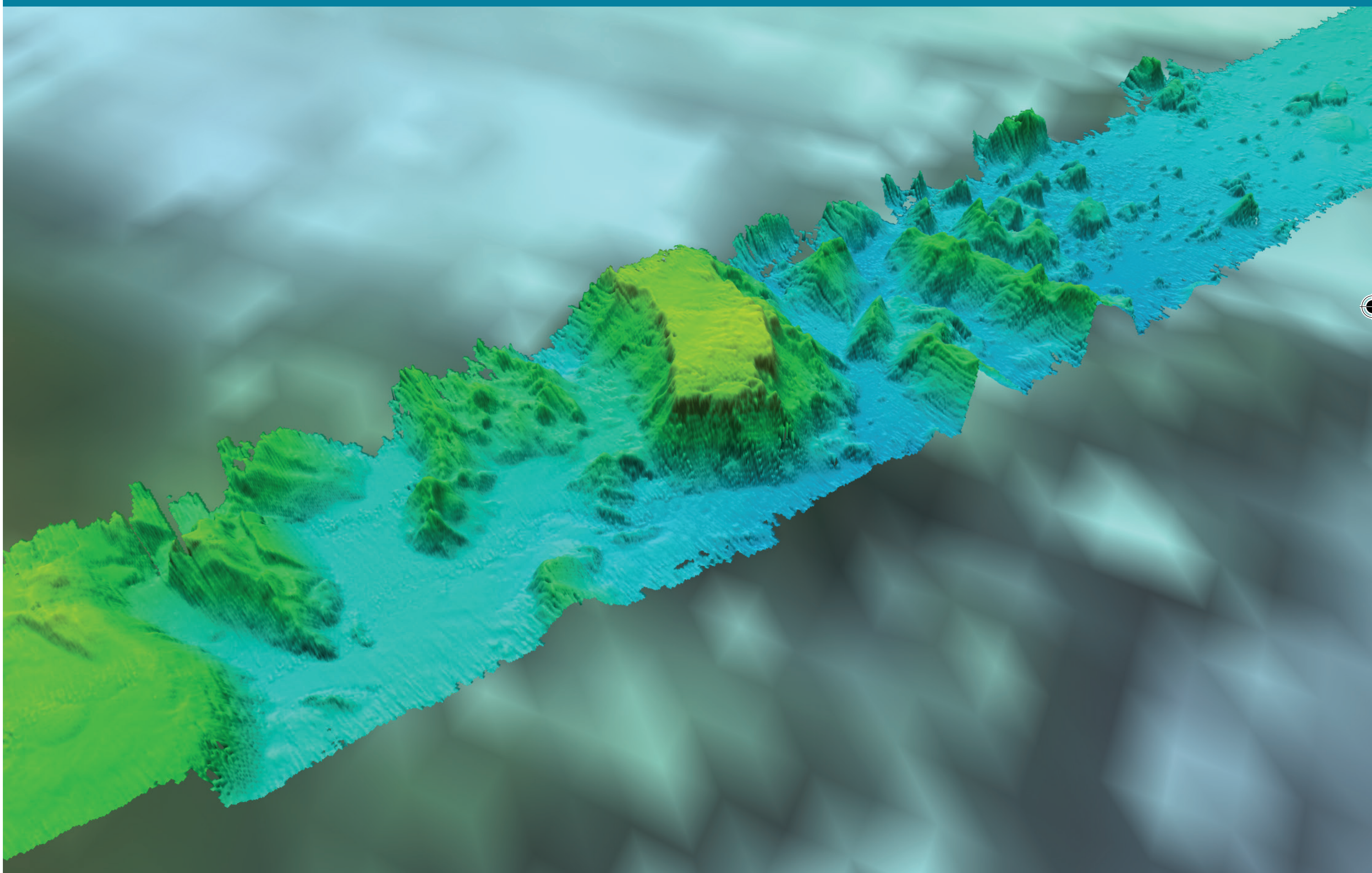
27TH ROGER REVELLE COMMEMORATIVE LECTURE

The Quest to Map the Global Ocean

FEATURED SPEAKER **LARRY MAYER, PH.D.**



March 17, 2026 | 5:30 PM

NAS Auditorium and Virtually

NATIONAL ACADEMIES *Sciences Engineering Medicine*

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 27th 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, we welcome you to a lecture by Dr. Larry Mayer, Professor and Director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. Tonight's lecture will examine the scientific, technological, and logistical challenges of mapping the global ocean, where nearly three-quarters of the seafloor remains unmapped despite its central role in supporting marine ecosystems, infrastructure, and economic activity. The lecture will explore how advances such as multibeam sonar and autonomous and uncrewed platforms are transforming seafloor mapping. It will also highlight national and international initiatives aimed at accelerating the global ocean and U.S. Exclusive Economic Zone.

Sponsorship

The Ocean Studies Board thanks the National Aeronautics and Space Administration and the National Science Foundation for their continued support. 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*
www.nationalacademies.org/osb/ocean-studies-board

Speaker Biographies

Larry Mayer

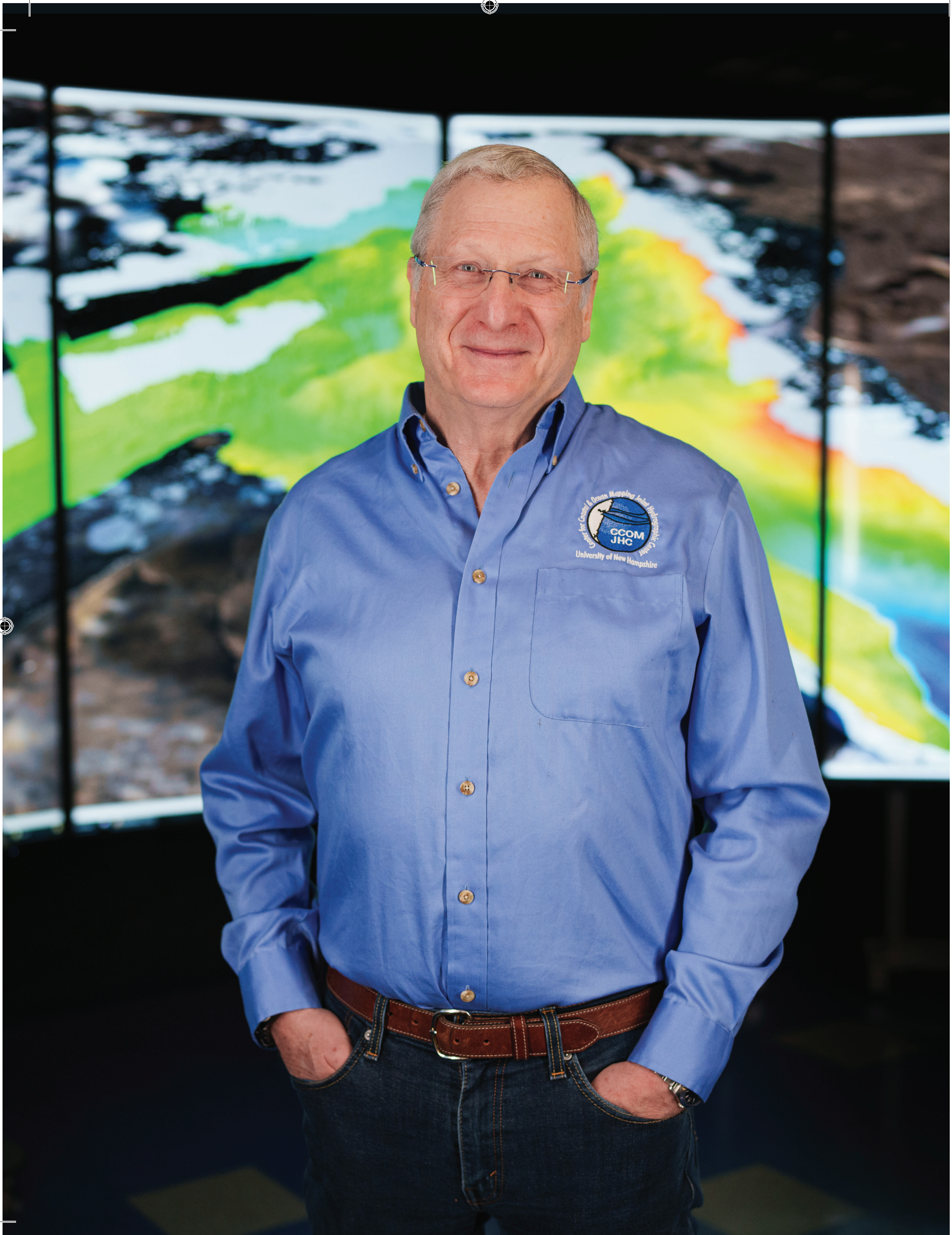
Center for Coastal and Ocean Mapping
University of New Hampshire

