay Aquarium, California; John Horne, University of Washington, Seattle; Raphael Kudela, University of California, Santa Cruz; Jennifer Magnusson, Bellingham School District, Washington; Edith Widder, Ocean Research and Conservation Association, Florida

The 2009 EARTH teacher workshop brought 22 teachers from around the U.S. to Monterey to learn how to integrate real-time data, educational standards, and tested curriculum in an interactive and engaging way for their students. Participants generated lesson plans on harmful algal blooms, sea-level rise, hydrothermal vents, salmon fishery, and the Eye-in-the-Sea camera system. Since the workshop was held before the National Marine Educators Association meeting, several of the EARTH teachers gave presentations about the program to the broader educational community at that meeting, and coordinated a field trip to MBARI for the visiting educators. The EARTH website was also revised to be more intuitive and to include more links to current MBARI research. The site saw a 40 percent increase over the previous year in the number of visitors and an even greater increase in the number of pages viewed. The project team will be striving to support workshop participants to run similar workshops in their communities to share what they have learned at the MBARI workshop.

Feasibility of a Digital Video Archive

Project leads: Charles Paull, Brian Schlining
Project manager: Nancy Jacobsen Stout
Project team: Lori Chaney, Danelle Cline, Duane Edgington, Dale Graves, Linda Kuhnz, Lonny Lundsten, Todd Ruston, Kyra Schlining, Susan von Thun, Todd Walsh

A system architectural plan was begun, providing information for video acquisition, transfer, short and long-term storage, backup, metadata management, usage rights management, integration with existing analytical programs, and internal and external distribution. Video highlights of interest to the public were regularly distributed via MBARI's external web, YouTube, and the Monterey Bay Aquarium. These small-scale distribution trials continue to provide valuable information about best formats and best practices for external video distribution. New digital video compression techniques were employed in side-by-side comparisons at varying levels of compression. It is expected that such analysis will ultimately provide detailed metrics for determining video compatibility among operating systems, suitability for various web applications and usability for scientific research at a given compression. These trials are expected to provide access to professional video digitization services, video management and search systems, as well as video engineering, distribution, and rights management expertise.

High-Resolution, Near-Surface Seismic Refraction Tomography

Project leads: David Caress, Rich Henthorn
Project manager: David Caress
Project team: Mark Chaffey, William Kirkwood, Paul McGill

Work began on development of a high-resolution seismic refraction capability to image the shallow structure of the seafloor subsurface. The basic concept is to combine a swept-frequency (chirp) acoustic source operated on or near the seafloor with multiple ocean bottom hydrophones as receivers to observe acoustic signals that propagate through the shallow subsurface. Progress was made with field trials on ROV *Ventana*, although the noise emitted by the ROV itself conflicted with the sounds the hydrophones targeted. Another test involved deploying a hydrophone in the path of the AUV mapping vehicle, which determined that the AUV would be a much more suitable platform for the acoustic chirp refraction source than a hydraulic ROV. The project team will now focus on reconfiguring the system as an AUV-based experiment.

Juan de Fuca Boreholes (I and II)

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

Boreholes drilled on the eastern flank of the Juan de Fuca Ridge have been fitted with instruments to study fluid flow within the crust, its impact on the ocean and crust, and for the first hole-to-hole flow experiments. In addition to the three current holes, three more boreholes are to be drilled and outfitted in 2010. The MBARI portion of this collaborative project supports OsmoSamplers placed in the boreholes to measure the background chemical conditions and changes observed throughout the experiment. The data provided by this project should profoundly improve our understanding of fluid processes within oceanic crust, and will help develop new tools and methods that can be applied in many settings.

Marine Metadata Interoperability (MMI)

Project lead: Carlos Rueda
Project manager: Duane Edgington
Project team: John Graybeal
Collaborators: Luis Bermudez and Philip Bogden, Southeastern Universities Research Association, Washington, D.C.; Matthew Howard, Texas A&M University, Austin; Andy Maffei and Al Plueddemann, Woods Hole Oceanographic Institution, Massachusetts; Karen Stocks, San Diego Supercomputer Center, University of California

The MMI Project helps make it easier for scientists to find, access, and use data sets available from various ocean observing systems. The project's goal is to promote collaborative research in the marine science domain, by simplifying the incredibly complex world of metadata into specific, straightforward guidance. MMI provides advice and resources for data management. In 2009 the MMI team enhanced the project's extensive website, adding many guides and training materials. The website hosts a large number of vocabularies for marine science.

Midwater Ecology

Project lead: Bruce Robison
Project manager: Kim Reisenbichler
Project team: Rob Sherlock
Collaborators: Stephanie Bush, University of California, Berkeley; Steven Haddock, George I. Matsumoto, and Ken Smith, MBARI; Richard Norris and Karen Osborn, Scripps Institution of Oceanography, La Jolla, California

Researchers began to test the hypothesis that an expanding oxygen minimum zone (OMZ) is changing the abundance and distribution patterns of the midwater fauna in the Monterey region. The project team is approaching the question in two ways: first, by mining the midwater time-series data of oxygen concentrations and animal vertical distributions; and second, by measuring the physiological characteristics of key species to determine the role of oxygen concentration on their vertical range and abundance. Preliminary results show that as the top of the OMZ has shoaled over the last 16 years, the mean depth of several species that normally live above the OMZ, has also shifted upward. Likewise, the bottom of the expanding OMZ is correlated with a downward shift in the distribution centers of other species that typically live below the OMZ. The Midwater Ecology group also participated in the northern expedition (see page 11). The vision for the future is to incorporate results from the current studies into a model that this research group has been building of midwater community structure and dynamics.

Midwater Time Series

Project lead: Bruce Robison
Project manager: Rob Sherlock
Project team: Kim Reisenbichler, Kris Walz
Collaborators: Stephanie Bush, University of California, Berkeley; Kyra Schlining and Susan von Thun, MBARI

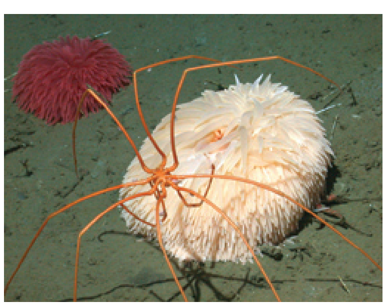
Quantitative video transects, made primarily using ROV *Ventana*, are recorded at sea, then annotated in the lab. Over time they provide a frame of reference to assess how midwater communities respond to change. These data are unique in longevity and scope and provide insight into the dynamics and ecology of midwater communities. In 2009 annotations were completed for all recognizable organisms in the 2,062 transects conducted from 1997 to 2010. This was a major milestone and brings to date a timeline spanning 17 years (additional transects from 1993-1997 have been annotated only for 10 key species). Physical data—oxygen, temperature, and salinity—are also linked to the population dynamics, providing a unique way to observe change over time and to distinguish human impact from natural cycles. Future goals are to automate the data collection process by employing AUVs as the quantitative imaging platforms, and to streamline image processing through the use of image-recognition software such as MBARI's AVED.

