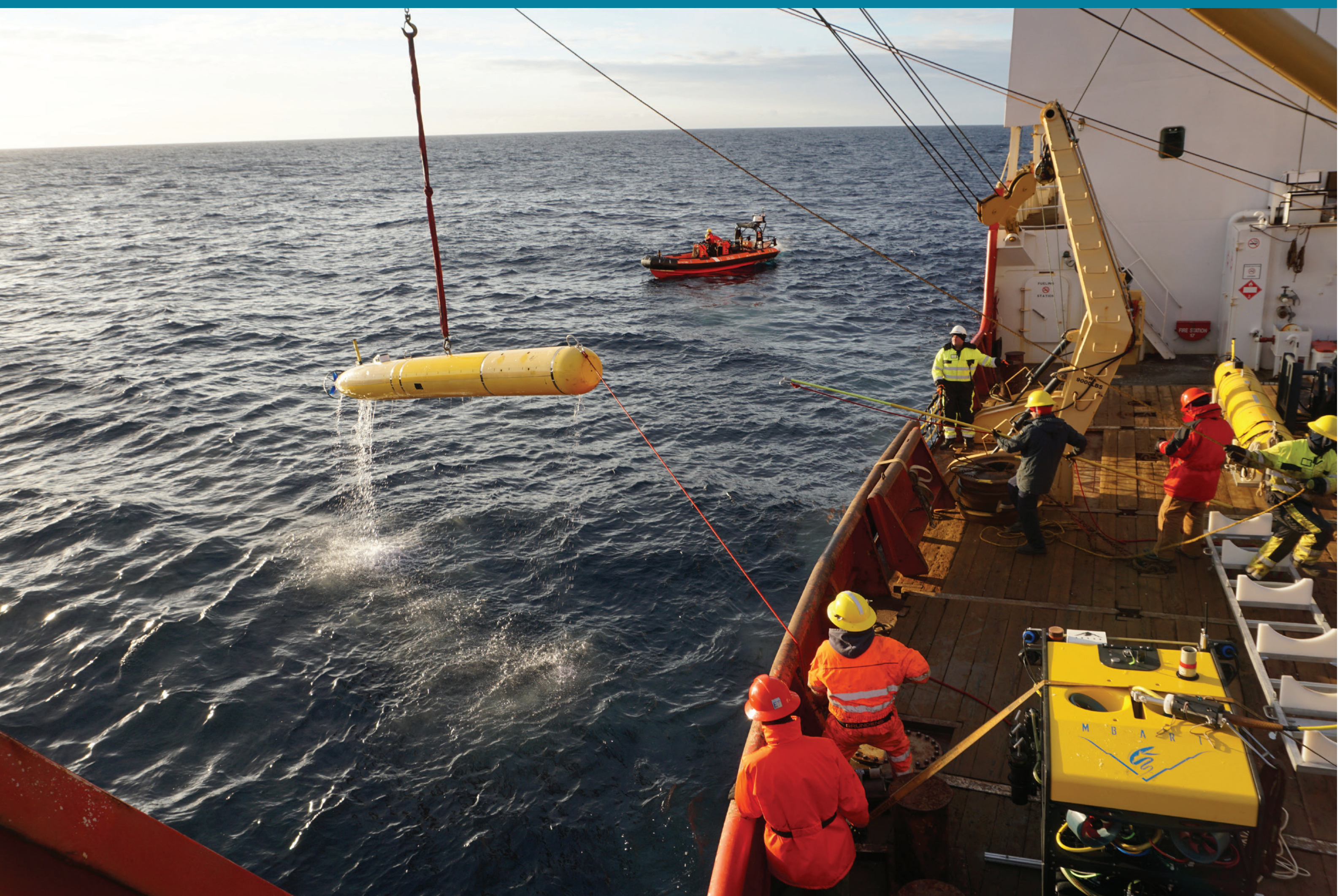
26TH ROGER REVELLE COMMEMORATIVE LECTURE

Oceanography in the Age of Intelligent Robots and a Changing Climate

FEATURED SPEAKER **CHRIS SCHOLIN**



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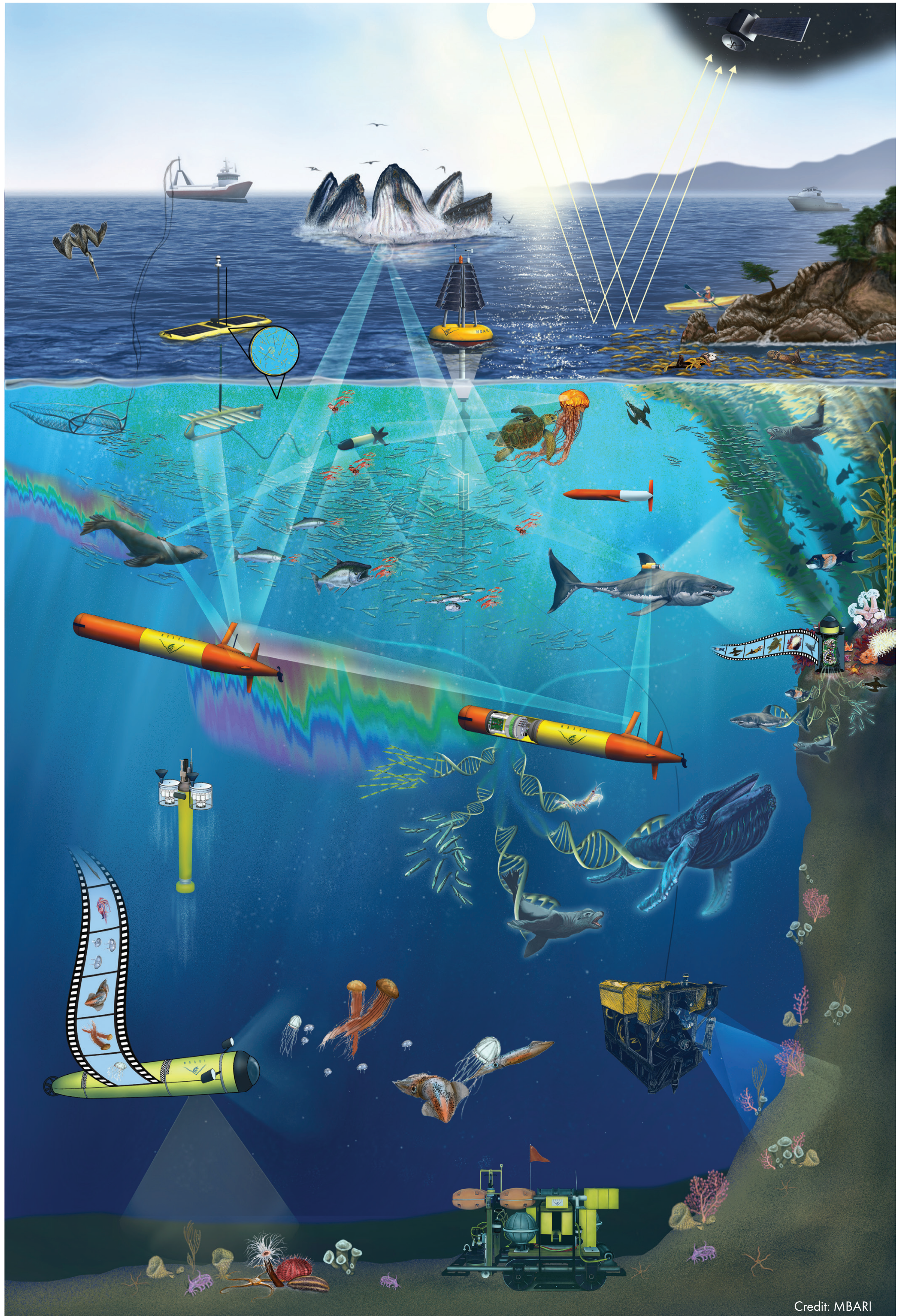

Credit: MBARI

Dear Lecture Participant

On behalf of the Ocean Studies Board of the National Academies of Sciences, Engineering, and Medicine, we would like to welcome you to the 26th Annual Roger Revelle Commemorative Lecture. This lecture was created by the Ocean Studies Board in honor of Dr. Roger Revelle to highlight the important links between the ocean sciences and public policy.

Tonight's Lecture

This evening, for the 26th annual lecture, Dr. Chris Scholin from the Monterey Bay Aquarium Research Institute (MBARI) will explore how the advent of robotic and artificial intelligence technologies have transformed ocean exploration, overcoming the challenges posed by the sea's depth, vastness, and inaccessibility. Dr. Scholin will provide examples of how these technologies have revolutionized ocean research and enabled scientists to further the efforts of visionary scientists such as Roger Revelle. The introduction for this lecture will be given by Dr. Marcia McNutt, president of the National Academy of Sciences.