LARRY MAYER is Professor and Director of the Center for Coastal and Ocean Mapping at the University of New Hampshire. He graduated magna cum laude with an Honors degree in Geology from the University of Rhode Island in 1973 and received a Ph.D. from the Scripps Institution of Oceanography in Marine Geophysics in 1979. At Scripps, he worked with the Marine Physical Laboratory's Deep-Tow geophysical package, applying this sophisticated acoustic sensor to problems of deep-sea mapping and the history of climate. Dr. Mayer was selected as an astronaut candidate finalist for NASA's first class of mission specialists, after which he had a postdoctoral position at the University of Rhode Island, assistant professorship at Dalhousie University, and the NSERC Industrial Research Chair in Ocean Mapping at the University of New Brunswick. In 2000, Dr. Mayer became the founding director of the Center for Coastal and Ocean Mapping at the University of New Hampshire and the co-director of the NOAA/UNH Joint Hydrographic Center.

Dr. Mayer has participated in more than 100 cruises over the last 50 years and has been chief or co-chief scientist on numerous expeditions. His current research focuses on increasing the efficiency and effectiveness of seafloor mapping and remote characterization of the seafloor as well as advanced applications of 3-D visualization to ocean mapping problems and applications of mapping. He has served on many panels and committees including the Ocean Studies Board, which he chaired for six years. He has been the recipient of many honors and has been elected to the Hydrographic Society of America Hall of Fame, the National Academy of Engineering, the Royal Swedish Academy of Sciences, and the Norwegian Scientific Academy for Polar Research.

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.


Center for Coastal & Ocean Mapping Joint Hydrographic Center
CCOM
JHC
University of New Hampshire

The Quest to Map the Global Ocean

The Ocean Studies Board is proud to present the 27th Annual Roger Revelle Commemorative Lecture featuring Dr. Larry Mayer.

Introduction: Mapping as Exploration

When asked to give the Revelle Lecture—and come up with a catchy title that would capture the essence of my talk—we came up with “The Quest to Map the World Ocean.” That sounded good, but it also led me to delve deeper into what a “quest” really was. Drawing on several formal definitions, I arrived at **“A long, adventurous search or journey undertaken to find or achieve something important involving challenges and obstacles….”** I felt that was an accurate description of what I would talk about, but, in all honesty, I would have to say that when I first entered this field, I was driven less by the altruistic goal of **“achieving something important,”** and more by the more selfish desire of **searching for adventure**.

From my earliest days growing up in an apartment building in the Bronx, I wanted to be an ocean explorer. Like many of my generation, I was inspired by Jacques Cousteau, and while it was the spectacular images of macrofauna and wrecks that folks like Cousteau and Bob Ballard produced that caught my imagination, I also recognized that these images were only minuscule snapshots of a vastly unknown ocean system—true exploration begins with mapping. This is what the early explorers did as they ventured into the unknown; Lewis and Clark, Magellan, and Captain Cook all started by making maps, establishing the spatial framework for all else that they and others would discover.

Human Perception, Imagery, and the Primacy of Vision

Mapping, in the context of exploration, is the process of creating a visual representation of spatial data. Visual representation is central to mapping because spatial exploration is fundamentally a sensory process, and, among the human senses, vision dominates both perceptually and neurologically. Approximately 30 percent of the neurons in the human brain are devoted directly to visual processing, and over 60 percent of the brain is involved in vision directly or indirectly (Billinghurst and Thomas, 2016). Throughout history, exploration has therefore been closely tied to imagery: telescopes pointed skyward, maps sketched from elevated vantage points, and, more recently, satellites imaging Earth from space with remarkable resolution.

Our modern approaches to understanding Earth's processes reflect this visual bias. Satellite imagery, digital terrain models, and geospatial visualization tools allow researchers to "see" processes unfolding across the continents. High-resolution imagery reveals glacier retreat, forest loss, urban expansion, and geomorphic change with unprecedented clarity. Mapping does not merely document these processes; it provides the spatial context necessary to interpret them quantitatively. Modern satellite-based digital elevation models provide the spatial framework upon which interpretation, navigation, governance, and both resource exploitation and environmental protection depend. Today, for the terrestrial components of Earth, advances in remote sensing, geodesy, and computing have produced near-global, meter-scale representations of Earth's surface. These datasets now underpin climate science, hydrology, ecology, hazard mitigation, and land-use planning. With a few keystrokes, anyone can extract this remarkable imagery for any terrestrial location with readily available applications like Google Earth. In stark contrast, when focused on the ocean's surface, the same sensors that spectacularly map terrestrial components of Earth provide little information about our oceans, which represent 71 percent of Earth's surface and the largest continuous environment on the planet. This disparity is striking and frightening as the ocean exerts a disproportionate influence on our planet. Ocean circulation regulates climate; the seafloor controls deep-water pathways and mixing; maritime trade sustains the global economy; fisheries feed and support hundreds of millions of people; and submerged landscapes host ecosystems, resources, and cultural heritage (Figure 1).

The Physical Constraint: Why the Ocean Resists Optical Mapping

The principal barrier to comprehensive ocean mapping is physical rather than conceptual. The sensors used for satellite remote sensing typically rely on electromagnetic radiation—visible light, infrared, or radar—that propagates efficiently through air. In seawater, however, absorption and scattering dramatically reduce penetration depth. Even in the clearest open-ocean waters, visible light rarely penetrates beyond ~200 m; in most coastal waters, penetration is typically less than 50 m.

This limitation renders optical imaging ineffective for the vast majority of the seafloor and water column. The mean depth of the global ocean is approximately 3,700–4,000 m, with large areas exceeding 5,000 m; 94 percent of the world's seafloor is deeper than 200 m. Beyond these depths (and typically much shallower) the seafloor lies permanently beyond the reach of light-based remote sensing. This does not mean deep-sea optical imaging is impossible; rather, it requires placing sensors very close to the seafloor to overcome rapid light attenuation. As outlined by Chris Scholin in last year's Revelle Lecture (Scholin, 2025), this can be accomplished using cabled remotely operated vehicles (ROVs) or free-swimming autonomous underwater vehicles (AUVs) which can be operated close to the seafloor and collect high-resolution optical imagery. Unfortunately, these vehicles move very slowly and, given the rapid attenuation of light, can only image a very small portion of the seafloor at a time.