Molecular Ecology of Marine and Aquatic Organisms

Project lead: Robert Vrijenhoek
Project manager: Shannon Johnson
Project team: Asta Audzijonyte, David Clague, Julio Harvey, Scott Jensen, Roman Marin III, Gene Massion, John Ryan, Chris Scholin, Alana Sherman

Collaborators: Monika Bright and Sigrid Katz, University of Vienna, Austria; Katharine Coykendall and Joe Jones, Environmental Genomics Core Facility, University of South Carolina, Columbia; Marina Cuhna and Ana Hilario, Universidade de Aveiro, Portugal; Hermann Erhlich, Dresden University of Technology, Germany; Shinzou Fujio, University of Tokyo, Japan; Shana Goffredi, Occidental College, Los Angeles, California; Andrezj Kaim, Instytut Paleobiologii Warszawa, Poland; Yasunori Kano, Ocean Research Institute, University of Tokyo, Japan; Steffen Kiel, Christian Albrechts University, Kiel, Germany; Ray Lee, Washington State University, Pullman; Crispin Little, Leeds University, United Kingdom; Mary McGann, U.S. Geological Survey, Menlo Park, California; Victoria Orphan, California Institute of Technology, Pasadena; Vicki Pearse, University of California, Santa Cruz; Greg Rouse and Nerida Wilson, Scripps Institution of Oceanography, La Jolla, California; Michel Segonzac, Institut Francais de Recherché pour l'Exploitation de la Mer, France; Tracey Smart and Craig Young, Oregon Institute of Marine Biology, Coos Bay; Nicole Stroncik, Potsdam University, Germany; Ellen Strong, National Museum of History, Washington D.C.; Andrew Thaler and Cindy van Dover, Duke Marine Laboratory, Beaufort, North Carolina; Shinji Tsuchida, Japan Agency for Marine-Earth Science and Technology, Japan; Paul Tyler, National Oceanographic Centre, Southampton, United Kingdom; Anders Warén, Swedish National Museum, Stockholm; Chad Widmer, Monterey Bay Aquarium, California; Yong-Jin Won, Ewha Womans University, Seoul, South Korea; C. Rob Young, Massachusetts Institute of Technology, Cambridge

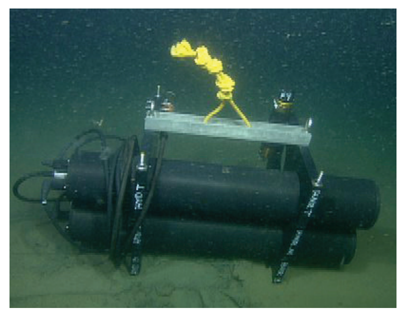
Research focused on assessing the ecological and evolutionary diversity of benthic marine invertebrates and pelagic zooplankton in Monterey Bay. Ongoing whale-fall investigations have concentrated on species diversity of *Osedax* bone-worms and their heterotrophic bacterial endosymbionts. Fifteen species of *Osedax* have now been discovered living at various depths in Monterey Bay. At least three of the Monterey species are also known to occur off the coast of Japan, a discovery that has created collaborative opportunities to examine rates of dispersal across the Pacific Ocean for these worms. The Eye-in-the-Sea camera system on the MARS cabled network recorded the degradation of mammalian carcasses by large mobile scavengers such as sleeper sharks and hagfish. Future efforts will couple the use of such observation platforms with minimally invasive tissue sampling methods for the molecular identification of these large scavengers. Recent studies of pelagic zooplankton involved the development of new molecular probes for use with various robotic sampling systems currently under development by MBARI.



Monterey Canyon Sediment Transport Acoustic Receiver (McStar)

Project leads: Gene Massion, Charles Paull
Project manager: Gene Massion
Project team: Thom Maughan, Wayne Radochonski, William Ussler

McStar is a battery-powered, self-logging acoustic receiver designed to listen for sediment transport events in Monterey Canyon. McStar will help researchers studying canyon dynamics acquire a qualitative understanding of the onset, duration, and periodicity of highly energetic sediment transport events using acoustic remote sensing techniques. A self-triggering event detector (STED), an expendable device for detecting and time stamping the onset of high velocity events, will be placed in the canyon while McStar will be placed on a safe ledge at the side of the canyon. Looking at the acoustic signature of the canyon just before and after a STED event will allow a qualitative description of these major sediment transport events to be developed. McStar was deployed successfully for 30 days in 2009. This new acoustic system will also be used to characterize methane bubbling at seeps in the Santa Monica basin and for upcoming research on submarine canyon dynamics.



Monterey Ocean Observing System (MOOS) Upper Canyon Experiment

Project leads: James Barry, Charles Paull
Project manager: Mark Chaffey
Project team: Larry Bird, John Ferreira, Kevin Gomes, Kent Headley, Mike Kelley, Brian Kieft, Chris Lovera, Ed Mellinger, Tom O'Reilly, Karen Salamy, William Ussler

The Monterey Ocean Observing System (MOOS) Upper Canyon Experiment aims to document the frequency and intensity of episodic sediment transport events in Monterey Canyon, and to utilize high sampling rates to characterize the physical processes active during these brief events. The companion technical goals of the project are to continue to improve the MOOS mooring portable observatory as a scientific tool and demonstrate that it can collect unique data sets that are not available through any other means. The surface mooring was successfully deployed in November 2009, with the rest of the system to be deployed in 2010. The project team will use this experiment to reinforce the effort to export the MOOS observatory mooring technology to the broader oceanographic community. The MOOS mooring remains unique for experiments that require real-time connectivity and significant instrumentation power at remote deep-sea locations for term deployments.

Mooring Maintenance

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

MBARI moorings have provided 20 years of time-series observations and are considered as model systems for the network of coastal observatories planned for U.S. coastal waters. A number of MBARI scientists as well as outside institutions use the data from the moorings. The moorings also serve as platforms for specific scientific investigations and instrument development. The M1 mooring has been the platform for the development of the pCO_2 analyzer and the longest time-series data set for a biogeochemical sensor in the surface waters. In addition to the M1 and M2 deployments, the M0 mooring was also maintained for another year.

Observing Complexity in the Coastal Ocean

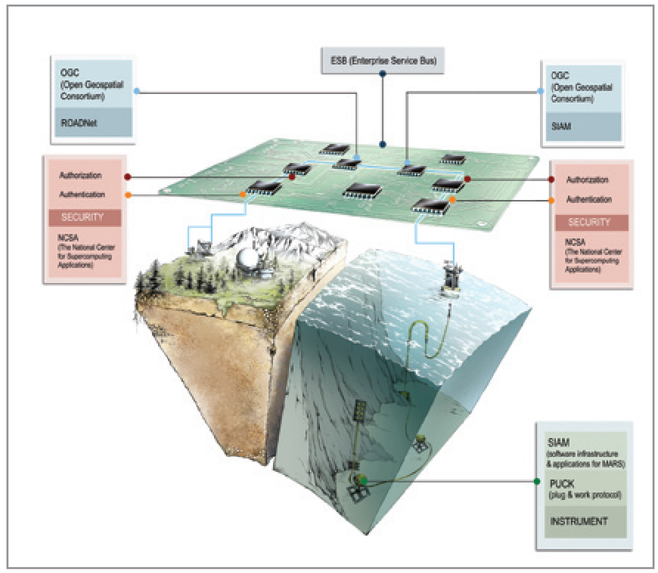
Project lead: John Ryan
Project manager: Erich Rienecker
Project team: Mike Kelley
Collaborators: James Gower, Institute of Ocean Sciences, Sidney, British Columbia, Canada; David Jessup, California Department of Fish and Game, Santa Cruz; Raphael Kudela and Adina Paytan, University of California, Santa Cruz; Margaret McManus, University of Hawaii, Manoa; Mark Stacey, University of California, Berkeley; Jonah Steinbuck and Brock Woodson, Stanford University, California

Research focused on land-sea connections and their role in plankton bloom ecology in Monterey Bay. Publications examined the dynamics and newly discovered harmful impacts of "red tide" blooms in Monterey Bay, the role of small-scale physics in the development of thin biological layers, and the role of regional physical oceanography in the development of fronts and their associated role in larval dispersal and settlement.

