THE OFFICIAL MAGAZINE OF THE OCEANOGRAPHY SOCIETY

Oceanography

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Chavez, F.P., P.G. Brewer, and C.A. Scholin. 2017. Celebrating 30 years of ocean science and technology at the Monterey Bay Aquarium Research Institute. *Oceanography* 30(4):18–25, https://doi.org/10.5670/oceanog.2017.420.

DOI

https://doi.org/10.5670/oceanog.2017.420

Celebrating 30 Years of Ocean Science and Technology at the Monterey Bay Aquarium Research Institute

By Francisco P. Chavez, Peter G. Brewer, and Christopher A. Scholin

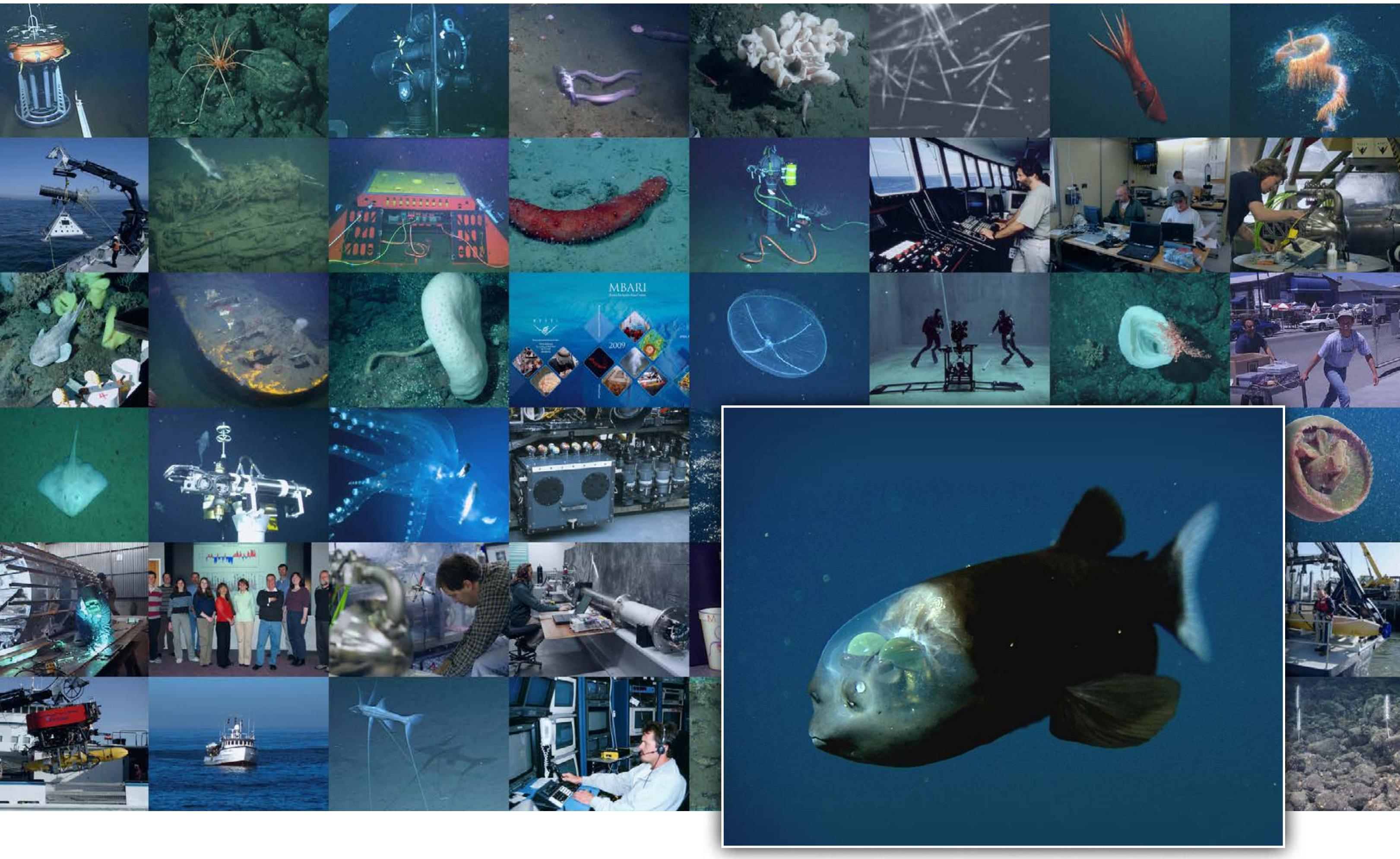
"The mission of MBARI is to achieve and maintain a position as a world center for advanced research and education in ocean science and technology, and to do so through the development of better instruments, systems and methods for scientific research in the deep waters of the ocean."