Sponsorship

The Ocean Studies Board thanks the National Aeronautics and Space Administration, the National Oceanic and Atmospheric Administration, the National Science Foundation, and the U.S. Geological Survey. This lecture series would not be possible without their generous support.

We hope you enjoy tonight's event.

Claudia Benitez-Nelson, *Chair, Ocean Studies Board*
Susan Roberts, *Director, Ocean Studies Board*
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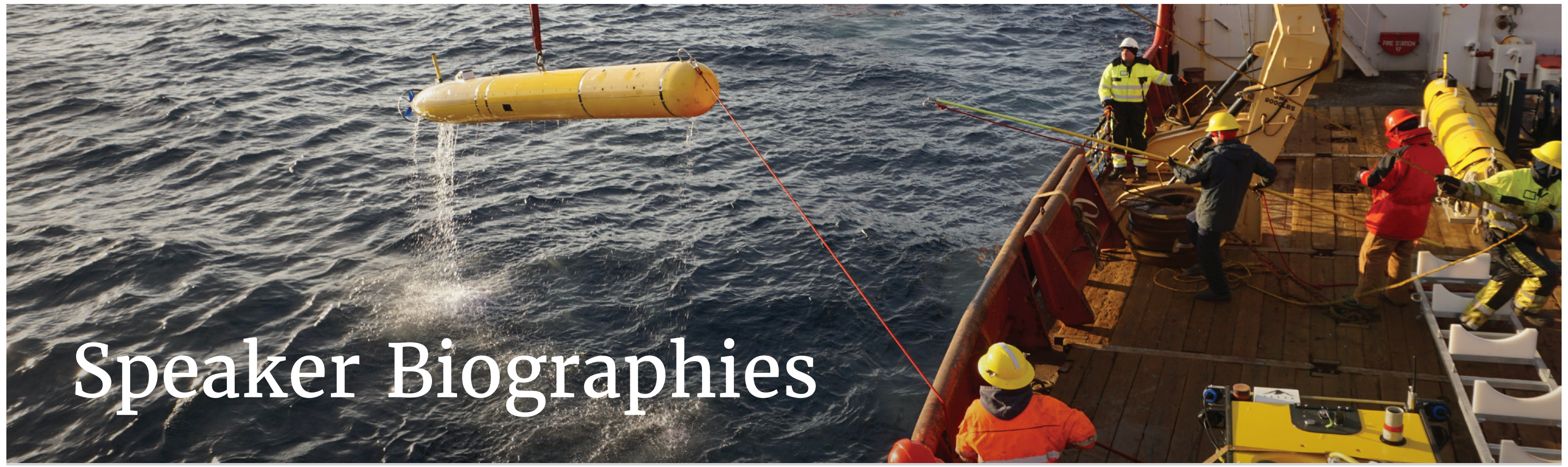


Speaker Biographies

Chris Scholin

President and Chief Executive Officer,
Monterey Bay Aquarium Research Institute

CHRIS SCHOLIN is a native of St. Louis, Missouri. He received a B.A. in Biology from the University of California, Santa Barbara, in 1984, and a M.A. in Molecular Biology and Immunology from Duke University in 1986. After working for a short time as a Research Assistant Professor at the University of South Carolina at Columbia, Chris entered the Massachusetts Institute of Technology – Woods Hole Oceanographic Institution (MIT/WHOI) Joint Program in Biological Oceanography with the objective of combining molecular biology and ecology in an ocean setting.

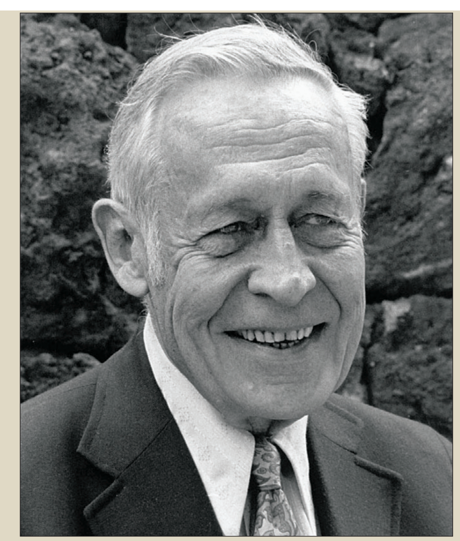
Chris earned his Ph.D. from MIT/WHOI in 1992 and came to the Monterey Bay Aquarium Research Institute later that year to focus on building molecular probes to detect waterborne microbes, in particular toxic and harmful algae. Working collaboratively with a team of engineers, his group pioneered the development of the Environmental Sample Processor (ESP), an instrument that collects water samples autonomously, concentrates microorganisms, and automates the application of molecular probes to detect particular species and substances they produce.

In 2009, 17 years after joining the institute as a Postdoctoral Fellow, Chris was selected to serve as President and CEO of MBARI. In addition to leading MBARI, Chris maintains an active research program that focuses on the development and application of ecogenomic sensors in coastal, open ocean, and deep-sea environments. He currently serves on the Board of Trustees of the Monterey Bay Aquarium Foundation. In 2021, Chris was awarded the Lockheed Martin Award for Ocean Science and Engineering from the Marine Technology Society.

Marcia McNutt

President, National Academy of Sciences

MARCIA MCNUTT (B.A. in physics, Colorado College; Ph.D. in Earth sciences, Scripps Institution of Oceanography) is a geophysicist and the 22nd president of the National Academy of Sciences. From 2013 to 2016, she was editor-in-chief of *Science* journals. McNutt was director of the U.S. Geological Survey from 2009 to 2013, during which time USGS responded to a number of major disasters, including the Deepwater Horizon oil spill. For her work to help contain that spill, McNutt was awarded the U.S. Coast Guard's Meritorious Service Medal. She is a fellow of the American Geophysical Union, Geological Society of America, the American Association for the Advancement of Science, and the International Association of Geodesy. McNutt is a member of the National Academy of Engineering, the American Philosophical Society and the American Academy of Arts and Sciences, a Foreign Member of the Royal Society, UK, the Russian Academy of Sciences, and the Chinese Academy of Sciences, and a Foreign Fellow of the Indian National Science Academy. In 1998, McNutt was awarded the AGU's Macelwane Medal for research accomplishments by a young scientist, and she received the Maurice Ewing Medal in 2007 for her contributions to deep-sea exploration.



Roger Revelle

Revelle was a pioneer in oceanography who over his 50-year career pursued innovative research and created a vision that still influences the field of oceanography to this day. A strong proponent of science communication and public policy, Revelle was a leader in encouraging the scientific community to devote time to address the "long-range problems of society" (Day, 2000, quoting Revelle, 1957). For his contributions to geophysics, Revelle was elected to membership in the National Academy of Sciences (NAS). Revelle's commitment to science policy is evident in his extensive contributions to the work of the NAS. Revelle served as a member of the Ocean Studies Board and its predecessor (Ocean Sciences Board) from 1983 to 1987. He also served on the Board on Atmospheric Sciences and Climate (1982–1986) and as a committee member for several influential National Academies' studies.

Oceanography in the age of intelligent robots and a changing climate

The Ocean Studies Board is proud to present the 26th Annual Roger Revelle Commemorative Lecture featuring Dr. Chris Scholin. This lecture discusses how the advent of robotic and advanced sensing and computing technologies has transformed ocean exploration.

In his opening remarks at the inaugural meeting of the Oceanography Society, David Packard spoke about an opportunity to accelerate progress in ocean science through technology development (Packard, 1989). The ocean, as he saw it, was the last frontier on Earth, and it did not garner the attention it deserved. Yet, it held untold mysteries and unseen landscapes, and many technical, scientific, and societally relevant discoveries awaited. That interest led to the founding of the Monterey Bay Aquarium Research Institute (MBARI; Barber, 1988; Chavez et al., 2017a). A combination and integration of three foundational technologies were projected to transform oceanography: remotely operated vehicles (ROVs), new types of sensors, and advanced computing and data systems. Starting with those building blocks, Packard's charge when founding MBARI was to "go deep and stay long" to improve our understanding of the ocean (Barber, 1988), and to "return data, not samples." This presentation draws from that legacy.

Packard was right. The advent of robotic and advanced sensing and computing technologies has indeed transformed ocean exploration. New tools and techniques have allowed us to overcome many, but by no means all, of the challenges posed by the sea's depth, vastness, and inaccessibility. Packard, like many others, understood that a sustained investment in basic research and engineering would pay future dividends in ways that could not be foreseen. Today, nearly 40 years after MBARI's founding, hybrid human-machine and fully autonomous systems are revealing an unprecedented perspective of the interplay between marine chemistry, physics, biology, and geology. Robots enable coordinated observations of the water column and seafloor in ways that humans cannot match, and extended missions in extreme environments. The acquisition of long-term monitoring data from far-flung corners of the globe, automated *in situ* analyses, real-time communications and data sharing, and active multimedia public engagement across continents are now a part of everyday oceanography. A new window into our ocean world is opening—one that was long imagined by visionary scientists, engineers, and science fiction writers alike.