Observatory Middleware Framework (OMF)

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

The prototype of a generalized Observatory Middleware Framework (OMF) integrates existing and proposed technologies and reduces duplication of functionality across various types of observatories. The OMF highlights the ability to readily integrate and configure instruments, data streams, processing, and storage resources into a customized observatory without concern for resource implementations. In 2009



the team developed an end-to-end prototype, from instrument interface to data store, with a standards-based interface to instruments, connection to an open-source Enterprise Service Bus, and integrated authentication and authorization of instruments and end-user researchers. An end-to-end demonstration of the OMF system was presented at the international Instrumenting the Grid workshop. The team also worked with the National Center for Supercomputing Applications to port the prototype system for other applications.

Ocean Observatory Initiative (OOI) Cyberinfrastructure

Project leads: Duane Edgington, Kevin Gomes
Project manager: Duane Edgington
Project team: Bob Herlien, Carlos Rueda, Brian Schlining

MBARI is participating in the design of the cyberinfrastructure system which is key to the integration of the various aspects of the Ocean Observatories Initiative, an environmental observatory effort which covers a diversity of oceanic environments, ranging from the coastal to the deep ocean.

Construction of the system began in 2009, with deployment phased over five years. The cyberinfrastructure design is based on loosely coupled distributed services; its elements are expected to reside throughout the OOI observatories, from seafloor instruments to deep-sea moorings to shore facilities to computing and archiving infrastructure. The MBARI team has participated in requirements-gathering and design workshops, as well as training in the use of the Observatory Middleware Framework and the Marine Metadata Interoperability project. Over the next five years, the MBARI team will continue to participate in design of the sensing and acquisition, data management, and common operating infrastructure subsystems of the OOI-CI.

Onboard Decision Making

Project lead/manager: Kanna Rajan
Project team: Thom Maughan, Tom O'Reilly, Frederic Py, Brent Roman, Hans Thomas
Collaborators: Elgar Desa, National Institute of Oceanography, Goa, India; Maria Fox, University of Strathclyde, Glasgow, United Kingdom; Felix Ingrand, Laboratoire d'Analyse et d'Architecture des Systemes, Toulouse, France; Conor McGann, Willow Garage, Menlo Park, California

The T-REX (Teleo-Reactive Executive) adaptive control software system has been deployed routinely on AUV missions, successfully detecting dynamic features of interest, such as ocean fronts, and triggering water samplers within these hotspots. The system was also used to detect and map a sediment plume laden with agricultural runoff flowing into Monterey Bay. Yet another novel advance using this system enabled a scientist to retarget an AUV from shore. After the scientist received CTD data from the AUV via satellite, he directed the AUV to map and sample a particular front. T-REX received these goals, re-planned on the fly by turning the AUV around to lock onto the front's hotspot. The long-term goal is to use such techniques to enable intelligent adaptive sampling targeted by a shore-side decision support system which integrates disparate data sources to aid scientists and operators on ship or shore where to direct one or more vehicles for further data collection and sampling.

One-Stop Shopping for MBARI Upper Water Column Data

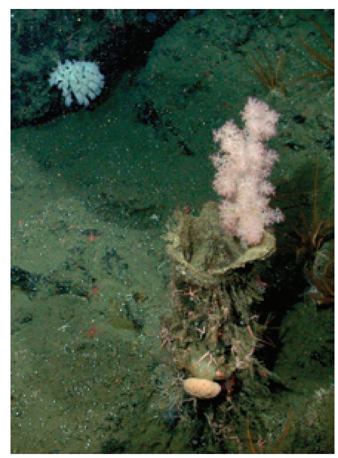
Project leads: Francisco Chavez, Mike McCann
Project manager: Mike McCann
Project team: Fred Bahr, Kevin Gomes, Reiko Michisaki, Brian Schlining

The effort to make MBARI data widely and readily accessible advanced with the configuration of a data-aggregation server for mooring data products generated by the Shore Side Data System. This simplified access to MBARI's multi-decadal archive of mooring data. The aggregated mooring data is used by the visualization code for reprocessing the six-year archive of CTD data collected with MBARI AUVs. The development and release of a Matlab™ Toolbox also enables easy access of the data-aggregation server. This Toolbox (http://code.google.com/p/nctoolbox) is now promoted from outside MBARI as a standard tool to be used by the ocean observing data system communities. The implementation of a prototype relational data server also helped with the integration of the Biological Ocean Group's data. These developments are part of the institute's process of employing community standards, then refining these standards to provide effective stewardship of our data archives.

Outline Video Annotation

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

Outline annotations of videos from MBARI ROVs continued on a daily basis. A still image annotation feature was added to the Video Annotation and Reference System (VARS). This technology is currently being tested on images taken with cameras mounted on the remotely operated vehicles; it will later be applied to the numerous still imaging projects under development including image mosaic techniques, benthic imaging AUV, and the Benthic Rover. This new capability will allow for cataloging, scientific analysis, search and retrieval of tens of thousands of existing still images, which until now, were underutilized and difficult to access. Members of the team continued to participate in a variety of outreach efforts, research cruises, data analysis projects, and scientific publications.



Precision Control Technologies for ROVs and AUVs

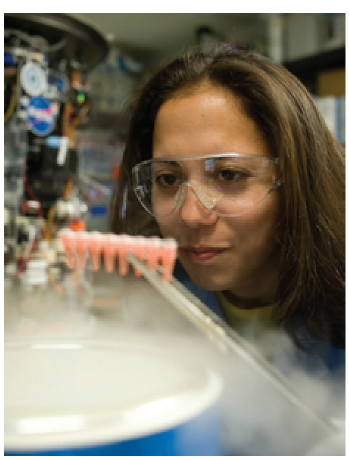
Project leads: Rob McEwen, Michael Risi, Steve Rock
Project manager: Steve Rock
Project team: James Barry, David Caress, T. Craig Dawe, Brett Hobson, Charles Paull, Bruce Robison, Brian Schlining, Hans Thomas

New aids were developed to improve an ROV pilot's ability to perform video transects over rugged terrain and to enable area-based surveys in these terrains. During field trials with the ROV *Ventana* the pilot commanded the lateral speed of the ROV while an automated system maintained constant distance from the canyon wall as well as the correct vehicle heading. Algorithms were also developed, and successfully field tested, which would enable an AUV to operate more safely and more aggressively in areas of rough terrain by exploiting the information available in a-priori bathymetric data. This activity is part of a larger effort to enable AUVs to perform tasks that previously required an ROV.