A thought experiment underscores the magnitude of this constraint. What would it take to create a "Google Ocean" of optical images with resolution analogous

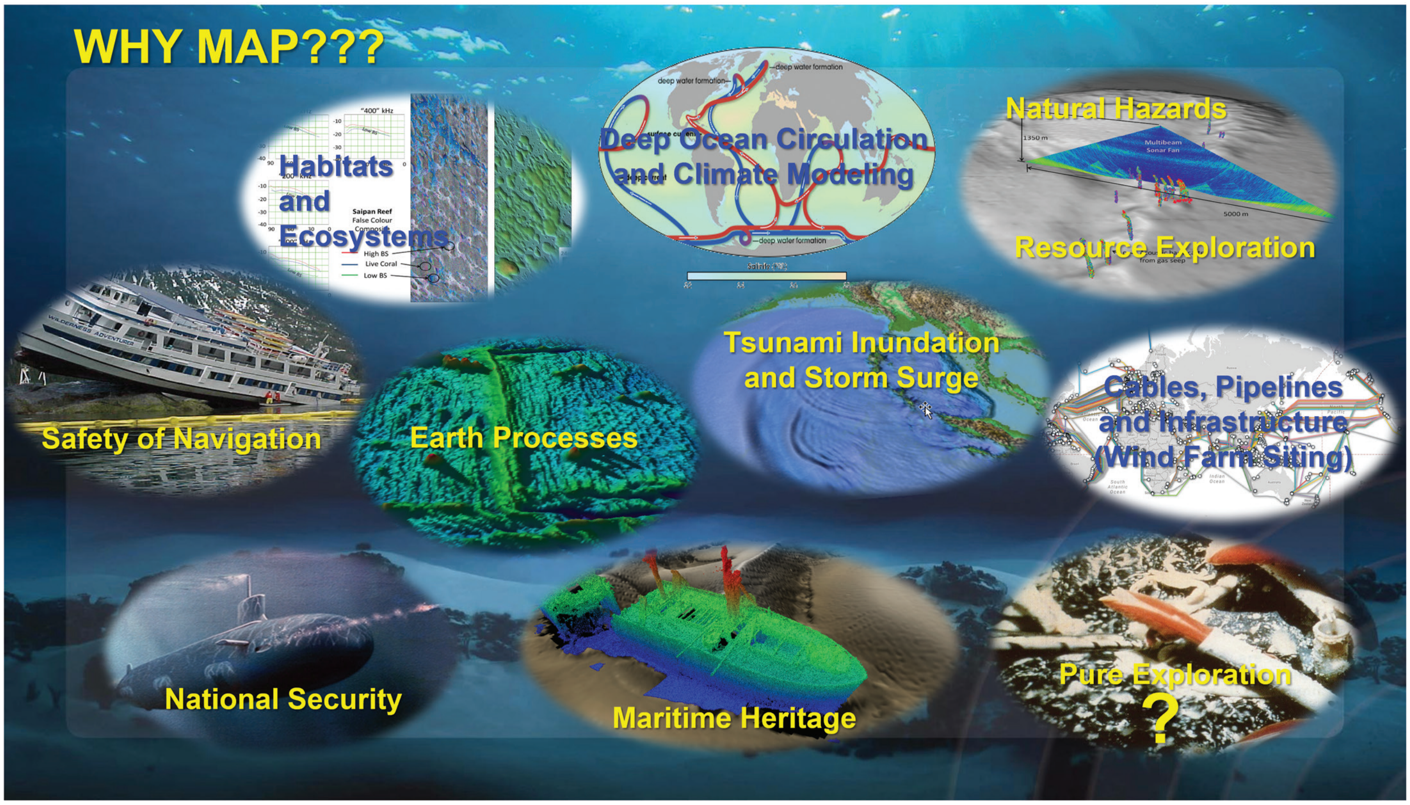


FIGURE 1 Some of the many reasons why ocean maps are important to understanding Earth processes. How do we manage and protect what we do not know and understand? Sources: Created by Larry Mayer, using adapted images from colleagues John Hughes Clarke and Tom Weber, with permission, along with Robert Simmon and Robert A. Rohde, NASA, Nasa Earth Observatory; Alaska Division of Spill Prevention and Response, https://dec.alaska.gov/spar/ppr/response-resources/ppor/southeast/; Howstuffworks.com, https://science.howstuffworks.com/transport/engines-equipment/question419.htm; Phys.org, https://phys.org/news/2024-06-giant-deep-sea-vent-tubeworm.html; Stocktrek/Getty Images; and Telegeography, https://submarine-cable-map-2024.telegeography.com/.

to that of Google Earth? To collect the optical imagery necessary to obtain the resolution provided by Google Earth, cameras would need to operate within roughly 10–20 m above the seafloor with a very limited field of view (~10 m). Given this limited field of view and the enormous area of the ocean floor, such an effort would require on the order of 34×10^9 images and, given the very slow rate of coverage for these vehicles, tens of millions of years to completely capture these images at realistic acquisition rates. Supporting these estimates, Bell et al. (2025) have estimated that, to date, all efforts to image the deep seafloor since 1958 have covered only .001 percent of the deep seafloor. These order-of-magnitude estimates make clear that optical mapping of the complete deep ocean is not merely impractical, it is physically untenable.

From Touch to Sound: Early Seafloor Mapping

LEAD-LINE SOUNDINGS AND MILLENNIA OF CONTINUITY

Given the limits of optical imagery—and thus the inability to use our sense of vision for mapping the seafloor—we had to turn to other senses, initially touch. For most of human history, seafloor depth measurements were made by direct physical contact. Weighted ropes or wires—lead lines—were lowered until they touched the bottom. This method, depicted in artifacts from Egyptian tombs dating back to at least 2000 BCE, remained essentially unchanged for nearly 4,000 years. Even as ship design, navigation, and seafaring expanded dramatically, the fundamental approach to measuring

FIGURE 2 Early contour map of the Atlantic Ocean based on lead-line soundings created by Lt. Matthew Fontaine Maury in 1854. NOAA, n.d.-a.

depth did not. Lead-line soundings can be accurate in shallow water under calm conditions, but they are slow, labor-intensive, and spatially very sparse. As water depth increases, uncertainty grows due to ship motion, current-induced line deflection, and difficulty in detecting bottom contact. Consequently, lead-line datasets provide only the coarsest representations of seafloor morphology (Figure 2).

SINGLE BEAM ECHO SOUNDING

Because sound waves propagate efficiently through seawater unlike electromagnetic waves, efforts to use sound (and thus the turn to using another sense: hearing), to measure depth and to identify icebergs accelerated in the early 1900s and marked a turning point in ocean mapping (NOAA, n.d.-b). Perfected through the Second World War, "single beam" echosounders were developed that allowed the rapid measurement of depth in any depth of water (assuming the frequency of the echosounder is low enough to allow it to travel to the deepest part of the ocean; for full-ocean depth measurements echosounders typically use frequencies of 12,000 cycles/sec or 12 kHz). Single beam echosounders transmit an acoustic pulse downward and then measure the time required for the echo to return to the vessel. If the speed of sound in the water column is known then the travel time can be converted to depth. This approach dramatically increased data acquisition rates and accuracy of depth measurements relative to lead lines.

Using an average speed of sound in seawater of 1,500 m/sec, a single measurement of depth with an echosounder in the approximately 11,000 m Challenger Deep of the Mariana Trench (the deepest place in the ocean) would take approximately 14.7 seconds for a sound wave to travel from the vessel to the seafloor and back to the vessel. A lead-line measurement in these water depths would take many hours, and it would likely be inaccurate.

While representing a tremendous leap with respect to the rate at which depth measurements could be made (and thus the number of measurements made on a given mission), single beam echosounders have limited spatial resolution on the seafloor. As the sound pulse leaves the echosounder on the ship, it expands much like a beam of light leaving a flashlight. By the time the sound pulse reaches the seafloor, it has ensonified a broad conical footprint that increases in size with increasing water depth. In deep water, this footprint can be kilometers wide, but the returned signal is a single depth measurement representing the shallowest feature within that footprint rather than the point directly beneath the vessel. As a result, single beam data are spatially ambiguous and require extensive interpolation between widely spaced tracks (Figure 3). The result is a rather defocused representation of the seafloor, averaged over the spatial footprint of the sonar (usually about one-third to one-half the water depth). Typically, to visualize these data, measured points of equal depth are connected with "contour" lines, offering a crude and widely interpolated representation of the distribution of depths in a region.