This presentation examines a number of technological innovations that are revealing surprising insights into the inner workings of our ocean and its inhabitants against the backdrop of a rapidly changing climate. The examples given are by no means a comprehensive review of the role that technology is playing in ocean exploration. Many individuals from organizations around the world have made lasting contributions that have brought us to this juncture. Here, several case studies are chosen to illustrate that ongoing process, and to pay homage to some of the scientists and engineers who set us on this course. We still have much to learn about the sea, its inhabitants, and the vital role it plays in sustaining the health of our planet and the wellbeing of society. Decades-long interdisciplinary science and engineering pursuits have ushered in a new era of discovery driven by bold ideas, serendipitous discoveries, and the allure of the largest and least explored habitat on Earth.

Taking the pulse of the planet

In 1957 Roger Revelle and Hans Suess captured the scientific community's imagination with their groundbreaking paper on CO_2 exchange between the atmosphere and the ocean (Revelle and Suess, 1957). They argued that CO_2 released from the burning of fossil fuels was accumulating in the atmosphere and that a significant fraction of the emissions had dissolved into the sea. Perhaps most importantly, they went on to say,

> "…human beings are now carrying out a large scale geophysical experiment of a kind that could not have happened in the past or be reproduced in the future…. This experiment, if adequately documented, may yield a far-reaching insight into the processes determining weather and climate."

Their findings were provocative, scientifically tantalizing, and urgently driven by increasing global industrialization. Increased atmospheric CO_2 could lead to changes in ocean chemistry and a warmer climate with potentially compounding amplifications due to a number of processes that were not well characterized at the time. The insight was brilliant, but the capabilities for testing this theory globally were in their infancy. Decades of research followed as investigators sought the means to conduct ocean-basin-scale measurements needed to assess predicted trends. The consequences of fossil fuel consumption were of tremendous importance societally, but at the time of Revelle and Suess' proclamation, that was not a part of public discussion and politics as it is today. In 1999, Peter Brewer elegantly recounted that history during the first Annual Revelle Lecture (Brewer, 2000).

Capturing time-space variations in the ocean's interior, at basin scales, accurately, is no small challenge. For many years, the only practical way to tackle this problem was by using crewed ships to conduct hydrographic surveys. Despite the analytical and logistical challenges, a picture of the exchange of CO_2 between the atmosphere and ocean slowly emerged (Brewer, 2013). Decades of work were required to establish the connection between the burning of fossil fuels and the reality of human-driven climate change and ocean acidification. Ironically, nearly 70 years after Revelle and Suess issued their "geophysical experiment" proposition, we now find ourselves scrambling to assess the promise and pitfalls of artificially stimulating the ocean to absorb more CO_2 to mitigate a climate crisis of our own making (e.g., Coale et al., 1996; Brewer, 2013; Bach and Boyd, 2021; National Academies of Sciences, Engineering, and Medicine, 2022; Levin et al., 2023; Smith et al., 2024).

Enter the robots

As ocean sensor systems matured, so too did the platforms on which they could be deployed. In addition to measurements acquired manually, scientists and engineers developed the means to automate air-sea CO_2 flux measurements aboard ships, moorings, and autonomous surface vehicles (ASVs) (Friederich et al., 1995; Chavez et al., 2017b; Chavez et al., 2018). It was apparent that seasonality and geographical location played an important role in when and where there was a net flux of CO_2 into or out of the sea (e.g., Takahashi et al., 2009). Other sensor systems for autonomously acquiring biogeochemical measurements, such as pH (Johnson et al., 2016) and nitrate (Sakamoto et al., 2017), also evolved along with improvements for *in situ* quantification of oxygen and optical parameters, all of which were deployable on autonomous underwater vehicles (AUVs) and ROVs. Development and use of these biogeochemical sensor suites were greatly aided by the availability of mooring technology and well-established time series studies that included routine ship-based hydrographic surveys (e.g., Karl, 2010, 2014; Chavez et al., 2017b). Now, after years of observations, the unmistakable trend of rising CO_2 in the atmosphere with concurrent changes in ocean pH and temperature has emerged (Figure 1; e.g., Thorne et al., 2024) along with complex biological and ecosystem manifestations (e.g., Doney et al., 2020; Alter et al., 2024).

Thanks to a remarkable confluence of technologies and dogged determination of scores of visionary scientists and engineers, it is now possible to observe ocean basin-scale carbon cycling using a distributed fleet of profiling floats—robots—which offer much more information at a far lower cost compared to ship-based surveys (Figure 2a, b; e.g., Johnson and Claustre, 2016; Claustre et al., 2020; Schofield et al., 2022; Sarmiento et al., 2023). A global fleet of floats now return sensor measurement data from remote regions of the globe in real-time, and the information acquired is freely accessible to anyone nearly instantly via the Internet (GO-BGC, 2025). This remarkable achievement has given ocean scientists the equivalent of a medical doctor's tool kit for rapidly assessing a patient's vital

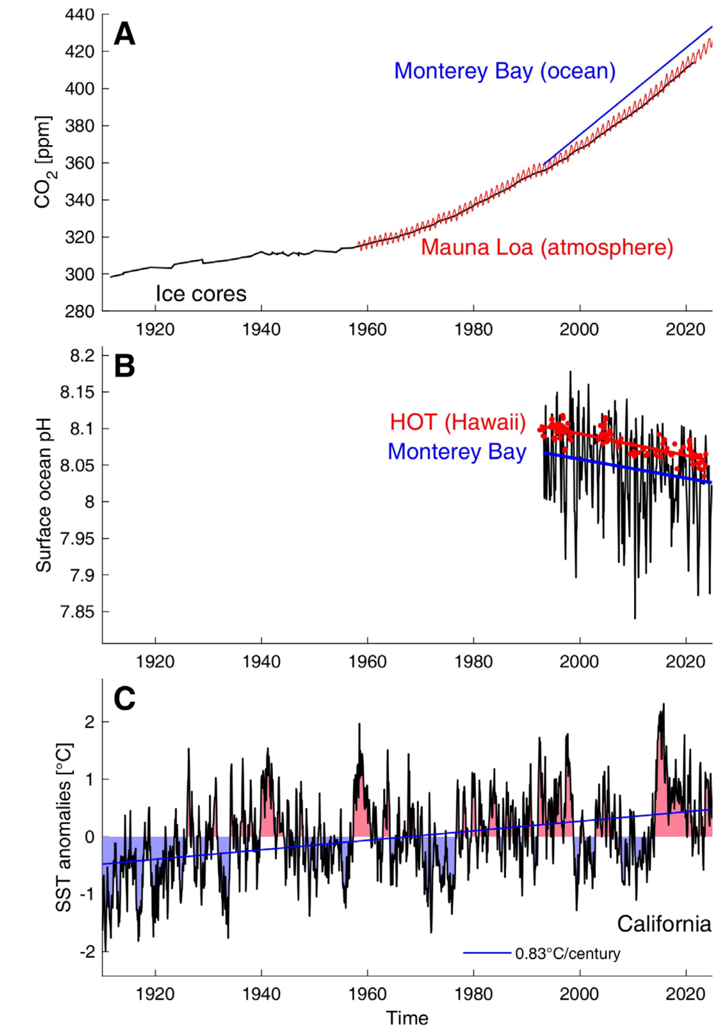


FIGURE 1 Time series from 1900 to present of (A) Atmospheric carbon dioxide (CO_2) measured from ice cores (black) and the Mauna Loa Observatory (red) on the Big Island of Hawaii (MacFarling Meure et al., 2006; Keeling et al., 2001); also shown is the trend in the partial pressure of surface ocean (pCO_2, a measure of CO_2 entering or exiting the sea) in Monterey Bay, California from the early 1990's (blue; updated from Chavez et al., 2017b); (B) Surface Ocean pH from the HOT time series program off Hawaii (red; Karl and Luka, 1996) and Monterey Bay California (blue; updated from Chavez et al., 2017b) from the early 1990's to the present. Note that pH scale is logarithmic; (C) Sea surface temperature anomalies (seasonal cycle removed) from the California Current along the US west coast (Huang et al., 2017). Clear trends are evident for all of the measurements. Credit: MBARI