— David Packard, 1990

In the spring of 1987, David Packard, co-founder of the Hewlett Packard Company, formalized creation of the Monterey Bay Aquarium Research Institute (MBARI). In doing so, he sought to foster a partnership among scientists and engineers who would dedicate their time to designing, building, and using novel instruments and systems to tackle pressing research issues within the ocean sciences. Packard's interest in ocean technology was sparked during his government service as the US Assistant Secretary of Defense from 1969 to 1971. Encouraged by two of his daughters, Nancy Burnett and Julie Packard, he created the Monterey Bay Aquarium Foundation in 1978. With personal backing from David and Lucile Packard, the Monterey Bay Aquarium opened its doors in 1984 with Julie Packard as its director. That development transformed a faded, seaside sardine-processing factory located in the storied Cannery Row of Steinbeck fame, into a world-renowned destination. The richness of Monterey's history, maritime heritage, and the wonders of the adjacent bay made for an ideal combination that not only met Packard's expectations, but also led to MBARI, a private, nonprofit oceanographic research institution that would complement the public-serving Monterey Bay Aquarium. With its iconic submarine canyon and location along the central California coast, Monterey Bay would serve as a natural laboratory for implementing his vision for MBARI.

In his 1989 address to participants of the inaugural meeting of The Oceanography Society, Packard highlighted three technological innovations that he felt would transform oceanography: remotely operated vehicles (ROVs), new sensors, and advanced computer science/data systems. By integrating and building on those core capabilities, ocean scientists and engineers would be poised to make incredible discoveries. A great deal has changed since Packard made that proclamation, at a time when MBARI's founding employees made the best of makeshift lab space that was simply defined by "wet" and "dry" designations. In those early days, efforts to establish facilities and refine the operation of R/V *Point Lobos* and ROV *Ventana* were all-consuming. An innovative database project was initiated so that ROV observations recorded on videotape could be quantified and cross-referenced with co-registered environmental measurements. Other sensor system developments were also just beginning, and a concerted effort to establish and standardize sustained chemical and biological