Probe Chemistries for Use with the Environmental Sample Processor (ESP)

Project leads: Roman Marin III, Christina Preston, Chris Scholin
Project manager: Christina Preston
Project team: Nilo Alvarado, Julio Harvey, Allison Haywood
Collaborators: Donald Anderson, Woods Hole Oceanographic Institution, Massachusetts; Ed DeLong and Elizabeth Ottesen, Massachusetts Institute of Technology, Cambridge; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; Cindy Heil, Florida Fish and Wildlife Conservation Commission, St. Petersburg; Mary Ann Moran and Vanessa Varaljay, University of Georgia, Athens; Julie Robidart and Jonathan Zehr, University of California, Santa Cruz; Robert Vrijenhoek, MBARI

Work concentrated around four themes: developing assays for nucleic acid extraction and amplification; refining direct capture of target biomolecules; reagent preparation in support of ESP operations; and technology transfer. These themes focus on transforming studies of microbial ecology and harmful algal blooms by collecting and processing samples remotely. Experiments exploring this concept spanned tests on moorings, a coastal pier, and the deep-sea MARS cabled observatory. Most notable was the first application of quantitative polymerase chain reaction aboard the ESP to detect specific genes of bacterioplankton autonomously in situ and the preservation of discrete samples for recovery of RNA post-deployment. This work showed that a single instrument can support the detection of multiple organisms using multiple detection strategies in a wide range of ocean environments. Future work will emphasize expanding the range of detection chemistries that can be used with sensors like the ESP, paying particular attention to high-density probe arrays that allow for parallel detection of numerous molecular signatures in a single sample. Development of reagent formulations that exhibit exceptional stability is also critical to extend the instrument's endurance in remote locations where frequent servicing of the instrument is not possible.



SENSORS: Ocean Observing System Instrument Network Infrastructure

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

Several collaborations have been developed to assist ocean observatory efforts around the world in adopting MBARI software infrastructure components developed for the Monterey Ocean Observing System (MOOS) and the MARS cabled observatory. SIAM (Software Infrastructure for MOOS) provides a flexible, portable architecture to manage instrument networks, while MBARI's plug-and-work protocol (PUCK) addresses the need for a serial instrument standard. The project team completed an extension to SIAM to support Ethernet instruments and tested it with an Ethernet video camera. They explored extending SIAM to incorporate device discovery. The team worked on moving PUCK forward as an industry standard, and participated in the Ocean Science Interoperability experiment. New versions of the PUCK reference design kit were built and distributed.

SURF Center (Sensors: Underwater Research of the Future): Applications of the Second Generation ESP

Project leads: Jim Birch, Chris Scholin
Project manager: Jim Birch
Project team: Nilo Alvarado, Cheri Everlove, Kevin Gomes, Julio Harvey, Allison Haywood, Scott Jensen, Roman Marin III, Gene Massion, Doug Pargett, Mike Parker, Christina Preston, Brent Roman
Collaborators: Don Anderson, Woods Hole Oceanographic Institution, Massachusetts; Ed DeLong, Massachusetts Institute of Technology, Cambridge; Gregory Doucette, National Ocean Service Marine Biotoxins Laboratory, Charleston, South Carolina; John Dzenitis, Lawrence Livermore National Laboratory, California; Peter Girguis, Harvard University, Cambridge, Massachusetts; Victoria Orphan, California Institute of Technology, Pasadena; Julie Robidart and Jonathan Zehr, University of California, Santa Cruz

The SURF Center team proved for the first time that the ESP could be operated for extended periods at depth. Deployed to 900 meters, the instrument successfully used the same DNA probe array and sample archival functionality as that proven to work in shallow waters, revealing time varying alterations in the microbial community as a function of changing environmental conditions. The instrument ran as a stand-alone system as well as networked via the MARS cabled observatory. The instrument was recognized by *R&D Magazine* as one of the 100 most technologically significant products introduced into the marketplace during 2009. Current work emphasizes incorporating a two-channel real-time polymerase chain reaction module for nucleic acid amplification. The team is working to extend operations to 4,000 meters and increase deployment duration. Over the next five years, the focus will be on improving the water sampling ability, making the instrument smaller and more energy efficient, and installing the ESP on autonomous vehicles or within a drifter, to be better able to follow fronts or features thereby improving our understanding of marine microbial ecology.

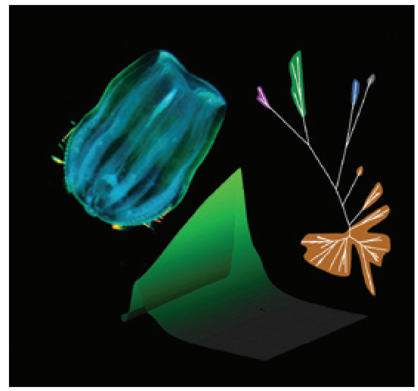
Zooplankton Biodiversity and Bio-Optics in the Deep Sea

Project lead/manager: Steven Haddock

Project team: Lynne Christianson, Warren Francis, Gerard Lambert, Meghan Powers, Nathan Shaner

Collaborators: William Browne, University of Miami, Florida; Allen Collins, Smithsonian Institution, Washington, D.C.; Rob Condon, Bermuda Institute of Ocean Sciences, St. George's; Casey Dunn and Rebecca Helm, Brown University, Providence, Rhode Island; Monty Graham, University of South Alabama, Mobile; Richard Harbison, Woods Hole Oceanographic Institution, Massachusetts; Mikhail Matz, University of Texas, Austin; Mark Moline, California State Polytechnic University, San Luis Obispo; Karen Osborn, Scripps Institution of Oceanography, La Jolla, California; Gustav Paulay, University of Florida, Gainesville; Philip R. Pugh, National Oceanography Centre, Southampton, United Kingdom; Bruce Robison, MBARI; Brad Seibel, University of Rhode Island, Kingston; Alison Sweeney, University of California, Santa Barbara; Erik Thuesen, Evergreen State College, Olympia, Washington

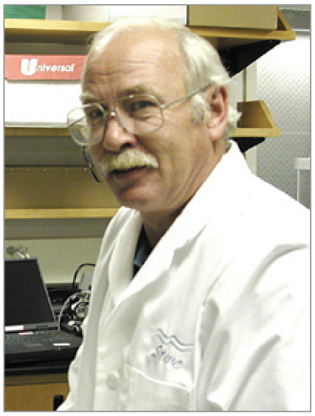
The research team's discovery of a fluorescent protein in a comb jelly was the first for this phylum, making Ctenophora only the fourth phylum so far known to have fluorescent proteins. In a comprehensive review, the research team cataloged more than 40 independent evolutionary events leading to luminescence. These findings suggest that bio-optical communication serves a central role in the ocean, although there has been almost no experimental evidence testing possible functions in a controlled setting. The group showed that fluorescence is used by jellies to attract prey. They have also made breakthroughs in characterizing the luminescence chemistry of the vampire squid, bioluminescent chaetognaths, and a yellow-luminescent polychaete worm. A major goal of the team is to establish a baseline of gelatinous animals, because there is scientific speculation that human-induced and naturally occurring changes in the deep sea may result in a drastic increase in abundance of gelatinous species. The near-term research requirements for this include describing the biodiversity of the fragile deep-living animals and developing methods and devices capable of distinguishing and quantifying this diversity.