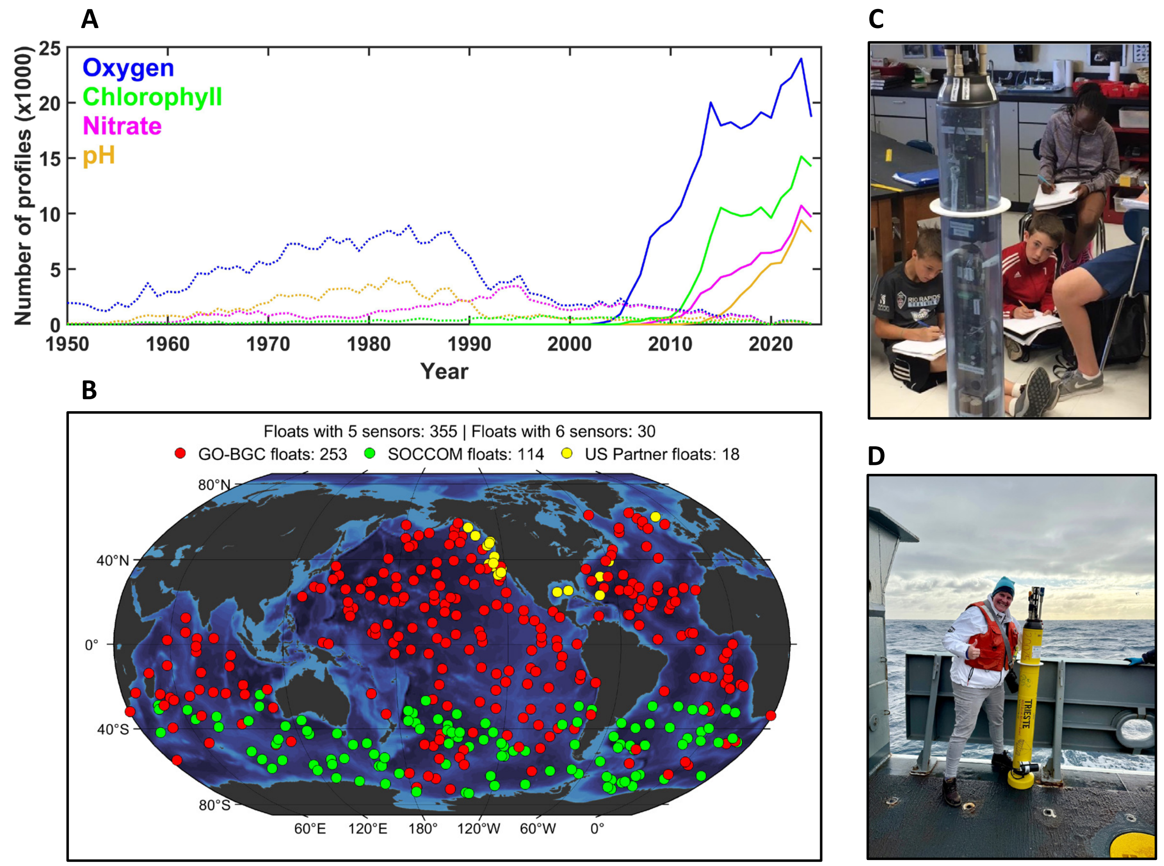


FIGURE 2 Biogeochemical sensing array. (A) Comparison of ship-based profiles for oxygen, chlorophyll, nitrate, and pH, and profiling floats that collect the same measurements. (B) Distribution of floats provided by GO-BGC, SOCCOM, and U.S. partners (GO-BGC, 2025). (C) School children learning about profiling float technology using a mockup with transparent housing. (D) Jennifer Magnusson launching a float named *Trieste* from the RV *Tommy Thompson* in 2024. The Ocean Studies Board (OSB), who oversees the annual Revelle Lecture, named and adopted the *Trieste* float in memory of former OSB member Don Walsh who, with Jacques Piccard, made the first historic dive to the depths of Challenger Deep. Images for (C) and (D) provided by G. Matsumoto and J. Magnusson, respectively, 2025. Credit: MBARI

signs. As a result, we now know that the Southern Ocean—one of the most inaccessible and difficult places to work—plays a major role in ocean-atmosphere carbon cycling and global climate modulation. And as the profiling float network grows and is sustained, we increasingly gain a perspective on how other oceanic regions are responding in-kind. These programs have also proven to have phenomenal education and outreach appeal Figure 2c, d). Groups can adopt floats, name them, even customize their housings, and follow them over time in conjunction with classroom lesson plans (Matsumoto et al., in press; Adopt-A-Float program, 2025; EARTH Lesson Plans, 2025). To date, people from all 50 U.S. states, Puerto Rico, Samoa, and over 15 countries have adopted floats.

Seeing is believing

Advances in biogeochemical measurements have only recently given us the means to observe the basic vital signs of the global ocean. Revealing pelagic ecosystem dynamics and the role that animals play in the marine carbon cycle poses an entirely different and arguably far greater challenge. Since the time of the Challenger Expedition (Thompson, 1887) trawl nets were used to search for life in the deep sea with success, but that method returns no context about the three-dimensional environment in which animals live, and it destroys fragile animals thus obscuring their presence. Diving into the depths to observe life in its natural habitat, up close and in-person, offered an entirely new understanding compared to what nets yielded.

William Beebe (1934), in his book *Half Mile Down*, recounted his personal experiences of being lowered into the sea in a bathysphere. He described an abundance of strange deep-sea animals that frequently glowed in bedazzling ways that defied his explanation. One of his team members, Else Bostelmann, a talented artist, created original works for National Geographic Magazine that reflected Bebee's accounts and brought deep-sea biology to the public's attention. Years later, more sophisticated expeditions followed using self-propelled crewed submersibles, including the use of single-person vehicles (e.g., Robison, 1983; Alldredge et al., 1984; Widder et al., 1989), opening a new chapter of deep-water research and exploration.

With MBARI's founding in the late 1980's, David Packard gave scientists and engineers a new platform for accessing the deep sea. His charge was to adapt an ROV dubbed *Ventana*, originally designed for use in the offshore oil and gas industry, for use as a multi-purpose research platform (Figure 3a, b). Prior to that time, no one had attempted to use an ROV for such purposes. Robison et al. (2017) offers a unique perspective on

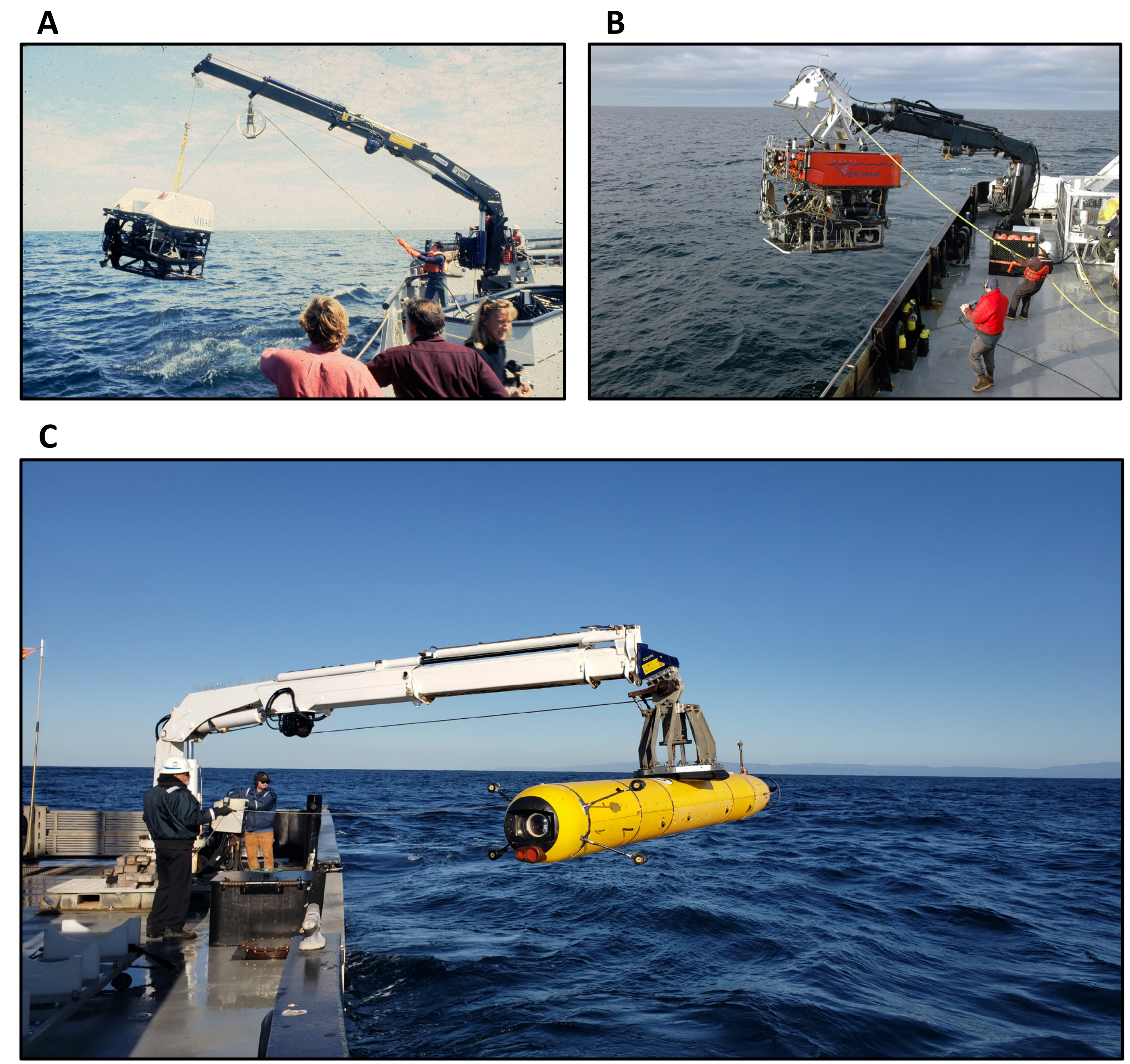


FIGURE 3 Evolution of platforms used for midwater research and time series studies at MBARI. (A) ROV *Ventana's* first launch in 1988 from the R/V *Point Lobos* © 1988 MBARI. (B) Modern day incarnation of *Ventana* being deployed from the R/V *Rachel Carson* Kim Fulton-Bennet © 2014 MBARI. (C) i2MAP AUV for conducting midwater surveys. Kim Reisenbichler © 2022 MBARI.