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

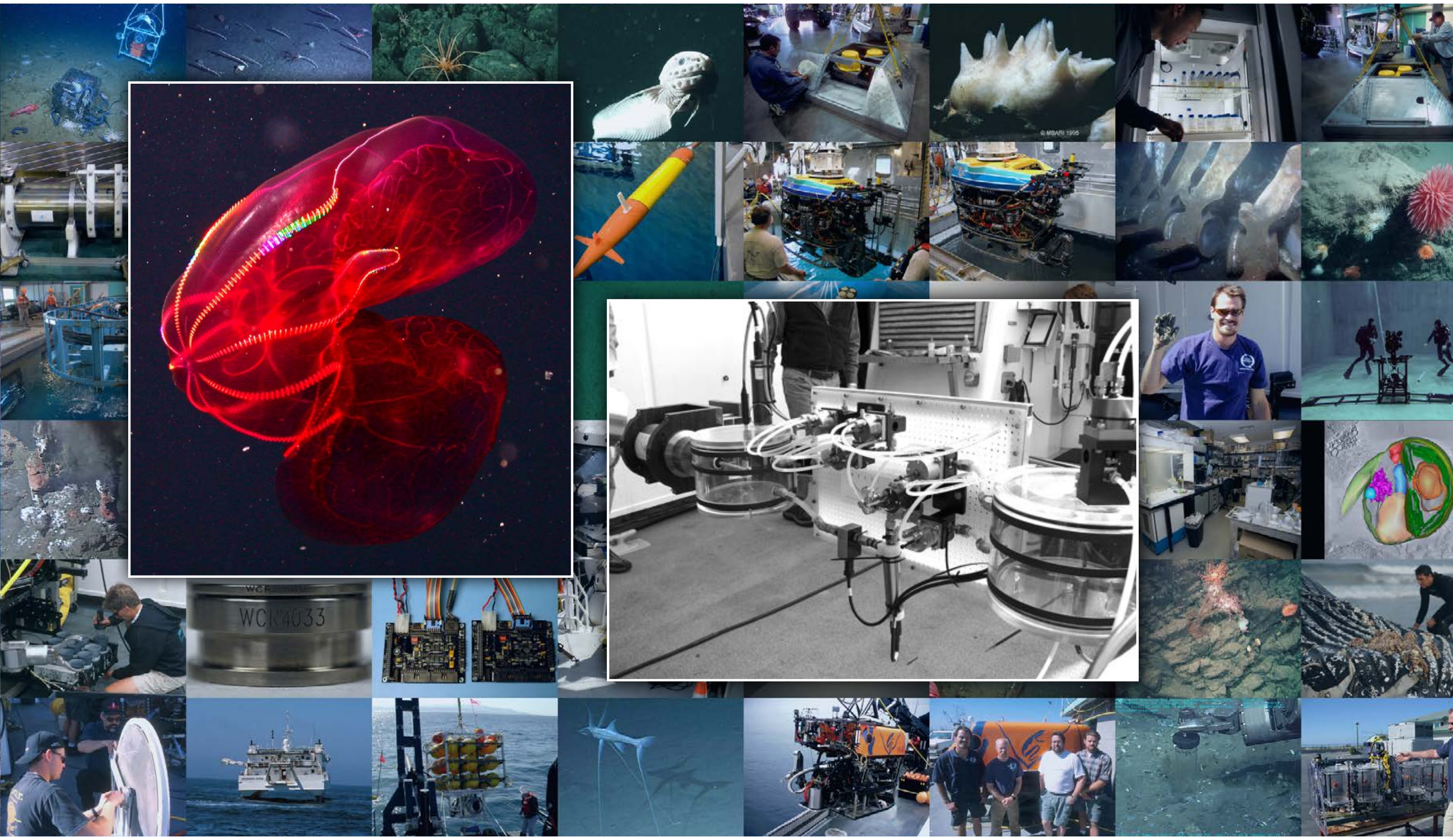


measurements in Monterey Bay began in earnest. Not long after, R/V *Western Flyer*, MBARI's present-day regional class research vessel, emerged as an artist's rendering on the wall, and ROV *Tiburon*, a custom-made vehicle around which that ship would be built, was still on the drawing board.

The idea of MBARI developing and operating sophisticated autonomous underwater vehicles (AUVs) as we know them today came not long after the institute's founding, but at that time such capabilities seemed a distant dream, far from realization—there was much work to be done to build the kind of institute Packard expected, and to prove its value to the oceanographic community at large. Thirty years later, we reflect on this legacy with this special issue of *Oceanography* to commemorate MBARI contributions that were inspired and made possible by Packard's vision, charge, and philanthropy. It is appropriate that *Oceanography* be the home for the special issue, as it was also the venue where MBARI was first introduced to the oceanography community at large (Barber, 1988).

Many of the papers in this collection have a strong scientific emphasis. However, underlying the science are the fundamental engineering efforts that Dave Packard envisioned and expected and without which the scientific advances would not have been possible. Early on and through its first 30 years, MBARI invested heavily in deep-ocean-rated ROVs and the ships required for their deployment and use. Hence, many of the papers in this special issue include, in various forms, science and technology associated with these platforms.

Robison et al. describe the coevolution of ROV-based midwater (from just below the surface to just above the deep seafloor) animal research and technology development. The first ROV *Ventana* dive occurred a year after MBARI was founded, a sign of the institute's early rapid growth. By 2017, the upgraded version of that original vehicle completed its 4,000th dive, a testament to its success as a platform for scientific exploration and discovery, as well as technology development. Robison et al. describe three important elements and results of their ecological research program: (1) repeated video transects and careful data management that allow for long-term studies of climate impacts on midwater communities, (2) new instrumentation and systems that provide a basis for measuring in situ respiration rates and fluid flow within and around animals, and (3) the coevolution of technical (ballast, thruster control) and human (talented ROV pilots) capabilities that have enabled in situ observation and experimental manipulation of animals with minimal disturbance. This paper concludes with a look forward in terms of the science and technology that will continue to fuel midwater ecological research. It highlights the addition of acoustics to complement video, and smaller and less-expensive