In memory of our friend and colleague

Steve Fitzwater
1952-2010

Senior Research Technician
MBARI Chemical Sensor Laboratory



Steve Fitzwater left an incredible legacy in ocean biogeochemistry, having played important roles in some of the most influential field experiments of the past 40 years. His Master's thesis work at Moss Landing Marine Laboratories with John Martin established the basis by which nearly all accurate measurements of primary production in the ocean are now made. He played a key role in the development of methods to measure carbon export and participated in almost all of the U.S. Joint Global Ocean Flux Study field programs.

Steve was the logistical organizer for the successful IronEx I, IronEx II, and SOFEX iron fertilization experiments. He organized and wrote the first paper from the MBARI MOOS Upper-Water-Column Science experiment, describing iron transport from the upwelling center at Año Nuevo, off the Central California coast. He coordinated the field work for the Sampling and Analysis of Iron experiment with some 20 labs from around the world. Most recently, Steve had been coordinating the field work for MBARI's Land/Ocean Biological Observatory and was participating in development of a novel carbon dioxide sensor.

Awards and Degrees

Environmental Sample Processor Team

(Jim Birch, Cheri Everlove, Scott Jensen, Roman Marin III, Doug Pargett, Christina Preston, Brent Roman, Chris Scholin)
*R&D Magazine 47*th Annual R&D 100 Award

Marcia McNutt

100 Most Influential Alumni, University of California, San Diego

Bruce Robison, Kim Reisenbichler

Paper on the barreleye fish, *Macropinna microstoma*, Number 41 of the Top 100 Discoveries of the Year in 2009, *Discover Magazine*

Bruce Robison

Ed Ricketts Award for Lifetime Achievement in the Field of Marine Science, Monterey Bay National Marine Sanctuary

Alexandra Worden

Scholar, Canadian Institute for Advanced Research

David Packard Distinguished Lecturer

Professor Farooq Azam of Scripps Institution of Oceanography is presented with a medal by MBARI President and Chief Executive Officer Chris Scholin (right) to commemorate his selection as the 2009 David Packard Distinguished Lecturer. The distinguished lecturer program was established to recognize outstanding performance in marine science and engineering. Azam, an internationally acclaimed marine microbial ecologist, is known for shifting the paradigm for how oceanographers conceptualize microbial communities and biogeochemical processes, introducing the concept of the "Microbial Loop". Azam is also known for his extensive mentorship of students and postdoctoral researchers, many of whom have gone on to establish successful research programs and, like Azam, have garnered awards for their research excellence. Dr. Azam has authored or co-authored over 160 publications, is a Fellow of the American Academy of Microbiology, and a member of the Faculty of 1000.

Invited Lectures

Doug Au
National Student Leadership Council, University of California, Berkeley

James P. Barry
Keynote Address, Subseabed CO_2 Storage Symposium, Bergen, Norway

Keynote Address, Goldschmidt Conference, Davos, Switzerland

Lawrence Livermore National Laboratory, Livermore, California

International Marine Conservation Congress Ross Sea Conference, Washington, D.C.

Monterey Bay Aquarium, Monterey, California

Biological Impacts of Ocean Acidification Investigator Meeting, Kiel, Germany

Moss Landing Marine Laboratories, California

Commission for the Conservation of Live Antarctic Marine Resources Ross Sea Workshop, La Jolla, California

International Council for the Exploration of the Sea Deep-Sea Threat Symposium, Azores, Portugal

James G. Bellingham
Tropical Marine Science Institute, National University of Singapore

Keynote Speaker, Florida Conference on Recent Advances in Robotics, Florida Atlantic University, Boca Raton

Keynote Presentation, Center for Environmental Sensing and Modeling Workshop, Nanyang Technological University, Singapore

Symantec Lecture Series, Mountain View, California

Defense Advanced Research Projects Agency Vent Power Meeting, La Jolla, California

Chief of Naval Research, Washington, D.C.

Peter G. Brewer
Distinguished Lecture, Texas A&M University, Corpus Christi

Jefferson Fellowship Program, Pacific Grove, California

Yale University, New Haven, Connecticut

Distinguished Speaker, National Science Foundation combined Geosciences and Biological Sciences Divisions, Washington, D.C.

Francisco Chavez
International Marine Conservation Congress, Washington, D.C.

Princeton University, New Jersey

Fifth International Panel of Experts on the Peruvian Anchovy, Lima, Peru

International Meeting on Climate Change, Guayaquil, Ecuador

Ocean Biological Observatories, Mestre, Italy

International Fishmeal and Fish Oil Organisation Annual Conference, Vienna, Austria

Lynne Christianson
City College of San Francisco, California

David Clague
U.S. Geological Survey, Menlo Park, California

Logan Lecture, University of Ottawa, Canada

University of Munich, Germany

Judith Connor
Cyamus Regional Group, International Association of Aquatic and Marine Science Libraries and Information Centers, Marina, California

Monterey Bay Aquarium, Monterey, California

T. Craig Dawe
Plataforma Oceánica de Canarias, Telde, Gran Canaria, Spain

Duane R. Edgington
Fourth International Workshop on Distributed Cooperative Laboratories: Instrumenting the Grid Workshop, Alghero, Sardinia, Italy

Steve Etchemendy
European Seas Observatory Network of Excellence, Tromsø, Norway

European Seas Observatory Network of Excellence, Paris, France

Wave Power Symposium, Ente Vasco Energia, Bilbao, Spain

Sergey Frolov
University of California, Santa Cruz

Steven Haddock

Keynote Address, National Association of Biology Teachers, Denver, Colorado

Hopkins Marine Station of Stanford University, Pacific Grove, California

Keynote Address, Stanford University Molecular Imaging Group, Pacific Grove, California

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

University of California, Santa Cruz

American Society of Limnology and Oceanography, Nice, France

Julio Harvey

Sixth International Conference on Marine Bioinvasions, Portland, Oregon

Kent Headley

Keynote Speaker, Coral Reef Environmental Observatory Network Workshop, Melbourne, Australia

Ken Johnson

University of California, Santa Cruz

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

Hopkins Marine Station of Stanford University, Pacific Grove, California

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

University of Gothenburg, Sweden

Keynote Lecture, Marine Underwater Technology Conference, Gothenburg, Sweden

Shannon Johnson

Cuesta College, San Luis Obispo, California

National Oceanic and Atmospheric Administration Ocean Exploration Program, Aquarium of the Pacific, Long Beach, California

Heather Kerkering

San Francisco Ports and Harbor Safety Committee, California

West Coast Governors Agreement Workshop on Harmful Algal Blooms, Portland, Oregon

William Kirkwood

Moss Landing Marine Laboratories, California

Judith T. Kildow

National Association of Business Economists, San Francisco, California

Canadian Government Special Review, Ottawa, Canada

Monterey County League of Women Voters, Monterey, California

California State University, Monterey Bay, Seaside

Zbigniew Kolber

American Society of Limnology and Oceanography, Nice, France

International Symposium: Rising CO_2, Ocean Acidification, and Their Impacts on Marine Microbes, Honolulu, Hawaii

Western Photosynthesis Conference, Asilomar, California

Lonny Lundsten

California State University, Monterey Bay, Seaside

Gene Massion

Ocean Observatories Initiative Science Workshop, Baltimore, Maryland

George I. Matsumoto

Hawaii Institute of Marine Biology, Coconut Island

Monterey Bay Aquarium, Monterey, California

Science North, Sudbury, Canada

American Geophysical Union, San Francisco, California

Mike McCann

Naval Postgraduate School, Monterey, California

OceanSITES Data Management Meeting, Venice, Italy

Marcia McNutt

Keynote Presentation, Marine Geoscience Leadership Symposium, Washington D.C.