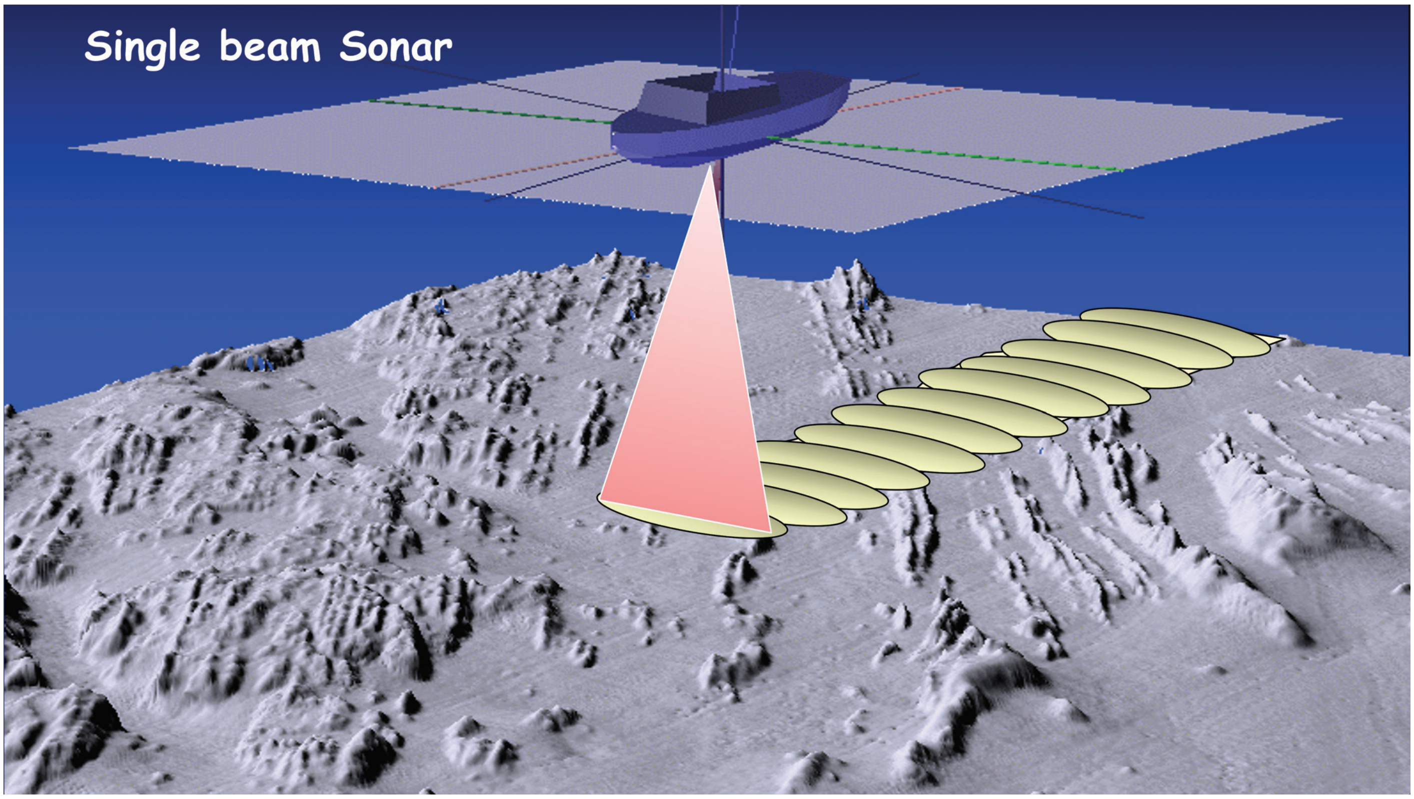


FIGURE 3 Geometry of a single beam sonar. Beam widens as it propagates from sonar on vessel and eventually ensonifies a large area on the seafloor but returns only a single shoalest depth in that footprint without the ability to know where in the footprint it came from. Source: John Hughes Clarke, Center for Costal and Ocean Mapping, University of New Hampshire.

Satellite Altimetry: A Global But Coarse View

In the late 1990s, Smith and Sandwell (1997) introduced an approach to estimating seafloor depths (bathymetry) from satellite altimetry measurements. Satellite radar altimetry introduced a fundamentally different approach to seafloor mapping. Rather than measuring the depth of the seafloor directly, altimeters measure the height of the sea surface with centimeter-scale precision. Variations in sea surface height reflect gravitational anomalies caused by changes in seafloor mass distributions: the excess mass of seamounts produces positive anomalies and a slight elevation of the sea surface, while the missing mass of trenches produce negative ones and a slight depression of the sea surface. By relating the dense gravity anomaly measurements to sparse known depth measurements, Smith and Sandwell (1997) were able to produce a global interpolated grid of predicted depths. These predictions work best for long-wavelength features (~10–15 km) and are particularly good at revealing large features like mid-ocean ridges, fracture zones, and trenches on a planetary scale (Figure 4). Satellite altimetry provided the first truly global view of the ocean basins and played a critical role in advancing plate tectonic theory but is inherently coarse. Typical spatial resolution is on the order of 10–15 km, (though a new satellite mission, SWOT, is providing resolution as fine as 4–5 km (Sandwell et al., 2025). Even this improved scale, however, is insufficient for resolving geomorphic features, habitat heterogeneity, or seafloor roughness relevant to ocean circulation and ecosystems. Satellite altimetry therefore provides a remarkable global perspective for understanding tectonic processes but is not a substitute for direct mapping.