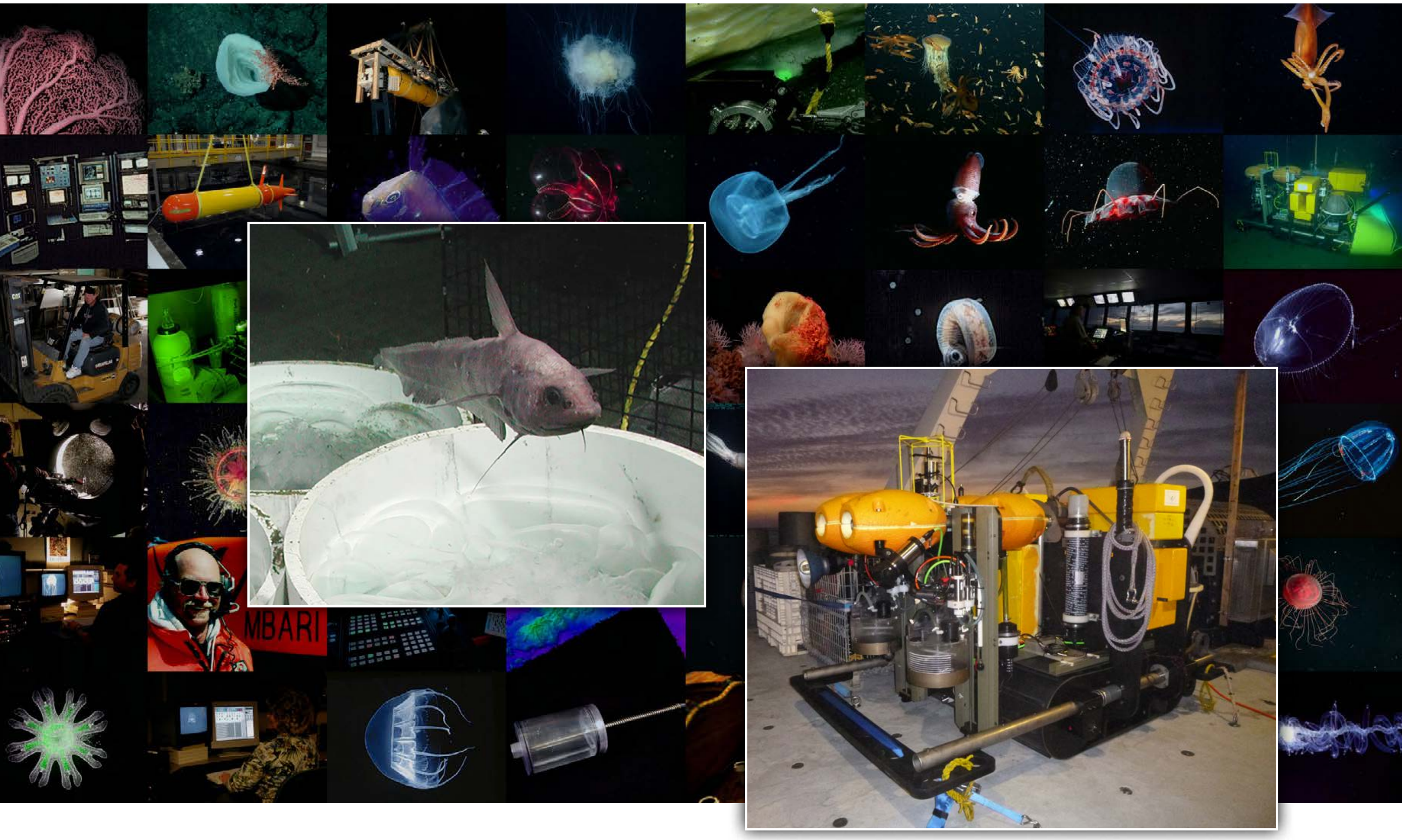


AUVs for furthering continued and sustainable water column operations at MBARI and elsewhere.

In a closely related paper, **Haddock et al.** describe their studies of bioluminescence, biodiversity, and behavior of midwater gelatinous animals. They use video data and animals collected with the ROV (or by divers in shallow water) in their efforts to provide a window into life in Earth's largest habitat. They highlight MBARI's Video Annotation and Reference System (VARS), where annotations from many thousands of hours of ROV video are curated. VARS has proven to be a valuable resource for deep-sea ecologists inside and outside of MBARI. Haddock et al. have moved beyond observations of bioluminescence to studies of the molecular basis of that phenomenon, as well as examination of the genetic and taxonomic diversity of midwater communities made possible by genome sequencing. The ability to observe animals in situ has led to the discovery of novel interspecies behaviors and interactions that were previously unknown.