the history of initiating and developing a midwater research program using ROVs along with Haddock et al. (2017). At the time of its introduction to the ocean science community, *Ventana*, and its support vessel *Point Lobos*, seemed unremarkable compared to storied crewed submersibles such as *Alvin* and *Johnson Sea Link* and their much larger mother ships. But it was soon apparent that ROVs offered tremendous capabilities and were highly adaptable. They quickly became integral to the discovery of new species and revelations of pelagic ecosystem structure and function, in particular, the prevalence and importance of gelatinous animals (Haddock, 2004; Robison, 2004). ROV time series studies also made possible the first-ever comprehensive description of a deep pelagic food web (Choy et al., 2017). All of these advancements were fundamentally enabled by telepresence—underwater video recordings—combined with concurrent measurements of temperature, oxygen, salinity, etc. The addition of robotic sensors and samplers to ROVs also made it possible to collect specimens and conduct unique in situ experiments. A recent example of the utility of what ROVs can enable scientifically is particularly well illustrated in the detailed description of a deep-sea animal new to science that for years was known only as the "mystery mollusk" (Robison and Haddock, 2024). ROVs have proven to be valuable tools for evaluating the impacts of rising levels of CO_2 on ocean biology and chemistry both in the water column and on the seafloor (e.g., Robison et al., 2017; Barry et al., 2017; Brewer et al., 2017). In today's world, ROVs are integral to ocean exploration and are proliferating. The technology continues to evolve rapidly, making it more capable, accessible, and affordable.

Operating ROVs is less costly and logistically less complex than crewed submersibles, but it still requires a surface support ship and skilled crew. In a step toward reducing the dependency on crewed ships, AUVs are being modified to conduct similar surveys. The i2MAP vehicle built at MBARI (Figure 3c) carries imaging and acoustic systems along with other sensors to reproduce midwater transect capabilities that had long been refined using ROVs. The platform is able to travel faster than an ROV and is quieter (Reisenbichler et al., 2016; Robison et al., 2017). Other AUVs along these lines are becoming more common and trending smaller in size for both water column and seafloor observations. Just as robots have improved our capacity for biogeochemical sensing, ROVs and AUVs now offer another suite of platforms and tools for probing the "large scale geophysical experiment" that Revelle and Suess foretold.

The Data Deluge

Obtaining high resolution underwater video observations and conducting *in situ* experiments have proven to be an effective means for documenting ecosystem changes that are occurring over time. For example, in Monterey Bay, changes in oxygen in the water column are linked to observed changes in animal behavior, which in turn has significant implications for food web dynamics (e.g., Figure 4; Robison et al., 2017). A key enabling technology that has made this observation possible is the Video Annotation and Reference System (Schlining and Stout, 2006; VARS Overview, 2025). VARS provides the means to expertly identify what is seen in underwater imagery—a process known as annotation—and merge it with concurrent measurements of relevant physical and chemical parameters. The result is a searchable data base that contains geolocated quantitative sightings of particular animals cross referenced with the environmental conditions under which they were observed. VARS is an open-source application and has been adopted by a number groups, including Australia's Commonwealth Science and Industrial Research Organization (CSIRO), Oregon State University, the University of Hawaii School of Ocean and Earth Science and Technology (SOEST), and the National Oceanic and Atmospheric Administration (NOAA). At MBARI, VARS has grown to include nearly 29,000 hours of underwater imagery from which almost 11 million observations of over 4,400 unique "concepts" (animals, debris, geologic formations, etc.) are cataloged. Nearly 600 peer-reviewed publications and over 300 new species have been described drawing from that archive. The Deep-Sea Guide (2025) offers a publicly accessible portal for accessing a portion of VARS content.

With the ever-growing collection of imagery from a multitude of platforms, humans can no longer keep pace with the demand for video annotation and the ancillary data that comes with it. Machine learning is now playing

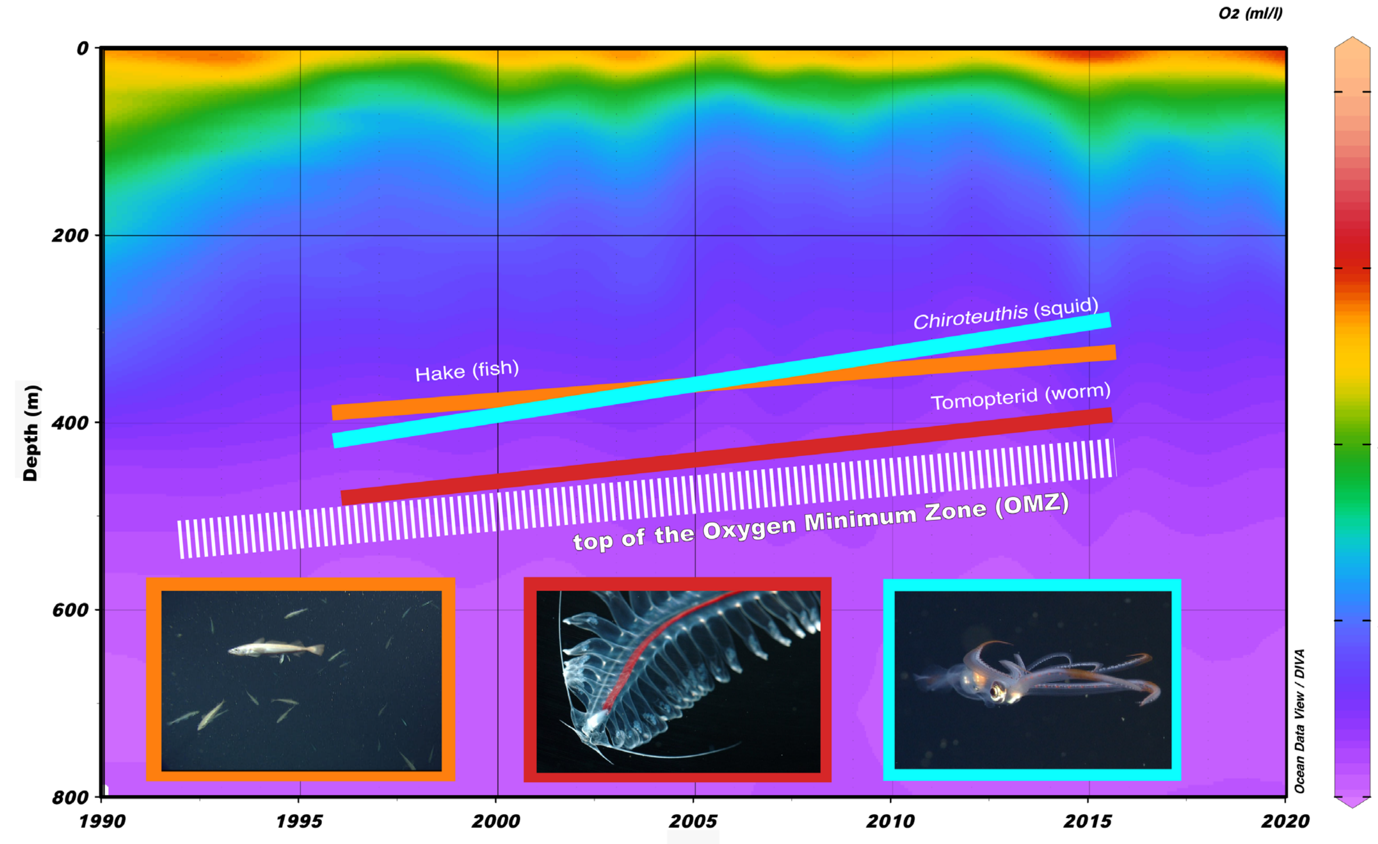


FIGURE 4 Time series observations showing the displacement of several midwater animals towards the surface in response to a shoaling oxygen minimum zone (after Robison et al., 2017). Images © 2025 MBARI.

a central role in processing that information. The VARS annotation pipeline has been improved by using computer models trained on approximately 900,000 localizations of over 1,600 expertly curated concepts to assist with image annotation and identifications (Figure 5; VARS-ML, 2025). In an effort to federate and coordinate this line of research, FathomNet (2025) offers a publicly accessible platform for sharing images and accessing artificial intelligence and machine learning tools to accelerate the analysis of ocean visual data (Katija et al., 2022; Crosby et al., 2023). A companion program, FathomVerse (2025), a free mobile game, offers an interactive science community experience where players engage with real ocean images collected by researchers and robots from around the world. Participants playing the game contribute to improving computer algorithms used to chronicle ocean life while learning about the animals they see, which is proving to be a technologically novel way to expand participation in ocean exploration and discovery.