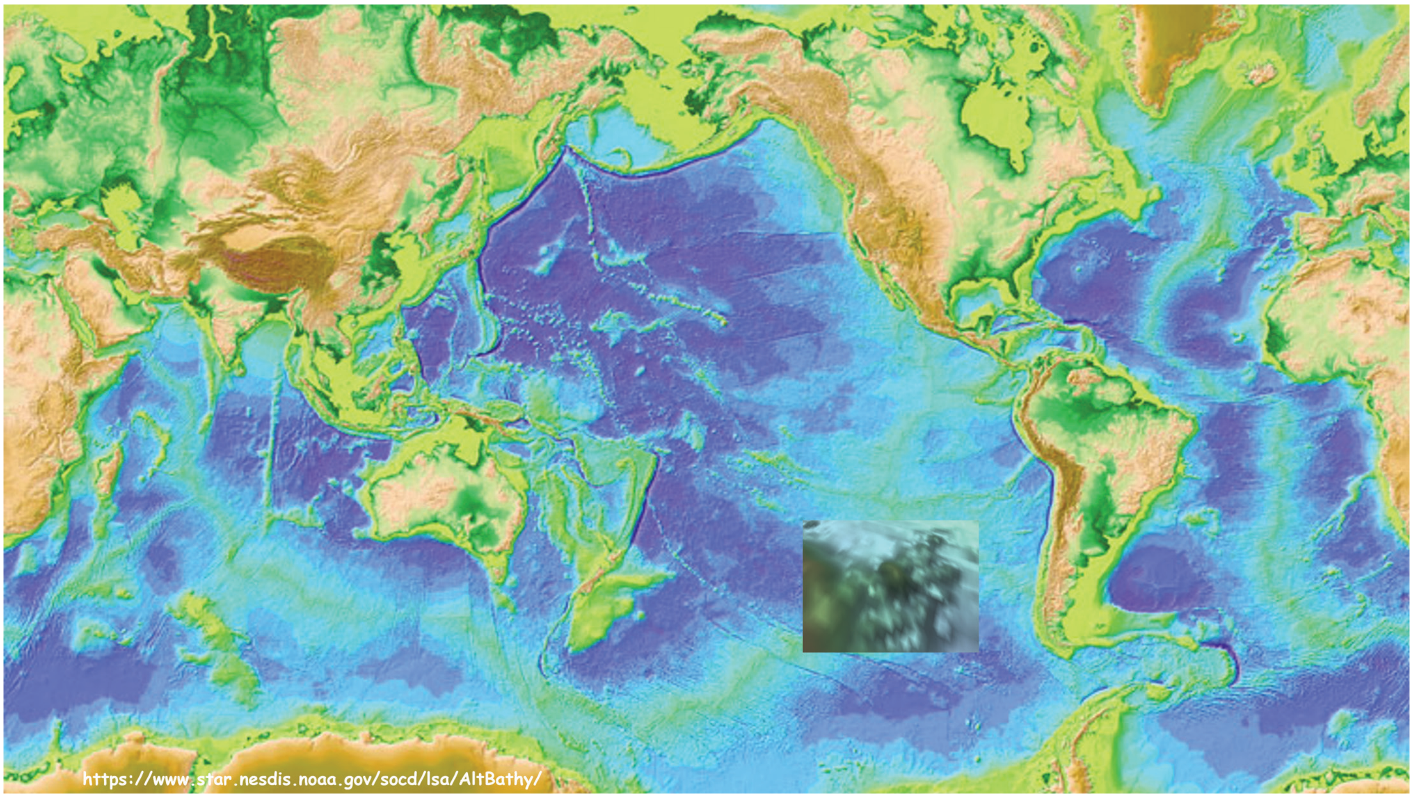


FIGURE 4 Global predicted bathymetry from satellite altimetry provides wonderful estimate of global bathymetry at low spatial resolution that is good for understanding tectonic-scale features but of limited use for understanding many ocean processes. Inset shows zoom of 200 x 200 km area at scale of satellite altimetry derived bathymetry. Source of satellite altimetry derived bathymetry: Smith and Sandwell, 1997.

Multibeam Sonar: A Revolution in Ocean Mapping

The most transformative advance in ocean mapping came with the development of multibeam echosounders (MBES) which evolved out of classified military systems in the mid-1970s and 1980s. Unlike single beam systems, multibeam sonars use a separate transmitter and receiver. The transmitter produces a fan of sound that is thin in the along-track direction and wide—typically five to seven times the water depth—in the across-track direction. The receiver simultaneously creates many, often hundreds, of small fans that are narrow in the across-track direction and wide in the along-track direction. The intersection of the transmit and receive pulses on the seafloor results in hundreds of small ensonified areas on the seafloor (beams), each producing a highly accurate depth measurement (Figure 5). Typical swath widths are four to seven times the water depth (>20 km in 4,000 m of water) and the size of the beam footprint (controlling the lateral resolution of features on the seafloor) is typically on the order of 0.017 percent of the water depth (for a 1 degree beam), and thus, the spatial resolution of features in 4,000 m of water is on the order of 70 m. Hundreds of these high-resolution soundings are collected with each "ping" of the sonar (which takes place at rates ranging from many tens per second to once every 5–10 seconds depending on water depth), enabling thousands of highly accurate soundings to be collected each hour over a relatively wide swath of the seafloor. This dramatic increase in data density represented a fundamental change in our ability to map the seafloor and revolutionized the use of bathymetric data to understand ocean processes.

The introduction of multibeam sonar would not, on its own, have resulted in a revolution in ocean

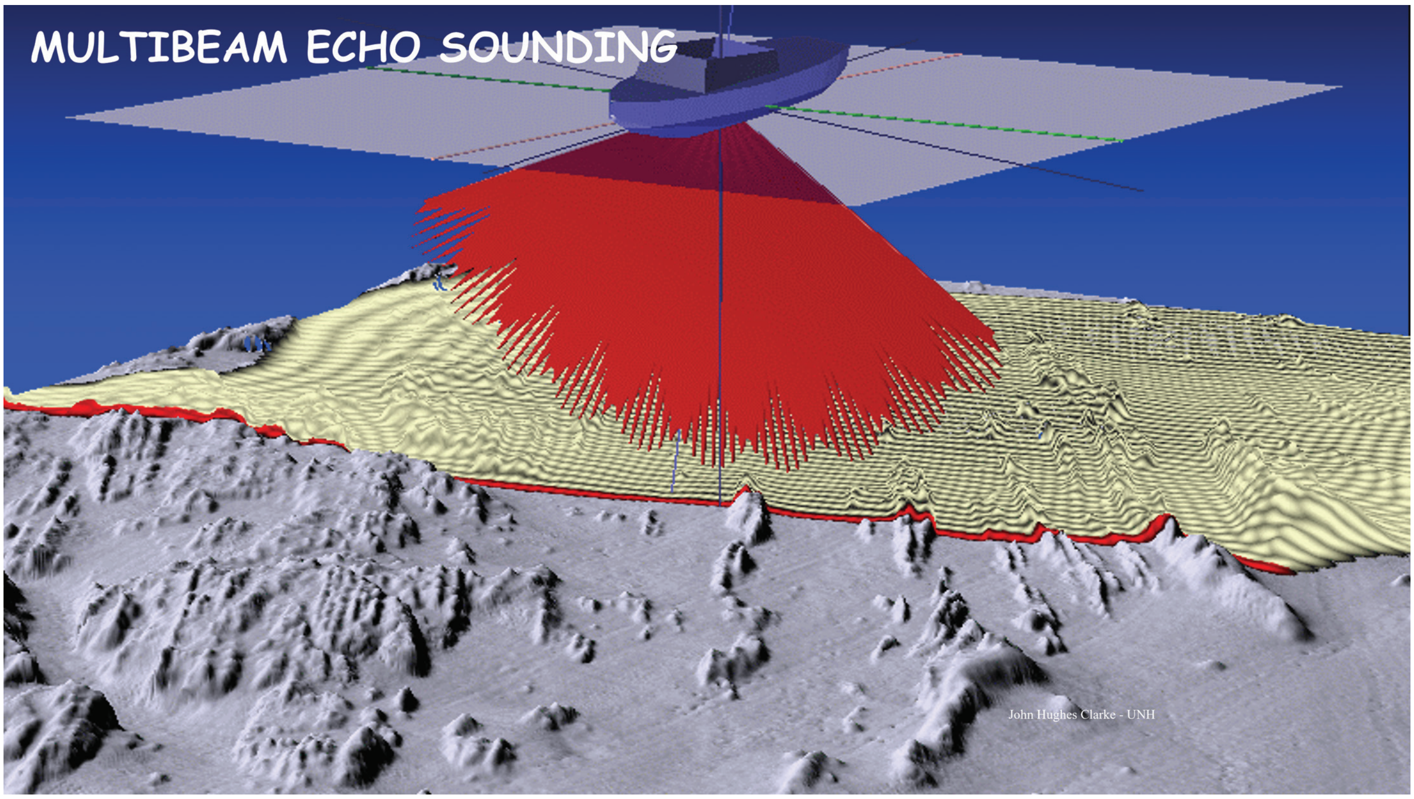


FIGURE 5 Geometry of multibeam sonar swath. Hundreds of individual high-resolution depths are measured simultaneously across a swath that is five to seven times the water depth wide. Source: John Hughes Clarke, Center for Coastal and Ocean Mapping, University of New Hampshire.