Brewer et al. describe the use of ROVs and associated instruments to execute novel geochemical experiments in the deep sea. They focus on three topics: (1) testing long-proposed ideas of deep-sea carbon dioxide (CO_2) disposal so as to ameliorate climate change, (2) studies of deep-sea methane hydrates, both as a natural occurrence and as a possible source of extractable energy, and (3) development of deep-sea Raman spectroscopy systems and their applications. Their first attempts to inject liquid CO_2 in deep water led to unexpected discoveries and highlighted the importance of in situ experiments. Eventually, they succeeded at a depth over 3,000 m and watched the results in awe through the live ROV video feed. The success of this effort led to serious questions about the environmental consequences of deep-sea CO_2 disposal and the ocean acidification problem in general. Brewer et al. also describe elegant Raman-sensed experiments to create gas hydrates within sediments, as well as experiments that debunked the expectations that CO_2 injection within a methane hydrate reservoir could simultaneously achieve CO_2 disposal and methane gas recovery. In closing, these authors look at the impacts of increasing temperature on the rates of oxidation of organic matter in the ocean by microbes. They conclude that, based on first principles, microbial communities will increase their ocean oxygen consumption rates in a warmer world, leading to greater competition between microbes and the higher organisms, with shallower oxygen losses and corresponding changes in the marine food web.

Barry et al. describe studies of the effects of increasing CO_2 on life in the sea. The early injections of liquid CO_2 described above led MBARI engineers to design a system that was equivalent to those used in terrestrial environments—Free Air CO_2 Enrichment (FACE)—to test the impacts of rising atmospheric



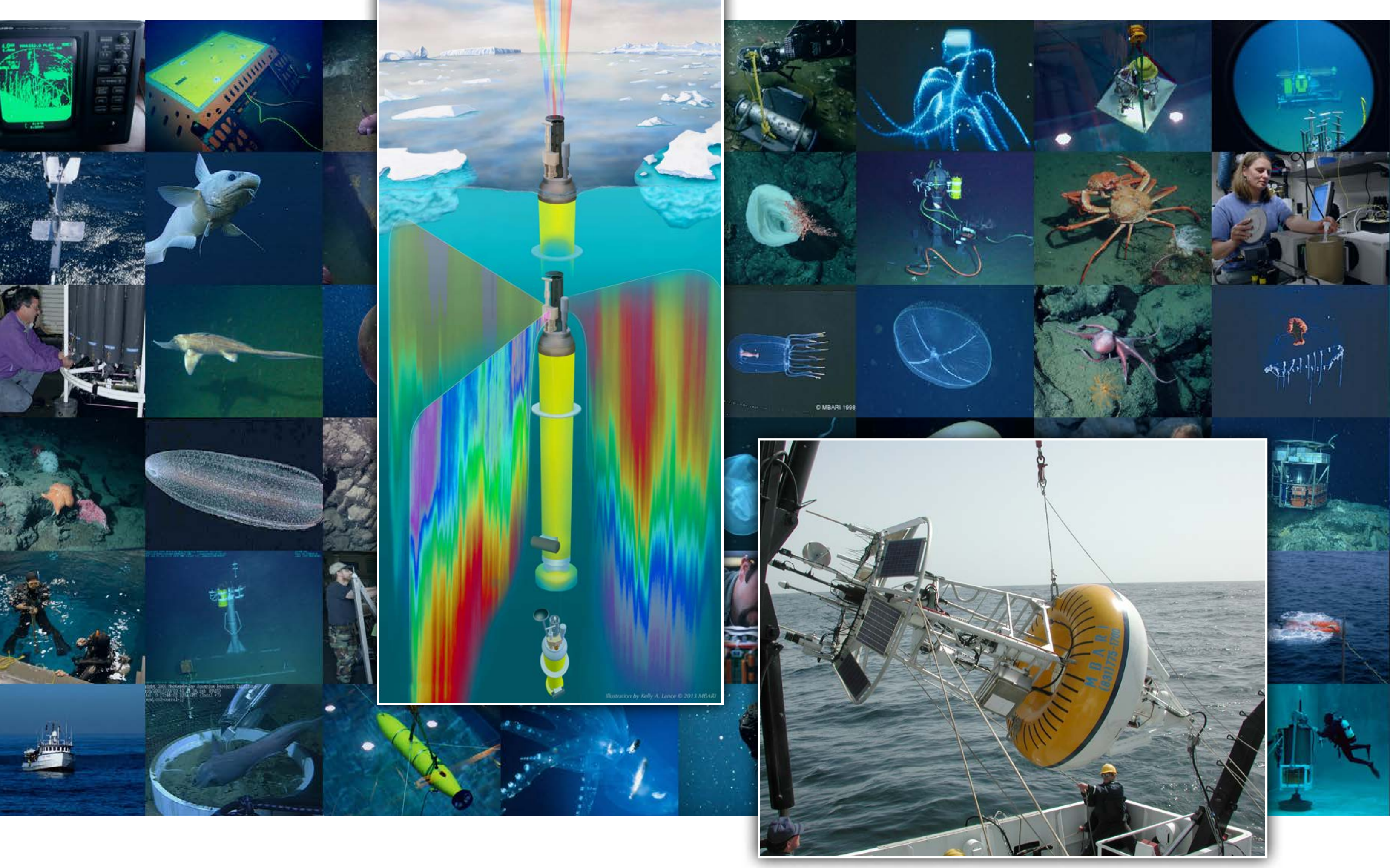
CO_2 on plant communities. Free Ocean CO_2 Enrichment (FOCE) would serve as the ocean analog to FACE. Barry et al. were the first to use the FOCE system to study the effects of high CO_2 on marine animals. FOCE was an engineering feat, requiring a system that could be transported and deployed in the deep sea, inject CO_2 in a tightly controlled fashion into a contained space with captive animals, and then measure resulting chemical and biological changes. The FOCE system has also been adapted to shallow water use, including at the Great Barrier Reef. With that introduction, the bulk of this paper focuses on development and use of a new laboratory-based coastal Upwelling Simulator. Coastal upwelling, by bringing deeper, lower pH waters to the surface, makes these regions more acidic relative to other open-ocean environments. These upwelling environments are sensitive to ocean acidification and decreasing oxygen. The Upwelling Simulator can physically replicate changes in temperature, carbon dioxide, and oxygen, allowing scientists to observe how animals that are subject to multiple stressors respond over time, including to conditions that may be experienced in the future in a high-CO_2 world.