Travel Dynamics International Expedition, Great Lakes

Tom O'Reilly

Polytechnic University of Catalunya, Vilanova, Spain

Ocean Observatories Initiative Sensor Workshop, Portland, Oregon

European Seas Observatory Network of Excellence Best Practices Workshop, Brest, France

Charles Paull

Shell Research Lab, Houston, Texas

Society for Sedimentary Geology, Torres de Paine, Chile

American Association of Petroleum Geologists Pacific Section Meeting, Ventura, California

Anadarko Petroleum, Houston, Texas

ExxonMobil Exploration Company, Houston, Texas

Keynote Address, Submarine Mass Movements and Their Consequences, Fourth International Symposium, Austin, Texas

Christina Preston

Moss Landing Marine Laboratories, California

San Francisco State University, California

Kanna Rajan

Office of Naval Research Unmanned Systems Review, Orlando, Florida

GMV Aerospace and Defence, S.A., Madrid, Spain

Heriot-Watt University, Edinburgh, United Kingdom

University of Strathclyde, Glasgow, United Kingdom

University of Washington, Seattle

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

IBM Research – India, New Delhi

Birla Institute of Technology and Science, Goa, India

Defence Research Development Organisation, Center for Artificial Intelligence and Robotics, Bangalore

Indian Institute of Technology, Chennai, India

Wonderfest, University of California, Berkeley

Steve Ramp

Office of Naval Research Internal Waves in Straits Experiment Planning Meeting, Honolulu, Hawaii

Office of Naval Research Internal Waves in Straits Experiment Planning Meeting, Taichung, Taiwan

Pacific Coast Ocean Observing System Board of Governors, Seattle, Washington

Erika Raymond

International Council for the Exploration of the Sea International Symposium, Horta, Portugal

Bruce Robison

Ricketts Memorial Lecture, Monterey Bay National Marine Sanctuary Symposium, Monterey, California

Hopkins Marine Station of Stanford University, Pacific Grove, California

Steinbeck Institute, Monterey, California

John Ryan

Stanford University, California

Moss Landing Marine Laboratories, California

Coastal and Estuarine Research Federation, Portland, Oregon

Brian Schlining

American Geophysical Union, Toronto, Canada

Kyra Schlining

Hartnell College, Salinas, California

Christopher Scholin

Environmental Protection Agency, Cincinnati, Ohio

Center for Microbial Oceanography: Research and Education, University of Hawaii, Manoa

International Research Institute of Stavenger, Norway

Mount Desert Island Biological Laboratory, Maine

Hopkins Marine Station of Stanford University, Pacific Grove, California

NASA Astrobiology Institute, Mountain View, California

Lawrence Livermore National Laboratory, Livermore, California

U.S. Food and Drug Administration, Maryland

Ken Smith

Hopkins Marine Station of Stanford University, Pacific Grove, California

University of California, Santa Cruz

Sasha Tozzi

Hartnell College, Salinas, California

Western Photosynthesis Conference, Asilomar, California

William Ussler

University of North Carolina, Chapel Hill

Michael Vardaro

Moss Landing Marine Laboratories, California

Robert C. Vrijenhoek

Korean Polar Research Institute, Incheon

Microbiology Society of Korea, Jeju Island

Keynote Address, Ewha Womans University, Seoul, Korea

Sixth International Symbiosis Society Congress, University of Wisconsin, Madison

University of Alabama, Birmingham

University of Georgia, Athens

Occidental College, Los Angeles, California

Alexandra Worden

Integrated Microbial Biodiversity meeting of the Canadian Institute for Advanced Research, Pacific Grove, California

Pacific Northwest National Laboratory, Richland, Washington

Plenary Session, U.S. Department of Energy (DOE) Genome to Life and U.S. Department of Agriculture-DOE Plant Feedstock Genomics Annual Meeting, North Bethesda, Maryland

University of British Columbia, Vancouver, Canada

Western Photosynthesis Conference, Pacific Grove, California

Yanwu Zhang

Office of Naval Research Unmanned Maritime Systems Technology Review Meeting, Orlando, Florida

Farewell

The MBARI staff gathered in October to bid farewell to President and Chief Executive Officer Marcia McNutt (front center, in pink). McNutt headed the institute for 12 years and left after being appointed by President Barack Obama as director of the U.S. Geological Survey.

Mentorships

Nancy Barr

Laura Vollset, graduate summer intern, University of California, Santa Cruz (illustrating the Observatory Middleware Framework, the oxygen minimum zone, and ocean acidification)

James P. Barry

Thomas Knowles, M.S. student, Moss Landing Marine Laboratories (effects of ocean acidification on the shallow water jellyfish, *Aurelia*)

Kristy Kroecker, Ph.D. student, Stanford University (patterns of succession in shallow subtidal habitats in a natural CO_2 venting site off Italy)

Craig McClain, postdoctoral fellow (faunal patterns and processes in Monterey Canyon and on Davidson Seamount)

Eric Pane, postdoctoral fellow (acid-base balance of deep-sea animals under climate stress)

James G. Bellingham

Sergey Frolov, postdoctoral fellow (exploring the economic drivers for detecting and predicting harmful algal blooms)

Karen Parker, graduate summer intern, Moss Landing Marine Laboratories (oxygen sensor evaluation for the *Tethys* Long Range AUV)

Peter G. Brewer

Keith Hester, postdoctoral fellow (geochemistry of gas hydrates as determined using in situ laser Raman spectroscopy)

Peter G. Brewer, William Kirkwood

Xin Zhang, Ph.D. student, Ocean University of China, Qingdao (engineering a pore-water sampling probe for laser Raman spectroscopy)

David Caress

Katie Maier, Ph.D. student, Stanford University (mapping AUV data from the Lucia Chica surveys offshore Big Sur)

David Caress, Charles Paull

Abena Temeng, M.S. student, Stanford University (distributary channel development of the Newport Canyon-Channel System)

Francisco Chavez

Joel Craig, graduate summer intern, Georgia Institute of Technology (what CTD fluorescence/bottle chlorophyll tells us about phytoplankton)

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

Francisco Chavez, Zbigniew Kolber

Sasha Tozzi, postdoctoral fellow (microbial energy cycle in the ocean)

Francisco Chavez, John Ryan

Hey-Jin Kim, postdoctoral fellow (modeling physical-biological coupling in the California Current system)

David Clague

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

Marilena Calarco, Ph.D. student, University of Rome (submarine geology of Pantelleria)

Levin Castillo, M.S. student, University of Quebec at Chicoutimi (large Archean lava flows and modern analogs)

Danilo Cavalaro, Ph.D. student, University of Catania, Italy (the submarine geology of Etna Volcano)

Brian Dreyer, postdoctoral fellow (U-Th systematics of Axial Seamount lavas)