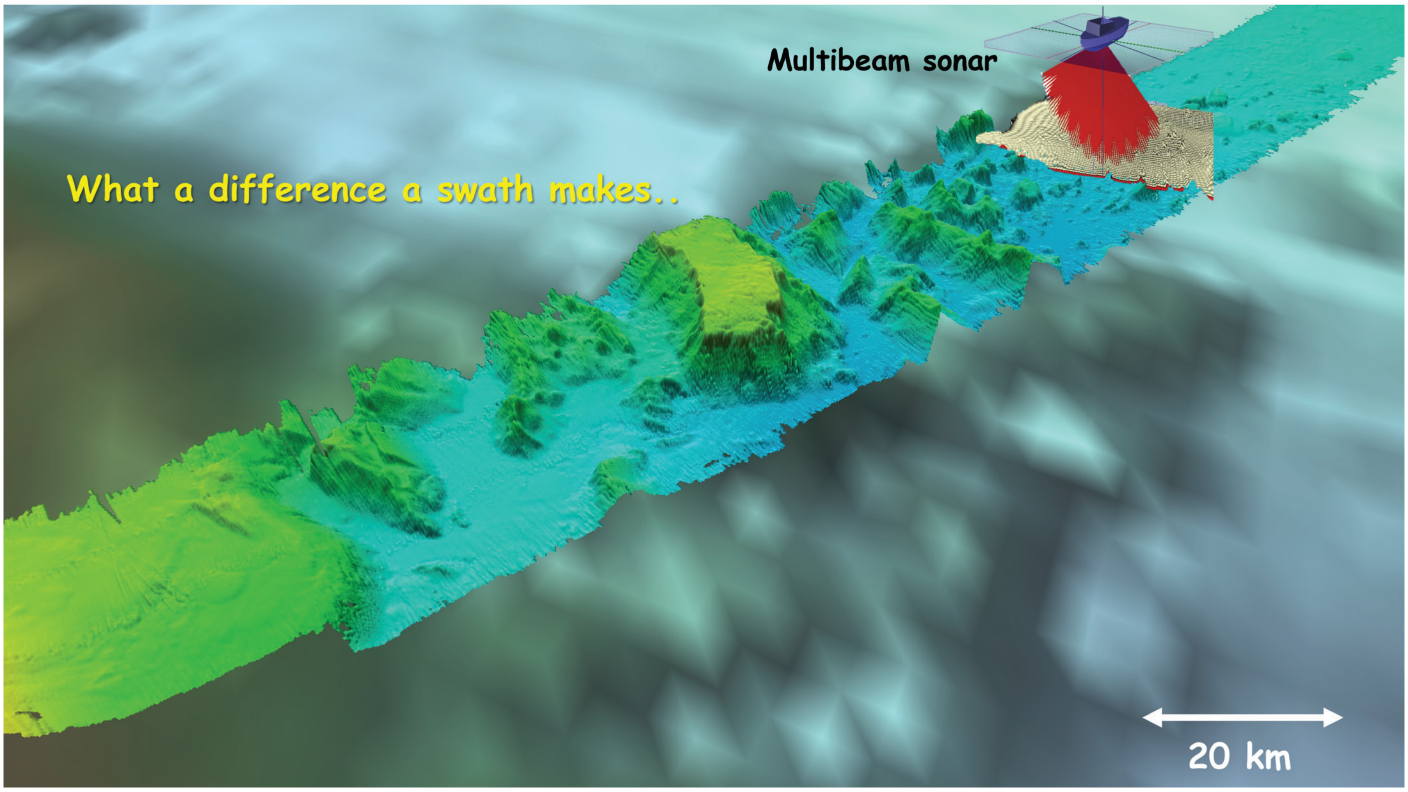


FIGURE 6 A single swath in 4,000 m of water north of Hawaii—showing the difference between the resolution of multibeam sonar data (detailed swath in bright colors) and single beam and satellite altimetry derived bathymetry (underlying image).

mapping. Fortunately, as these new sonar technologies were developed, there were concomitant advances in precise navigation, high-quality motion sensors, accurate sound-speed profiles, advanced computing, and sophisticated visualization tools. It is only through the careful integration of these components that the thousands to millions of raw acoustic travel times collected by multibeam sonars can be converted into accurate high-resolution digital terrain models. The density of data acquired by multibeam sonar allows us to return to the central role that vision plays in exploration, as the high density of multibeam sonar data support the use of modern visualization techniques that allow the production of realistic looking sun-illuminated three-dimensional (3-D) images that allow scientists to recognize patterns, infer processes, and generate hypotheses in ways that were impossible with sparse datasets (Figure 6), including details of volcanic constructs, fault scarps, submarine landslides, channels, sediment waves, and flat-topped seamounts (guyots) that record past sea-level exposure. Such features provide direct evidence of tectonic, volcanic, and sedimentary processes and inform models of crustal formation, slope stability, and sediment transport. Equally important, detailed bathymetry enables quantitative analyses of seafloor roughness and slope, parameters that strongly influence ocean circulation and mixing. Seamounts and rough terrain enhance turbulence and energy dissipation, affecting deep-water stratification and heat transport—key components of climate models.

Beyond Depth: Acoustic Backscatter and Seafloor Characterization

Modern multibeam systems record not only depth but also the intensity of the returned acoustic signal, known as backscatter. Backscatter varies with the properties of the seafloor, most importantly its roughness and hardness. Thus, careful mapping of seafloor backscatter provides insights into the nature of the substrate. When combined with bathymetry, backscatter allows scientists to move from identifying *where* the seafloor is (from the bathymetry) to inferring *what* it is composed of. Applications include identification of seafloor type and items on the seafloor (e.g., wrecks and other infrastructure), benthic habitat mapping, detection of anthropogenic disturbances such as dredge spoil disposal, and many more (Figure 7).

Imaging the Water Column: A Second Acoustic Revolution

From their inception, multibeam sonars were focused on the return from the seafloor, originally only collecting depth data and then, as the systems became more sophisticated, adding seafloor backscatter measurements. To collect seafloor data, the acoustic wave had to travel through the water column, and, as computational and data storage capabilities improved, multibeam sonars began to offer the option of acquiring data in the water column. While immensely increasing data volumes, water column data also offered tremendous new insights into processes both at and near the seafloor and in the ocean's volume. Fish schools, zooplankton layers, and other biological aggregations produce strong acoustic scattering signals in the water column. Fishery sonars had been imaging the water column for years; however, these sonars were single beam sonars ensonifying only a narrow sector of the water column. In contrast, water column data from multibeam sonars offered the opportunity to see the distribution and behavior of fish