Smith et al. describe long-term monitoring efforts on the abyssal plain at Station M below the California Current at over 4,000 m depth. This work began in 1989 and includes sediment trap measurements of organic carbon flux and time-lapse camera observations of the seafloor. The observing system has evolved over time, and its records now cover nearly 30 years of operation. Reports based on the system range widely from relationships, to climate alternations, to unique observations of episodic, high-flux organic carbon deposition events. Smith et al. describe the evolution of observing at Station M and offer a blueprint for the next generation of abyssal systems. The benthic observatory infrastructure now includes three continuously deployed moorings and a mobile benthic lander known as Rover. One of the moorings continues the traditional sediment trap time-series collections, while a second sediment trap mooring is used to capture and preserve material for genetic and microscopic analyses. A custom-made Sedimentation Event Sensor (SES) mooring provides a means for imaging the rain of particles at hourly resolution, and Rover autonomously crawls across the seafloor around Station M measuring benthic respiration rates while also optically imaging the seafloor. Once or twice per year, *Western Flyer* transits to the site to service the instrumentation and to deploy the ROV for additional sampling. A Wave Glider periodically visits the array between ship visits to communicate with the SES mooring and Rover to confirm normal operations, and to collect sea surface environmental information. For the future, Smith et al. envision two new technological developments that will enhance long-term benthic observations:

a "park-and-fly AUV" to replace the periodic ship-based ROV video transects, and a Vertically Integrated Profiling Event Responder (VIPER) to trace episodic deposition events as they transpire from surface to seafloor.

Clague et al. describe how they use high-resolution AUV surveys coupled with surgically precise ROV sampling to characterize volcanic eruptions on the Juan de Fuca and Gorda Ridges off the Pacific Northwest. Development of the mapping AUVs has allowed imaging of deep-sea bathymetry at much higher resolution than is possible from a ship. The AUV maps used by these authors have a resolution of 1 m when the mapping vehicle cruises 50 m above the bottom. The high-resolution maps are made possible by state-of-the-art data processing and precision navigation. The maps have allowed Clague et al. to direct ROVs for targeted sampling of important features. Using this technology, the team was able to map Axial Seamount in 1998, 2011, and 2015 both pre- and post-eruption in some areas. These descriptions are likely the most extensive for any submarine volcanic activity worldwide, highlighting the complexity and magnitude of important seafloor processes in ways that were not possible to measure previously.