Machine learning and artificial intelligence can also be used aboard remotely operated and autonomous platforms to process visual and other sensory data in real-time. Without any human intervention, vehicles can adapt to dynamic environmental conditions by leveraging physical, chemical, and biological cues, enabling them to track marine life over extended periods (e.g., Zhang et al., 2021a, b; Katija, 2023) and navigate complex terrain in the absence of detailed maps (e.g., Troni et al., 2025a, b). The power and potential of machine learning and artificial intelligence is only beginning to alter our ability to observe the ocean holistically. There is no doubt that this will be an area of rapid innovation in the years ahead that will transform data acquisition, analysis, and dissemination both ashore and at sea. This technology is also an effective means for engaging the next generation of ocean enthusiasts. Robots supercharged with artificial intelligence offer something for everyone. Whether it is the science they enable, the imagery they produce,

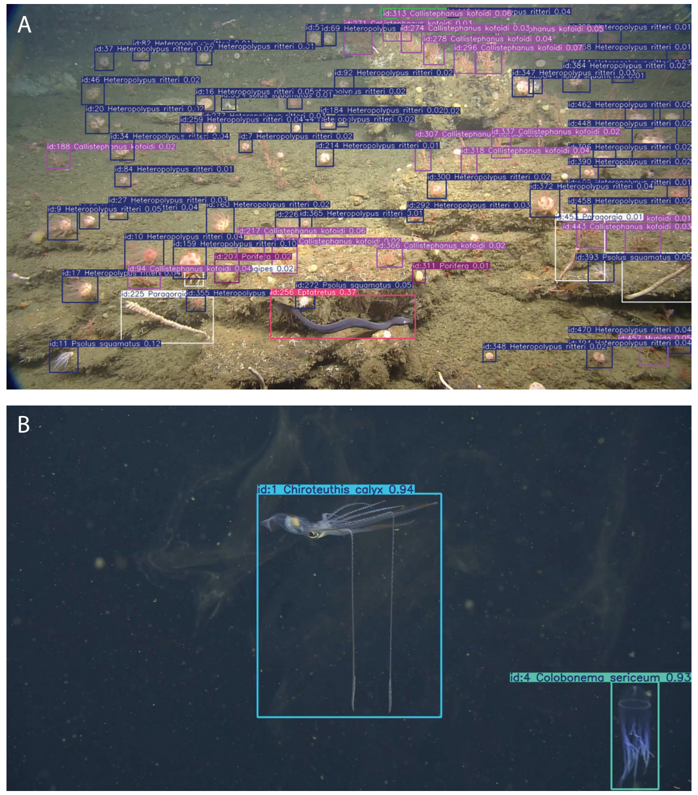


FIGURE 5 Frame grabs of video being processed using an integration of MBARI's Video Annotation and Reference System (VARS) with advanced machine learning tools (VARS-ML) to identify and track animals on the seafloor (A) and in the water column (B). The VARS-ML initiative combines the expertise of marine scientists, engineers, and data scientists. To learn more, see VARS-ML (2025; Source: Lonny Lundston and Nancy Jacobsen Stout). Images © 2025 MBARI.

the computational capability that makes them "smart", the missions they undertake, or just the impressiveness of the machine itself, there is no doubt that in the public's eye modern day robots are fascinating.

The Biological Carbon Pump and Vertical Migration

World Wars I and II sparked a revolution in ocean engineering. Submarines were proving to be very effective at sinking combatants and ships carrying supplies to aid the war effort, and a technological advance was needed to detect and intercept them. Sonar (SOund Navigation And Ranging) offered an answer while providing a way to gauge the depth of the seafloor too. As the technology was refined, it became clear that a reflective layer was sometimes present in the water column that at times was so dense it gave a false sense of the actual depth of the seafloor, even to the extent that ships travelling in uncharted waters reported the presence of phantom shoals. Stranger still, that feature was usually observed to move in rhythm with the time of day, rising at night and descending during the day. The deep scattering layer (DSL) as it came be known was later associated with dense aggregates of animals (e.g., Ritche, 1953; Dietz, 1962).

The advent of sonar had revealed something amazing: diel vertical migration. Animals who spent daylight hours in the twilight of the deep rose at night to feed, and when descending back to the depths during the day drew organic carbon with them. This behavior accelerates the transport of carbon from surface to deep waters—a phenomenon known as the biological pump—contributing to the ocean's role in modulating climate while also providing food for animals and microbes throughout the water column and on the seafloor (e.g., Robison et al., 2005; Brierley, 2014; Honjo et al., 2014; Smith et al., 2017; Archibald et al., 2019). The same processes can also transport microplastics, which has led to the suggestion that a large, previously unknown reservoir of marine microplastics may be contained within animal communities living in the deep sea. (Choy et al., 2019).

Comprehensively investigating the players and processes that transform and transport organic matter from the sea surface to the seafloor over decades is not easy (Messié et al., 2023). The distribution and behavior of the participants and the material they transform and produce varies tremendously in time and space, and with that our ability to model biologically driven carbon flux and resultant climate influence is challenged. Persistent observations of the ocean using a variety of tools is a necessary step towards meeting that grand challenge (e.g., Karl, 2014; Chavez et al., 2021a).

Listening and decoding what animals leave in their wake

It is truly amazing what you can learn by listening. The history of ocean soundscape analysis is a great example. In the mid-4th century BCE, the ancient Greek philosopher Aristotle in his landmark work History of Animals noted that sea creatures produced sounds (cf. Thompson, 1910). Ancient mariners also marveled at the mysterious noises that occasionally resonated through the hulls of their ships. Over millennia, these astute observations gave way to curiosity-driven research and wartime pursuits that exploited ocean sound. Following World War II, revelations about the lives and vocalizations of charismatic megafauna piqued the public's interest, popularizing the idea of an ocean soundscape and highlighting the mysteries of marine mammal communication (e.g., Schevill and Lawrence, 1949; Payne and McVay, 1971). In an all too familiar fashion, it did not take long to learn that human activities are a source of ocean soundscape pollution that can be injurious to marine wildlife (e.g., Hildebrand, 2009). Although the notion of an ocean soundscape is ancient, and its use in ocean studies has long been the subject of intensive research and development, we continue to make remarkable discoveries by simply listening with increasingly sophisticated means for doing so.

Today, detailed observations of the comings and goings of animals and their prey is greatly enhanced by soundscape analysis (e.g., Oestreich et al., 2022, 2024; Ryan et al., 2022, 2025). The combination of both passive and active acoustic observations has proven useful in investigating predator foraging behaviors and the ecology of fear (e.g., Benoit-Bird et al., 2019; Urmy and Benoit-Bird, 2021). "Listening with light" by way of using fiber optic cables as vibration sensors—a technique known as distributed acoustic sensing (DAS)—is the latest evolution in the ongoing push to broaden access to and analysis of the ocean soundscape (Saw et al., 2025). By combining fleets of ASVs and AUVs equipped with acoustic, imaging, and water sampling payloads, a new perspective on the movements of animals traversing the environment in response to ever changing ocean conditions is emerging, including by tracking the traces of "genetic soup" shed in their wakes (e.g., Zhang et al., 2021b; Figure 6).

The history of using organisms' DNA and RNA (etc.) to reveal what species are present and how they are responding to their environment shares much in common with the development and application of ocean imaging and acoustics. The tools and techniques employed have storied pasts and spring from the creativity and insights of many investigators over decades. What has come to be known as "ecogenomics" is deeply rooted in subcellular biological studies and molecular analytical methods for detecting

FIGURE 6 A fleet of long range AUVs (Hobson et al., 2012) fitted with different imaging, water sampling, and eDNA collection payloads alongside a Liquid Robotics Wave Glider, all readied for deployment in Monterey Bay. The fleet of vehicles is able to coordinate observations for an extended period of time to provide a multifaceted view of dynamic ecosystem processes (after Zhang et al., 2021a, b). Susan von Thun © 2017 MBARI.

and decoding the very essence of life itself. Just as underwater imaging and soundscape analysis grew from industries and for purposes unrelated to ocean ecology, the advent of molecular biology, nucleic acid sequencing, bioinformatics, etc., was adopted by ocean scientists, forever altering the course of modern marine biology. Microbial ecologists arguably led the way (e.g., Pace, 1985; Karl, 2014).