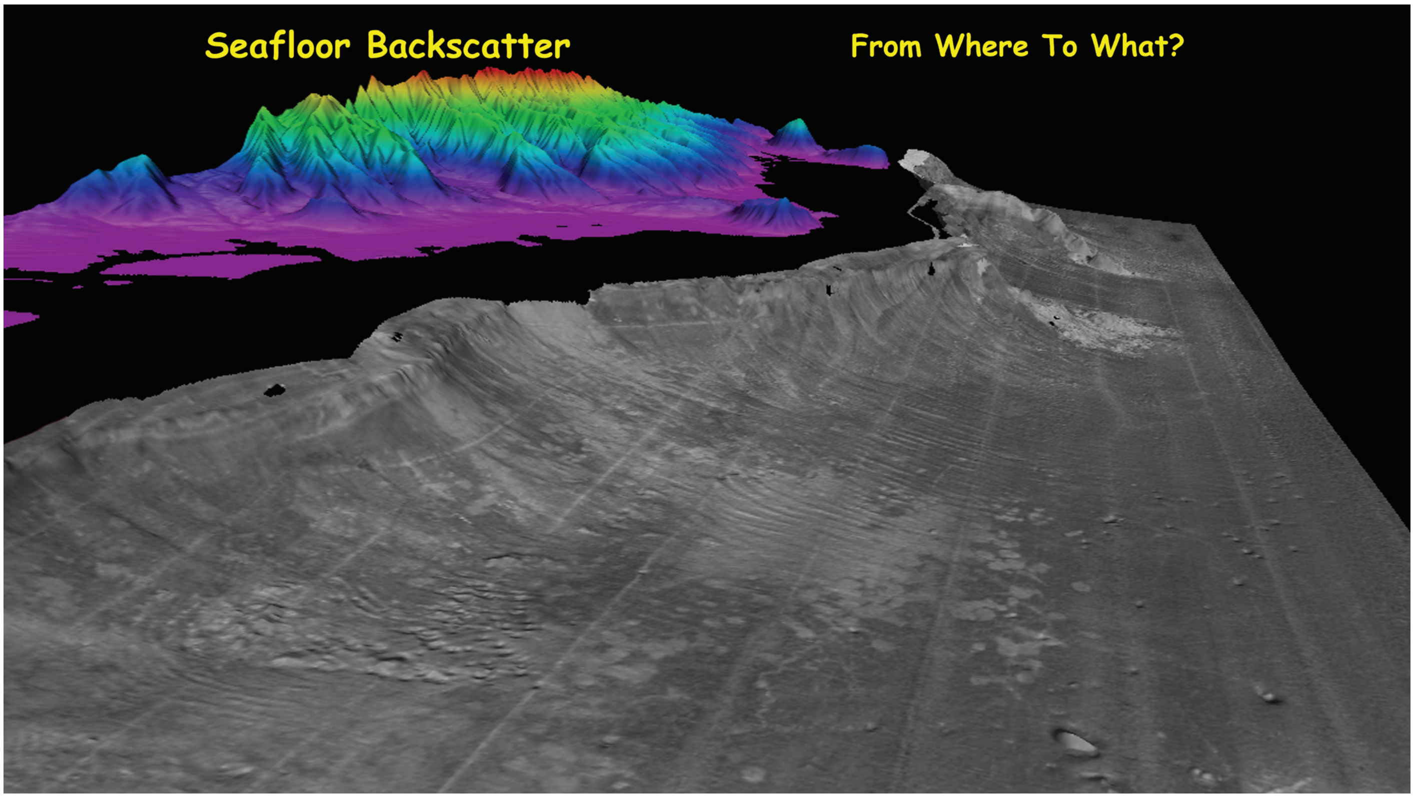


FIGURE 7 Multibeam sonar backscatter data draped on top of bathymetry data off the island of Oahu, Hawaii. Bright white (high-backscatter) regions towards top of figure (off Diamond Head) indicate volcanic flows while more subtle round lighter areas near bottom of image indicate dredge material that had been removed from Pearl Harbor and dumped in 400–600 m of water offshore. Source: James Gardner, Center for Coastal and Ocean Mapping, University of New Hampshire.

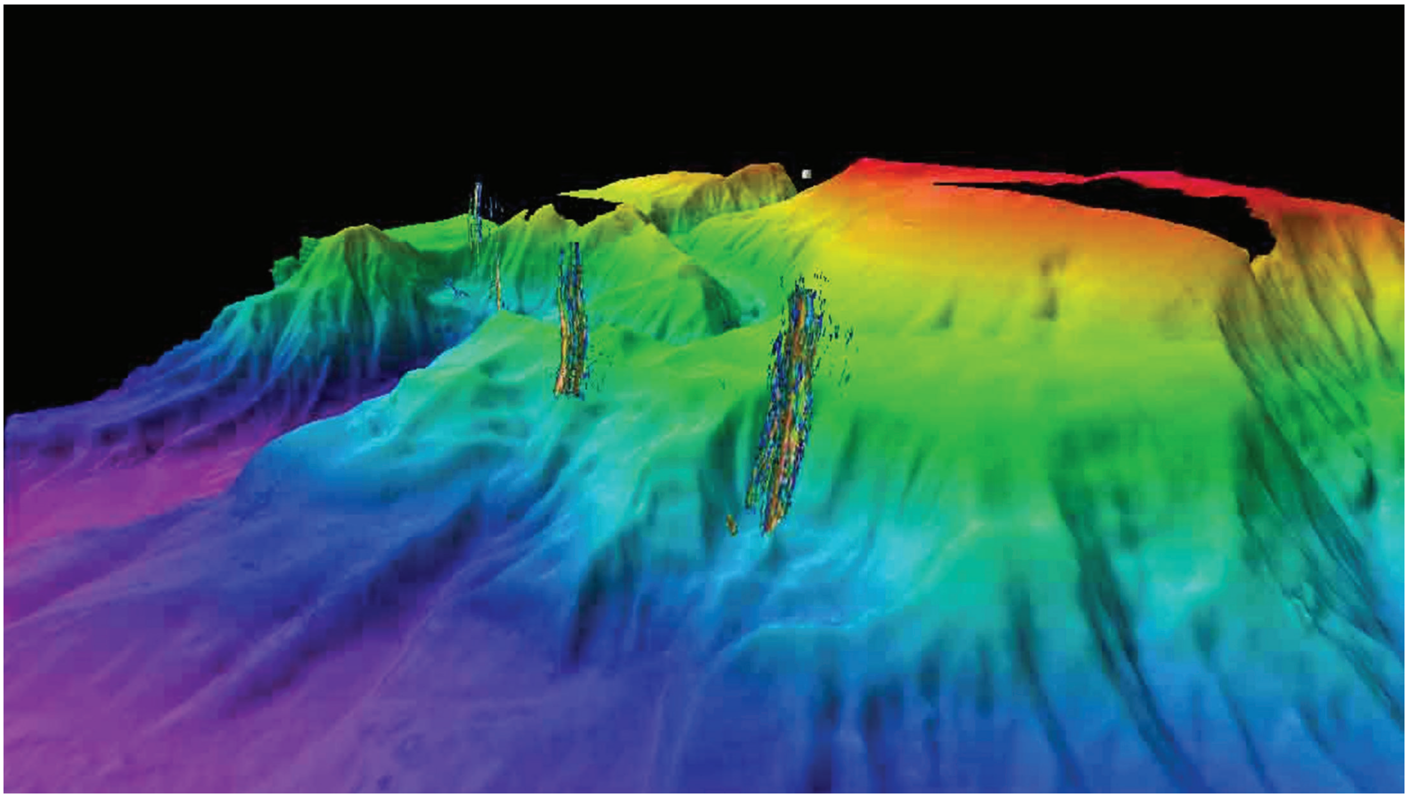


FIGURE 8 Natural gas seeps, each about 1,400 m high, off Mendocino California during early testing of multibeam sonar water column data collection on the NOAA Vessel *Okeanos Explorer*. Source: James Gardner, Center for Coastal and Ocean Mapping, University of New Hampshire.

schools and other targets simultaneously over a wide area, addressing the important question of whether fish were avoiding the sonar vessel and thus biasing biomass estimates (Soria et al., 1996; Mayer et al., 2002). Similarly, gas seeps produce strong acoustic targets; the ability for multibeam sonars to visualize gas seeps was clearly demonstrated during the test of a newly installed water column–capable multibeam sonar on the NOAA vessel *Okeanos Explorer* off the coast of northern California where natural methane gas seeps rising more than 1,400 m from the seafloor were clearly seen (Gardner et al., 2009) (Figure 8).

Water column mapping proved invaluable during the *Deepwater Horizon* incident, where acoustic monitoring was used to assess wellhead integrity after capping (Hickman et al., 2013). These observations demonstrated the ability of multibeam systems to detect even small leaks and distinguish them from background noise and have led to the use of multibeam sonars to broadly map and estimate the distribution of both natural and man-made gas seeps in the oceans—an underestimated contributor to ocean acidification and in some cases atmospheric CO2 (Weber et al., 2012; Ruppel et al., 2024).

Perhaps one of the most exciting applications of midwater mapping is the ability of our sonar systems to reveal physical oceanographic changes in the water column. Internal waves, pycnoclines, turbulence, thermohaline staircases, mixed-layer depth, and anoxic layers have all been imaged acoustically (some with multibeam sonar and some with single beam fisheries sonars), in each case revealing fine-scale structure previously accessible only through direct point measurements with Conductivity, Temperature, and Depth sensors (CTDs) or microturbulence sensors (Colbo et al., 2014; Stranne et al., 2017, 2018; Weidner et al., 2020) (Figure 9). These observations are opening new horizons for the understanding of mixing processes and stratification in both polar and temperate oceans.