Iain Faichney, Ph.D. student, Townsville University (formation of drowned coral reefs, Maui-Nui Complex, Hawaii)

Christoph Helo, Ph.D. student, McGill University (formation of clastic deposits at Axial Seamount)

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

Jonathan Weiss, Ph.D. student, University of Hawaii (drowned reefs along the Hawaiian volcanic chain)

Danelle Cline, Duane Edgington

Marco Moreira, undergraduate summer intern, Universidade Federal de Minas Gerais, Brazil (automatic visual classification of events in underwater video)

Judith Connor

Amy Cebada, high school student, Pajaro Valley High School (effects of organic gardening on the environment)

Roberto Flores, high school student, Pajaro Valley High School (effects of organic gardening on the environment)

Dulce Guzman, high school student, Pajaro Valley High School (Stop Trashing Our Planet: comparison between an urbanized beach and a non-urbanized beach)

Julie Huang, high school student, Pajaro Valley High School (Stop Trashing Our Planet: comparison between an urbanized beach and a non-urbanized beach)

Katie Mach, Ph.D. student, Stanford University (wave-induced hydrodynamic forces on intertidal seaweeds)

Kevin Miklasz, Ph.D. student, Stanford University (reproductive strategies in articulated coralline algae)

Breanna Mireles, high school student, Pajaro Valley High School (Stop Trashing Our Planet: comparison between an urbanized beach and a non-urbanized beach)

Christine O'Neil, undergraduate student, Stanford University (Monterey Bay marine algae)

Edith Parades, high school student, Pajaro Valley High School (Stop Trashing Our Planet: comparison between an urbanized beach and a non-urbanized beach)

Miguel Perez, high school student, Pajaro Valley High School (effects of organic gardening on the environment)

Duane Edgington

Erika Raymond, postdoctoral fellow (applications of the ORCA Eye-in-the-Sea camera)

Kevin Gomes

Durga Pavani Brundavanam, undergraduate summer intern, Mississippi State University (moving more of the prototype functionality of the Observatory Middleware Framework into the Apache ServiceMix Enterprise Service Bus)

Steven Haddock

Katherine Elliott, undergraduate summer intern, Franklin Olin School of Engineering (developing the Jellywatch.org website)

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

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

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

Michelle Schorn, undergraduate summer intern, Yale University (cloning of siphonophore photoproteins)

Andy Hamilton

Roman Marin IV, undergraduate summer intern, Cabrillo College (wave energy for vertical profiling applications)

Heather Kerkering, Steve Ramp

Taryn Takahashi, undergraduate summer intern, Stanford University (educational module on harmful algal blooms for the CeNCOOS web site)

Megan Kelso, graduate summer intern, Stanford University (CeNCOOS in San Francisco Bay)

Linda Kuhnz

Joshua Barraza, high school student, Pajaro Valley High School (native dune habitats)

Adriana Briceno, high school student, Pajaro Valley High School (native dune habitats)

Jackeline Castorena, high school student, Pajaro Valley High School (energy use reduction strategies)

Richard Lopez, high school student, Pajaro Valley High School (energy use reduction strategies)

Evelyn Martinez, high school student, Pajaro Valley High School (energy use reduction strategies)

Bruny Mora, high school student, Pajaro Valley High School (energy use reduction strategies)

Dominic Porraz, high school student, Pajaro Valley High School (energy use reduction strategies)

Eddie Sumano, high school student, Pajaro Valley High School (native dune habitats)

George I. Matsumoto

Margaret Aranda, high school student, Pajaro Valley High School (marine debris)

Katie Armintrout, high school student, Pajaro Valley High School (marine debris)

Beatriz Collazo, high school student, Pajaro Valley High School (marine debris)

Alena Dooner, undergraduate summer intern, Monterey Peninsula College (communicating the science of ocean acidification to a high school audience)

Diego Gonzalez, high school student, Pajaro Valley High School (developing a protocol for detecting the presence of domoic acid in the waters off the Santa Cruz Wharf)

Jose Jimenez, high school student, Pajaro Valley High School (developing a protocol for detecting the presence of domoic acid in the waters off the Santa Cruz Wharf)

Elisabet Moya, high school student, Pajaro Valley High School (developing a protocol for detecting the presence of domoic acid in the waters off the Santa Cruz Wharf)

Elda Ortiz, high school student, Pajaro Valley High School (marine debris)

Alicia Reyes, high school student, Pajaro Valley High School (developing a protocol for detecting the presence of domoic acid in the waters off the Santa Cruz Wharf)

Richelle Valentino, high school student, Pajaro Valley High School (marine debris)

Tom O'Reilly

Devin Bonnie, undergraduate summer intern, Hope College (applying SIAM and PUCK technology to the Great Lakes Observatory instruments)

Charles Paull

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

Jon R. Rotzien, Ph.D. student, Stanford University (sand depositions in deep-sea channels)

Josh Plant

Rosemary Alvarez, high school student, Pajaro Valley High School (urban/agricultural runoff and water quality)

Reyna Angeles, high school student, Pajaro Valley High School (urban/agricultural runoff and water quality)

Fabian Cortez, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville sloughs)

Jasmin Magana, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville sloughs)

Daniel Navarro, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville sloughs)

Lizette Ramos, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville sloughs)

Daisy Ruiz, high school student, Pajaro Valley High School (urban/agricultural runoff and water quality)

Roxana Valadez, high school student, Pajaro Valley High School (urban/agricultural runoff and water quality)

Christian Vega, high school student, Pajaro Valley High School (aquatic invertebrates: indicators of water quality in Watsonville sloughs)

Kanna Rajan

Sergio Jimenez Celorro, Ph.D. student, University of Carlos III de Madrid (machine learning for environmental state estimation using hidden Markov models)

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

Alhayat Ali Mekonnen, graduate summer intern, Heriot-Watt University (plan visualization for autonomous underwater vehicles)

Steve Ramp

Zhonghua Zhang, Ph.D. student, Stanford University (numerical modeling of the generation and propagation of nonlinear waves in the South China Sea using the Stanford SUNTANS model)

Bruce Robison

Stephanie L. Bush, Ph.D. student, University of California, Berkeley (behavior and ecology of deep-sea squids)

Steve Rock

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

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

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

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

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

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

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

John Ryan

Dustin Carroll, M.S. student, Moss Landing Marine Laboratories (oceanographic and land-sea processes in Carmel Bay)

Michael Jacox, Ph.D. student, University of California, Santa Cruz (modeling nutrient supply in the California Current system)

Bryant Mairs, graduate summer intern, University of California, Santa Cruz (autonomous surface vessels for coastal oceanography)

Christopher Scholin

Monika Frazier, undergraduate summer intern, University of Hawaii, Hilo (real-time water quality monitoring)

Julie Robidart, MEGAMER postdoctoral researcher, University of California, Santa Cruz (applications of the ESP for assessing microbial community structure and function)

Ken Smith

Amanda Kahn, M.S. student, Moss Landing Marine Laboratories (education and outreach for iceberg cruise)

Michael Vardaro, postdoctoral fellow (deep-sea bioturbation and the role of the echinoid, *Echinocrepis rostrata*)

Stephanie Wilson, postdoctoral fellow (particle flux associated with zooplankton feeding/defecation in the deep midwater)