In a surprising twist, Ficetola et al. (2008) discovered that DNA shed by frogs could be detected in the environment in which they lived even when you could not see the animals themselves, sparking an environmental DNA (eDNA) forensics revolution (e.g., Kelly et al., 2014; Stoeckle et al., 2024). The analysis of eDNA offers a noninvasive method for assessing biodiversity and tracking animal movements by collecting samples of water and sequencing the recovered material, making possible the simultaneous detection of marine organisms across multiple trophic levels (e.g., Chavez et al., 2021b). As eDNA analysis has evolved, our eyes have been opened to the notion of "genetic dark matter" that is recoverable from the environment but has no described source or, in some cases, no well characterized function (e.g., Venter et al., 2004; Roux et al., 2015; Delmont et al., 2022). Analysis of the sea's genetic soup tells us that there is a great deal of marine life and genetic capacity that has not yet been described.

Just as machine learning and artificial intelligence have played a huge role in analyzing and reacting to ocean imagery and sound, they are likewise fueling the analysis of eDNA to synthesize an integrated picture of a complex web of life. Although the detection and real-time analysis of imagery, sound, and other bulk water properties are now commonly employed to guide autonomous platforms to undertake targeted field observations, devices that enable *in situ*, "hands off," real-time analysis of eDNA and other cellular metabolites are still very much in their infancy (e.g., Scholin et al., 2017). With a few notable examples (e.g., Truelove et al., 2019, Thielen et al. pers. comm.), marine eDNA surveys rest largely on the acquisition, preservation, and return of samples for shoreside analysis (Yamahara et al., 2019; Zhang et al., 2021a; Trulove et al., 2022; Preston et al., 2023). Despite the progress, scaling up the use of robots that enable integrated optical, acoustic, and 'omic characterization of the sea presents a very significant technological challenge when compared to using profiling floats to conduct global scale biogeochemical observations.

To the seafloor

Descending to the seafloor, whether in a crewed submersible or ROV, has been likened to being dropped into a pitch-black room and using only a flashlight to see what lies ahead. Remarkable discoveries have been made by picking dive sites that are known to offer different types of terrain where one might expect to find something novel. The discovery of the "octopus garden" near the base of Davidson Seamount offers an excellent, recent example of using ship-acquired bathymetry to guide an exploratory ROV dive that serendipitously uncovered something remarkable (King and Brown, 2019). No doubt that method works, but the area that can be covered is limited, and for the most part, you have no detailed map to lead the way. AUVs are changing that calculus. Low resolution surface vessel-based maps can now be used to guide higher-resolution AUV-based surveys. AUVs can run in close proximity to the ground compared to a vessel at the sea surface, thus providing much more detail on what lies below. The combination of nested surface vessel-AUV-ROV surveys has greatly aided our understanding of underwater landscapes and how they evolve over time, which now informs choices on what locations to pick to observe more closely and repeatedly to improve the odds of finding something novel (e.g., Caress et al., 2008, 2012; Paull et al., 2010; Paduan et al., 2018).

Even highly detailed bathymetric surveys fail to reveal much about the animals that inhabit the seafloor. With relatively few exceptions, most life on the seabed is sub-meter scaled and often transparent to acoustic energy. By combining high-resolution laser and optical imagery with acoustic mapping, a truly astounding view of the seafloor emerges (Figure 7). The systems for acquiring that information can be deployed on ROVs (e.g., Caress et al., 2024) and are extendable to AUVs, greatly expanding the area that can be surveyed in detail. Processing the imagery collected using machine learning techniques also holds promise for significantly

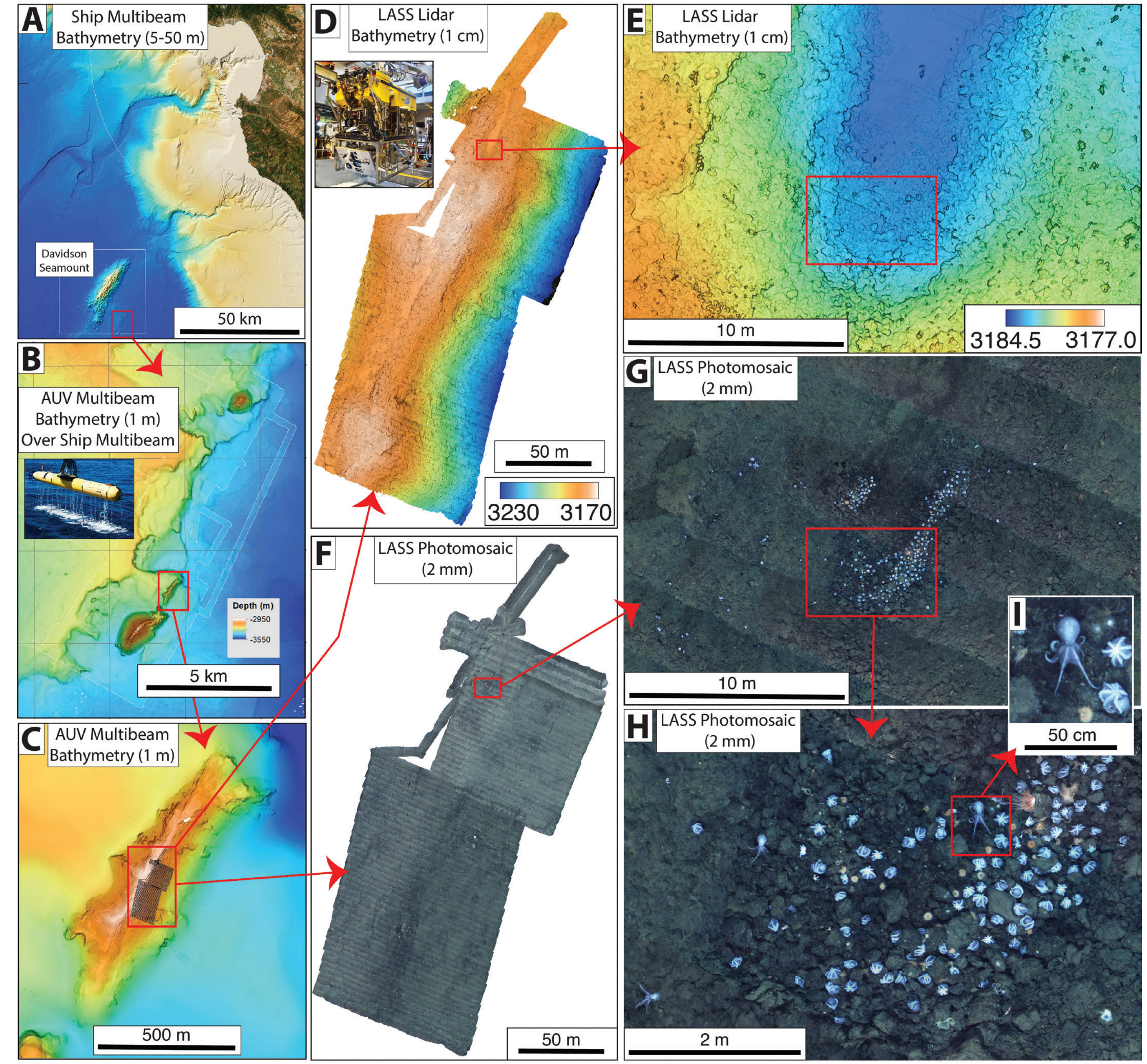


FIGURE 7 The use of nested resolution seafloor mapping to reveal the Octopus Garden. (A) Seafloor bathymetry collected using ship-based multibeam sonar, yielding bathymetry with 5-50m resolution depending on water depth. The red box indicates the location of the Octopus Garden pearl octopus (*Muusoctopus robustus*) brooding site, southeast of Davidson Seamount. (B) MBARI's seafloor mapping AUV (inset) provides 1m resolution bathymetry shown here overlain on the base map acquired from ships. The red box shows the location of Octopus Garden Ridge. (C) Octopus Garden Ridge at 1m-scale overlain with ROV survey track lines. (D) The ROV-mounted Low Altitude Survey System (LASS) (inset) is used to provide 1cm resolution bathymetry and 2mm resolution seafloor photography using a combination of multibeam sonar, lidar, and color still cameras; (D) and (E) show the 1cm LASS lidar bathymetry at two map scales. (F), (G), (H), and (I) show the 2mm-scale color photomosaics at four map scales, zooming in to individual animals. Source: David Caress and James Barry. Images © 2025 MBARI.

speeding up quantitative assessments of specific animals or other features of interest even while the vehicle is underway. Further study of the famed octopus garden provides a stunning example of what is possible when combining different modes of seafloor visualizations to inform targeted studies that not long ago would have seemed a pipedream (Barry et al., 2023). Similar studies of deep-sea coral and sponge communities found serendipitously at Sur Ridge and elsewhere paint a similar picture (Girard et al., 2024; cf. Mapping Sur Ridge, 2025). These discoveries highlight what is possible by using a combination of hybrid human-machine and fully autonomous systems for visualizing the seafloor.