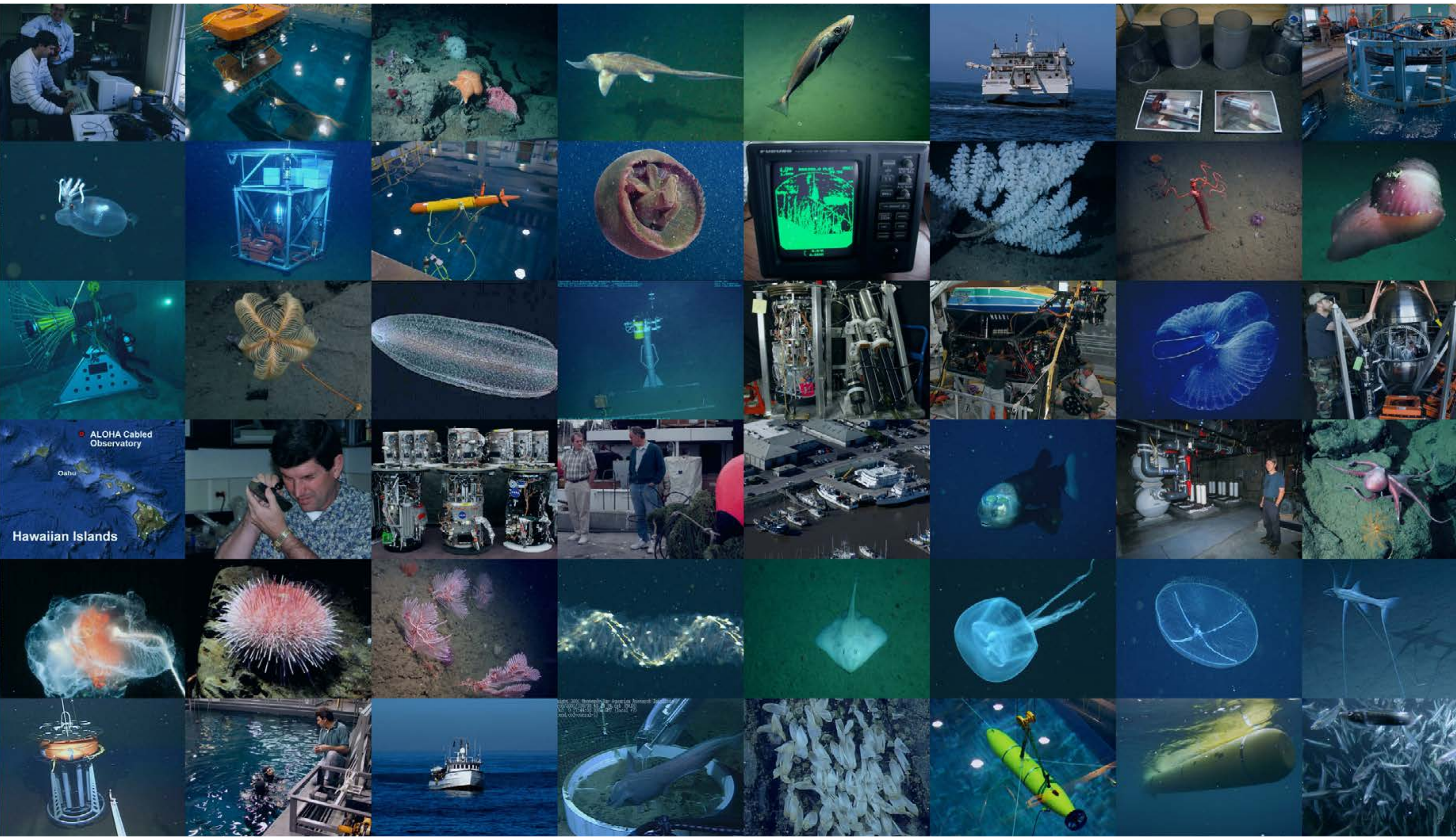
Scholin et al. provide the history and use of the Environmental Sample Processor (ESP), an autonomous robotic device that collects and processes water samples for molecular biological analyses. The ESP represents a classic example of the time and energy required to design and build a novel instrument de novo. The effort started in the early 1990s, inspired by progress in the biomedical field. The first scientific motivation was to devise an "early warning system" for microscopic algae known to produce toxins that can sicken humans and wildlife. Species-specific DNA probes for detecting particular organisms were designed and tested in a laboratory setting. That experience informed the design of an autonomous device that could apply those assays in situ by automating the steps of sample collection and probe application to provide an estimate of the abundance of particular species. The instrument also evolved to preserve samples for later laboratory analyses, such as high-throughput DNA sequencing. After 25 years of continued development, the general concepts associated with remote sample collection and processing remain as part of a new generation of ESP that occupies a much smaller footprint than its predecessors, thanks to new engineering solutions. In all, the ESP has progressed from a shipboard system to one that can be deployed on a mooring and then to one that can be integrated within an AUV. Progress in marine genomic analytical techniques and in situ sensing now offers a large array of novel assays that can be coupled with the ESP's sample handling capabilities. The application of this instrument to a variety of environmental problems has grown, and this trend is likely to continue in the future.