Susan von Thun

Kayelyn Simmons, undergraduate summer intern, Hampton University (observations of egg cases from the holopelagic polychaete family: Tomopteridae)

Robert C. Vrijenhoek

Asta Audzijonyte, postdoctoral fellow (statistical phylogeography of hydrothermal vent invertebrates)

Rahel Salathé, postdoctoral fellow at the Swiss National Science Foundation (bacterial endosymbiont variation among bone-eating *Osedax* worms)

Andrew Thaler, Ph.D. student, Duke University (phylogeography of *Ifremeria* snails from Manus Basin)

Alexandra Worden

Harriet Alexander, undergraduate summer intern, Wellesley College (molecular phylogenetic characterization of Monterey Bay to open ocean phytoplankton communities)

Marie L. Cuvelier, Ph.D. candidate, Rosenstiel School of Marine and Atmospheric Science, University of Miami (growth and grazing mortality rates of uncultivated globally important picophytoplankton taxa)

Elif Demir, postdoctoral fellow (quantitative approaches for enumerating picophytoplankton taxa)

Meredith Everett, Ph.D. student, Rosenstiel School of Marine and Atmospheric Science, University of Miami (fish physiology and gene expression)

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

Adam Monier, postdoctoral fellow (metagenomics of microbial communities across a gradient of marine biomes)

Cinda Scott, Ph.D. student, Rosenstiel School of Marine and Atmospheric Science, University of Miami (the genetic basis of evolved differences in gene expression in *Fundulus heteroclitus*)

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

Julie Vassar, undergraduate summer intern, Smith College (distribution of a novel uncultured protistan group)

Adams, L.G. and **G.I. Matsumoto** (2009). Enhancing ocean literacy using real-time data. *Oceanography*, **22**: 12-13.

Bernard, J.M., **J.P. Barry, K.R. Buck**, and V.R. Starczak (2009). Impact of intentionally injected carbon dioxide hydrate on deep-sea benthic foraminiferal survival. *Global Change Biology*, doi: 10.111/j.1365-2486.2008.01822.x.

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Burla, M., Baptista, A.M., Zhang, Y., and **Frolov, S.** (2009). Seasonal and inter-annual variability of the Columbia River plume: A perspective enabled by multi-year simulation databases. *Journal of Geophysical Research*, doi:10.1029/2008JC004964.

Bush, S.L., **B.H. Robison**, and R.L. Caldwell (2009). Behaving in the dark: Locomotor, chromatic, postural, and bioluminescent behaviors of the deep-sea squid *Octopoteuthis* deletron Young 1972. *Biological Bulletin*, **216**: 7-22.

Chao, Y., Z. Li, J. Farrara, J.C. McWilliams, **J.G. Bellingham**, X. Capet, **F.P. Chavez**, J.-K. Choi, R.E. Davis, J. Doyle, D.M. Fratantoni, P. Li, P. Marchesiello, M.A. Moline, J.D. Paduan, and **S.R. Ramp** (2009). Development, implementation and evaluation of a data-assimilative ocean forecasting system off the central California coast. *Deep-Sea Research Part II*, **56**: 100-126.

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Clague, D.A. (2009). Accumulation rates of volcaniclastic sediment on Loihi Seamount, Hawaii. *Bulletin of Volcanology*, **71**: 705-710.

Clague, D.A., J.C. Braga, D. Bassi, P.D. Fullager, W. Renema, and J.M. Webster (2009). The maximum age of Hawaiian terrestrial lineages: Geological constraints from Koko Seamount. *Journal of Biogeography*: doi: 10.1111/j.1365-2699.2009.02235.x.

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Dickey, T., N. Bates, R.H. Byrne, G. Chang, **F.P. Chavez**, R.A. Feely, A.K. Hanson, D.M. Karl, D. Manov, C. Moore, C. Sabine, and R. Wanninkhof (2009). The NOPP O-SCOPE and MOSEAN projects advanced sensing for ocean observing systems. *Oceanography*, **22**: 168-181.

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Evans, W., P. Strutton, and **F.P. Chavez** (2009). Impact of tropical instability waves on nutrient and chlorophyll distributions in the equatorial Pacific. *Deep-Sea Research Part I*, **56**: 178-188.

Faichney, I.D.E., J.M. Webster, **D.A. Clague**, C. Kelley, B. Appelgate, and J.G. Moore (2009). The morphology and distribution of submerged reefs in the Maui-Nui Complex, Hawaii: New insights into their evolution since the early Pleistocene. *Marine Geology*, **265**: 130-145.

Feng, Y., C.E. Hare, J.M. Rose, S.M. Handy, G.R. DiTullio, P.A. Lee, W.O. Smith Jr., J. Peloquin, **S. Tozzi**, J. Sun, Y. Zhang, R.B. Dunbar, M.C. Long, B. Sohst, and D.A. Hutchins (2009). Interactive effects of CO_2, irradiance and iron on Ross Sea phytoplankton. *Deep-Sea Research Part I*: **57** (3): 368-383 doi:10.1016/j.dsr.2009.10.013.

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Gertz, M., **C. Rueda**, and J. Zhang (2009). Interoperability and data integration in the geosciences. In: *Scientific Data Management: Challenges, Existing Technology, and Deployment*, edited by A. Shoshani and D. Rotem. Chapman & Hall/CRC Press, pp. 366-398.

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On the cover, from top image on front clockwise around to the back cover: ROV launch during the Antarctic iceberg expedition, bathymetric map of data collected with mapping AUV, ROV *Doc Ricketts*, Instrumentation Technician Thomas Hoover with the long range AUV, gas venting from seafloor during the northern expedition, testing sea urchin tolerance for increased carbon dioxide levels, siphonophore seen during the northern expedition, Electronics Technician Tom Marion, sea spider feeding on an anemone, researchers Chris Preston and Julie Robidart working on the Environmental Sample Processor.

Inside front cover: ROV *Phantom* is deployed from the Icebreaker *Nathaniel B. Palmer* in Spring 2009 with iceberg C-18A in background. Photo by Amanda Kahn. See story on page 12.

Inside back cover: The mapping AUV, *D. Allan B.*, is launched from the R/V *Zephyr* during the northern expedition. Data from the *D. Allan B.* were used to produce high-resolution maps that enabled targeted ROV dives for the study of gas vents and lava flows. Photo by David Caress. See story page 4.

Photo credits: 2, 3 (bottom): Todd Walsh; 3 (top): Craig Joseph, U.S. Department of Energy; 7: David Caress; 13 (right): Nicolle Rager Fuller, National Science Foundation; 14: Rob Sherlock; 18: Gernot Friederich; 19: Stoyka Netcheva, Atmospheric Science and Technology Directorate, Environment Canada; 22: Paul McGill; 23 (both): Todd Walsh; 24: Michael Ekern, University of St. Thomas; 31: Todd Walsh; 33: (bottom center): Linda Kuhnz; 33: (bottom left): Alexandra Worden; 36, 37 (both): Todd Walsh; 39: Steve Ramp; 41: David Caress; 44: Laura Vollset; 46, 48 (bottom): Todd Walsh; 48 (top): Kim Fulton-Bennett; 49: Todd Walsh; 53: Todd Walsh.

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