Despite that progress, the vast majority of the seabed has never been mapped at scales needed to reveal underwater landscapes in detail. Satellite altimetry-derived maps provide ~5 km grid resolution estimates of seafloor depth for the entire ocean bottom using gravity anomalies (Smith and Sandwell, 1997), but those maps provide only a coarse perspective on what lies below, much like a person viewing a large terrestrial mountain range, deep valley, or vast plain from a great distance. High-resolution maps of the seafloor acquired using surface vessel-mounted multibeam sonar varies linearly with water column depth, typically on the order of 2 m at 100m depth to 100m at 5000m depth (Mayer, 2006), but even those maps currently cover only ~26% of the ocean bottom. Visualizing the biological communities that live there requires much higher resolution, ideally cm or even mm scale, as shown in Figure 7. In other words, much of what lies below has never been seen by human eyes. Although the technology for doing that is available, actually accomplishing that goal globally is an enormous task and not likely to come to fruition anytime soon. Once again, robots offer a path forward for tackling that challenge since they can work when and where people cannot, dare not, or just prefer to avoid for many practical and logistical reasons.

A combination of crewed and uncrewed surface and subsurface vessels are now actively being employed to map the entirety of the seafloor as a contribution to the Seabed 2030 initiative. Seabed 2030 (2025) is a collaborative project sponsored by the Nippon Foundation and the General Bathymetric Chart of the Ocean (GEBCO) that aims to assemble all available bathymetric data into a single, freely accessible map for the benefit of all. Like the global fleet of profiling floats returning data on the vital signs of the world's ocean, Seabed 2030 is a great example of what can be accomplished through public-private partnerships and international cooperation and data sharing to grow our understanding of seafloor bathymetry. Given the task at hand and its relevance to society, it speaks to the age-old adage that "necessity is the mother of invention." Developing new means for comprehensively mapping the seafloor is ripe for innovation, following in the footsteps of developing and deploying platforms and sensors for assessing ocean biogeochemistry on a global scale.

Conclusions

The history of technology development in the quest to explore and observe the ocean has left a legacy of many enduring lessons. At least five takeaways are apparent:

- There is much to gain by working as an interdisciplinary team to tackle daunting challenges, even when those problems may require years or decades to overcome.
- Fostering an enduring peer relationship among scientists, engineers, and marine operations specialists in concert with the public fuels discovery.
- Being open-minded to what is possible even though it may seem improbable or counter to current thought begets innovation.
- "Failures" are inevitable if one attempts to do something that has not been done before; failures are stepping stones of transformative engineering development and scientific advancements.
- Never underestimate the potential of serendipity, and be open-minded to changing course when an opportunity or new technology presents itself.

The foregoing consideration of how ocean technology has evolved in recent years and how it has impacted ocean science is a powerful endorsement of those lessons and a tribute to all who have walked that path.

Much of the technological revolution that has been brought to bear on ocean exploration and observation was primarily driven by a variety of industries for purposes that often had nothing to do with marine science. Advancements in microelectronics, biopharma, aerospace, manufacturing, material and computer science, and other disciplines, as well as social media, have dramatically transformed our ability to access the sea, reveal its mysteries, and share the findings with a global audience. This cycle is accelerating. Every time we return to the ocean with new technologies in hand, we learn something new (e.g., Chisholm et al., 1988) and grow to appreciate the connection between societal wellbeing and the health of the sea.

Throughout history, we have approached ocean exploration and observation through a decidedly human sensory perspective. There is still much to learn. Ocean-dwelling animals experience their environment in many ways we humans have not yet learned to interpret or fully comprehend, such as their perception of electromagnetic fields and chemosensory abilities. Looking forward, it is likely that just as the use of biogeochemical, optical, acoustic, and 'omic sensing has revealed surprising insights about the interplay between marine chemistry, physics, biology, and geology, so too will new sensor systems give us a better appreciation of what ocean animals experience. As Bruce Robison (pers. comm) aptly put it:

> "To the inhabitants of the deep sea, their world must seem very different than it seems to us, because they are comprehending it with vastly different sensors than we have. The more we can perceive their world the way they do, the better we'll understand it. Our inherent biases limit us."

Revelle and Suess' "large scale geophysical experiment" is ongoing. We are in a race to learn more about the ocean and the seafloor, and the incredible diversity of life therein, as it undergoes increasingly rapid change due to human activities. A sustained commitment to technology development is integral to competing in that race. President J.F. Kennedy, who was a strong advocate for ocean exploration, marine conservation, and weather research, summed it up well at his 1961 commencement address at the U.S. Naval Academy:

> "Knowledge of the oceans is more than a matter of curiosity. Our very survival may hinge upon it."

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Revelle Alumni

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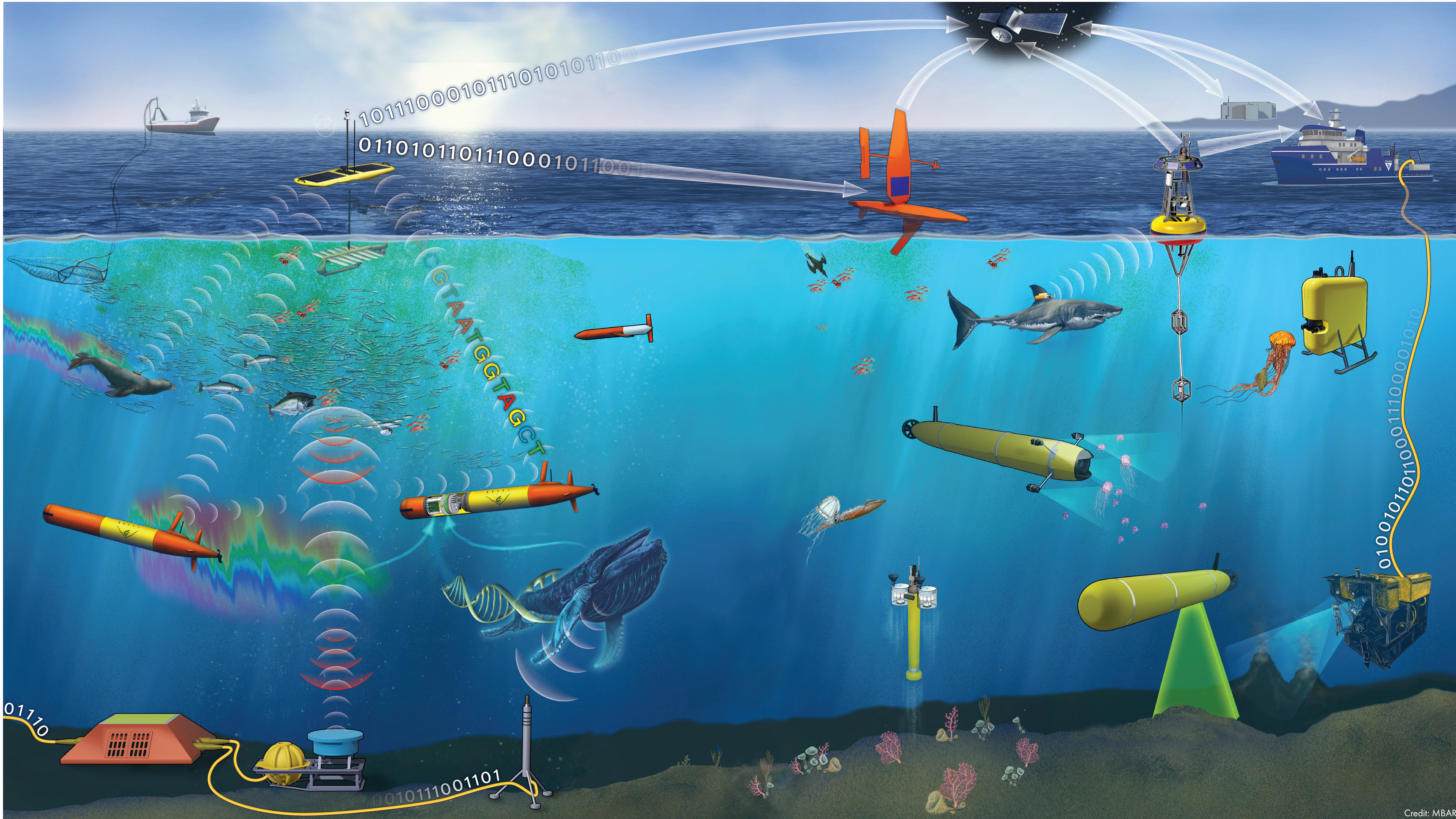
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