Sakamoto et al. explore a 15-year time series of nitrate measurements from a coastal mooring. The data were collected using an autonomous chemical sensor that elegantly exploits nitrate's ultraviolet radiation absorption. The In Situ Ultraviolet Spectrometer (ISUS) was designed and tested at MBARI before it was licensed to a commercial company. Initial testing was carried out on the M1 mooring in Monterey Bay, and the record begun in 2001 continues at present. Sakamoto et al. use the record to describe variations in nitrate dynamics from daily to interannual timescales. The daily variations allow for estimates of "new production" that can then be compared to traditional measures. On interannual timescales, the variability in nitrate is related to upwelling strength and large-scale climate indices associated with El Niño. ISUS instruments can now be found monitoring freshwater systems as well as on Argo profiling floats throughout the world ocean.

Chavez et al. discuss the science and technology associated with a multidisciplinary coastal time-series study. The team began focusing on Monterey Bay and the contiguous waters of the California Current in 1988 at the same time as similar efforts were getting underway at the Bermuda Atlantic Time Series (BATS) and the Hawaii Ocean Time-series (HOT) sites. The effort in Monterey Bay included biweekly to monthly ship visits and mooring-based observations. Traditional moorings were modified to carry established and emergent biogeochemical sensors. Site selection was based on logistics and history; the first vertical profiles at one of the sites date to the 1930s. The record collected quantifies the influence of climatic phenomena such as the El Niño-Southern Oscillation and the Pacific Decadal Oscillation, as well as anthropogenic impacts of rising levels of atmospheric CO_2. The ship and mooring time series of the sea surface pressure of CO_2, the longest of their type in the global ocean, capture a large decadal shift from slightly warmer to slightly cooler than average conditions in the mid to late 1990s. The cooler period displays higher nutrient levels and biological productivity, and also marks the beginning of a monotonic decrease in midwater oxygen. A recent period of prolonged warming from 2014 to 2016 stopped the trend of decreasing temperature and reduced the trend for increasing biological productivity. Chavez et al. conclude by presenting a vision for transitioning the time-series study to one that is fully autonomous, where ships are no longer needed for routine measurements and sample collections but instead are used for dedicated process studies. They also suggest that the transition from fixed site time-series investigations to long-term process studies will improve our overall understanding of complex ocean ecosystem dynamics.

The papers collected in this special



issue clearly demonstrate that Packard's directives to (1) concentrate on technology development, and (2) foster a culture of science/engineering peer relationships ultimately set in motion a sustained surge of innovations and discoveries that prove the value of his long-term vision. Those same values continue to drive MBARI's evolution to this day. Early on, Packard established a board of directors for MBARI that included eminent scientists and engineers and members of the Packard family. He was chair of the board until his passing in 1996; Julie Packard assumed that role soon thereafter and has provided the leadership needed for MBARI to continue to succeed. The entire MBARI community recognizes and values the support of its board, the Packard family, and the David and Lucile Packard Foundation.

In order to maintain its mission statement "position as a world center for advanced research and education in ocean science and technology," MBARI routinely refreshes its long-term vision, looking forward to the opportunities and challenges in coming decades. The current versions of the MBARI *Strategic Plan* (https://www.mbari.org/mbari-2011-strategic-plan) and *Technology Roadmap* (https://www.mbari.org/2014-technology-roadmap) reflect this forward-looking approach. These planning documents recognize that the ocean is undergoing profound ecosystem changes due to a combination of natural forces and human activities, changes readily apparent in the 30-year span since MBARI's founding. They also identify scientific and technological directions that will foster exploration and discovery. Given our current level of ocean ecosystem observation and understanding, it is clear that there are many mysteries to solve and discoveries yet to be made—the age of ocean exploration and discovery is far from over. We can only imagine what might be highlighted 30 years from now.

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ACKNOWLEDGMENT

The success of the Monterey Bay Aquarium Research Institute is a tribute to the vision of David Packard and his family, and to long-term support from the David and Lucile Packard Foundation. We also thank external reviewers for critical comments, and *Oceanography* and Dana Lacono for editorial support.

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ARTICLE CITATION

Chavez, F.P., P.G. Brewer, and C.A. Scholin. 2017. Celebrating 30 years of ocean science and technology at the Monterey Bay Aquarium Research Institute. *Oceanography* 30(4):18–25, https://doi.org/10.5670/oceanog.2017.420.