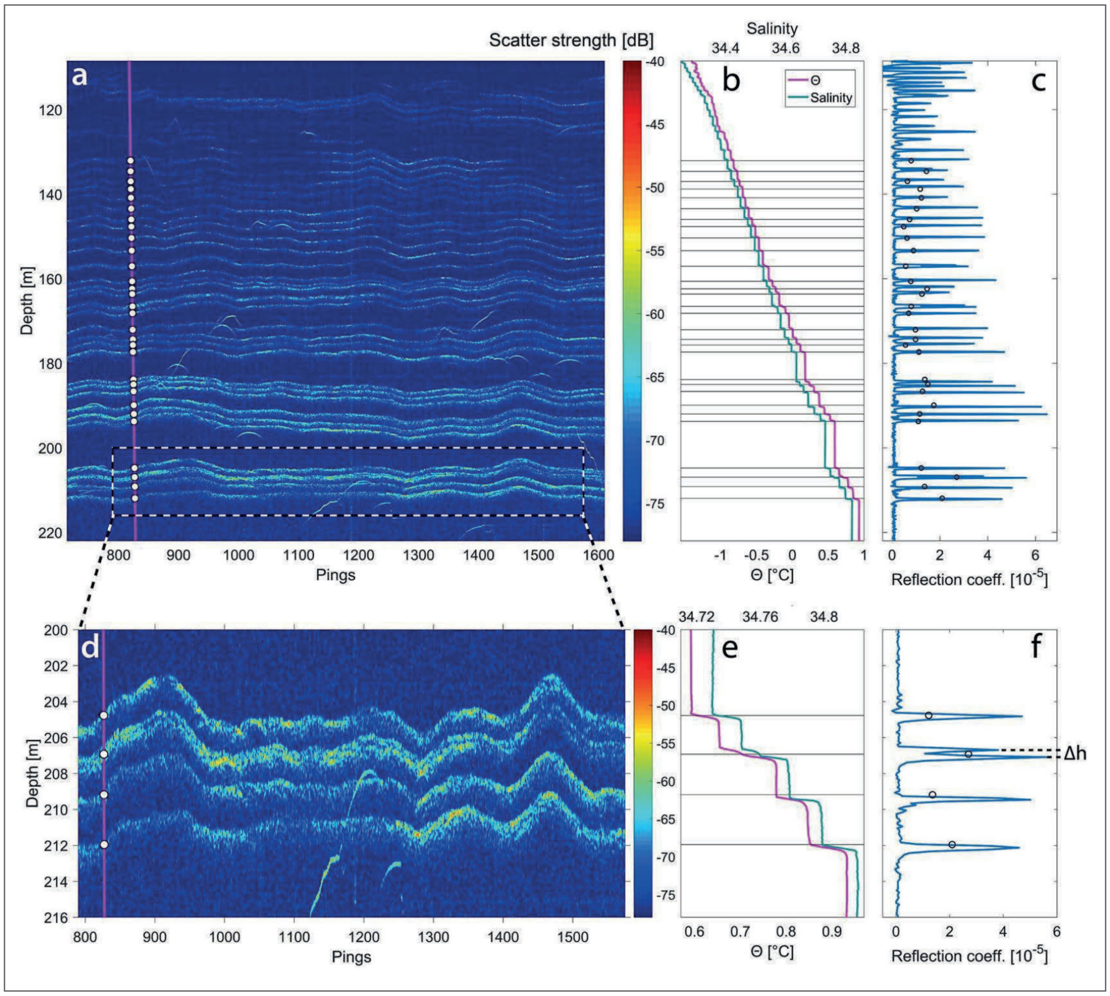


FIGURE 9 Fine-scale thermohaline structure (thermohaline staircases) revealed by broad-band single beam sonar in the high Arctic (a and d). Temperature and salinity profiles collected where purple line in a and b is (b and e) and reflection coefficients (change in acoustic response) calculated from temperature and salinity profile (blue line) and calculated from the acoustic response (black circles) c and f. Source: Stranne et al., 2017.

How Much Is Mapped?

We have come a long way, from 4,000 years of measuring depth with lead lines to modern multibeam sonars capable of covering wide swaths of the seafloor with high resolution. Most modern research vessels and many commercial and military vessels carry multibeam sonars, and these vessels have been collecting mapping data for the past 40 years. Despite these efforts, by 2017, only approximately 6 percent of the global seafloor had been mapped using modern techniques (i.e., single beam or multibeam sonars). Recognizing the critically important roles that mapping plays in understanding our oceans, the Nippon Foundation established an ambitious and aspirational international mission to inspire ocean mapping and deliver a complete seabed map for the benefit of people and the planet (see https://seabed2030.org/our-mission). This effort, the Nippon Foundation/GEBCO Seabed 2030 program, has established a series of regional centers that have been actively discovering unpublished existing data and facilitating the collection of new data, all of which are added to the publicly available GEBCO global bathymetric grid (see https://www.gebco.net/). Since its inception in 2017, global coverage of modern bathymetric data has increased from 6 percent to 27.3 percent in 2025 (Seabed 2030, 2025).

The United States also recognized the critical importance of mapping data for managing and protecting its offshore resources and established under a Presidential Memorandum an Interagency Council and Working Group on Ocean and Coastal Mapping along with an Implementation Plan for a National Strategy for Ocean Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone (NOMEC; see https://www.noaa.gov/ocean-science-and-technology-subcommittee/national-ocean-mapping-exploration-and-characterization-nomec-council). This effort contributes to the global Seabed 2030 effort and calls for the complete mapping of the deeper waters of the U.S. exclusive economic zone by 2030 and the shallow waters by 2040.

While these efforts have greatly accelerated the rate of seafloor mapping, almost 75 percent of the global seafloor remains unmapped. How long would it take to map the remaining 75 percent? Using our best estimate of the distribution of depths (as the mapping effort changes radically with water depth as the swath width changes) and assuming the use of current technology (large research vessels with deep water multibeam systems), it has been estimated that it would take between 200 and 350 ship-years to map the oceans deeper than 200 m at the resolutions specified by Seabed 2030 (Mayer et al., 2018). Assuming an average day rate of $50,000 per day for a large research vessel, the estimated cost would be between three and five billion dollars.

While it might seem unrealistic to spend several billion dollars to completely map the oceans, the reality is that we have spent much more than that to map other planets. To date, the global community has launched 18 orbiters to Mars, resulting in the near complete mapping of that planet at a resolution of 6 m or better (Zurek et al., 2024). Each mission costs somewhere between $300M and $1B, and thus more than approximately $11B has already been spent to map Mars. This is not to demean the tremendous technological achievement of mapping Mars nor the importance of these maps in understanding planetary origins and planning future missions, however, one cannot help but ask why we are not willing to put a similar level of investment into mapping our own planet. The typical response is that it is actually harder to map the deep ocean than it is to remotely map Mars from an orbiter (which is true), but as has been demonstrated above, even with current technology, we have the ability to map the entire ocean, and, for the same (or less of an) investment than we have put into mapping Mars, it can be done.

Can Technological Innovation Reduce the Cost and Effort?

The cost and time estimates discussed above assume the use of current technologies for ocean mapping—that is, the use of a large (often costing hundreds of millions of dollars) research vessel equipped with a multibeam sonar. Can technical innovations reduce these costs and make the goal of complete mapping of the ocean more obtainable? There are a limited number of large research vessels with many demands on their time beyond mapping. If we are to achieve comprehensive coverage, we must find means to scale ocean mapping beyond the use of traditional research vessels.

UNCREWED OR MINIMALLY-CREWED SURFACE VESSELS

One of the largest expenses associated with traditional research vessels is the cost of the crew. If we can eliminate or minimize the crew costs, significant savings can be had. AUVs have matured greatly over the past 60 years and are now available in a range of sizes serving many applications (Ma et al., 2025; Wynn et al., 2014). These vehicles typically operate near the bottom (and thus cannot use GPS for navigation), have limited endurance, and move rather slowly (in efforts to extend endurance). They present the only means to collect extremely high-resolution mapping data in very deep waters as their sonars are near the bottom; however, their slow speed, limited endurance, small area of coverage (because they are near the bottom), and navigational challenges make them less than ideal for comprehensive mapping of the global ocean at this time.

In contrast to fully-crewed research vessel, uncrewed or minimally-crewed surface vessels (USVs or MCSVs) offer the possibility to have platforms large enough to carry the large sonars needed to map in deep water as well as, potentially, the speed and endurance to efficiently scale the ocean mapping problem. Small uncrewed vessels have proven effective force-multipliers

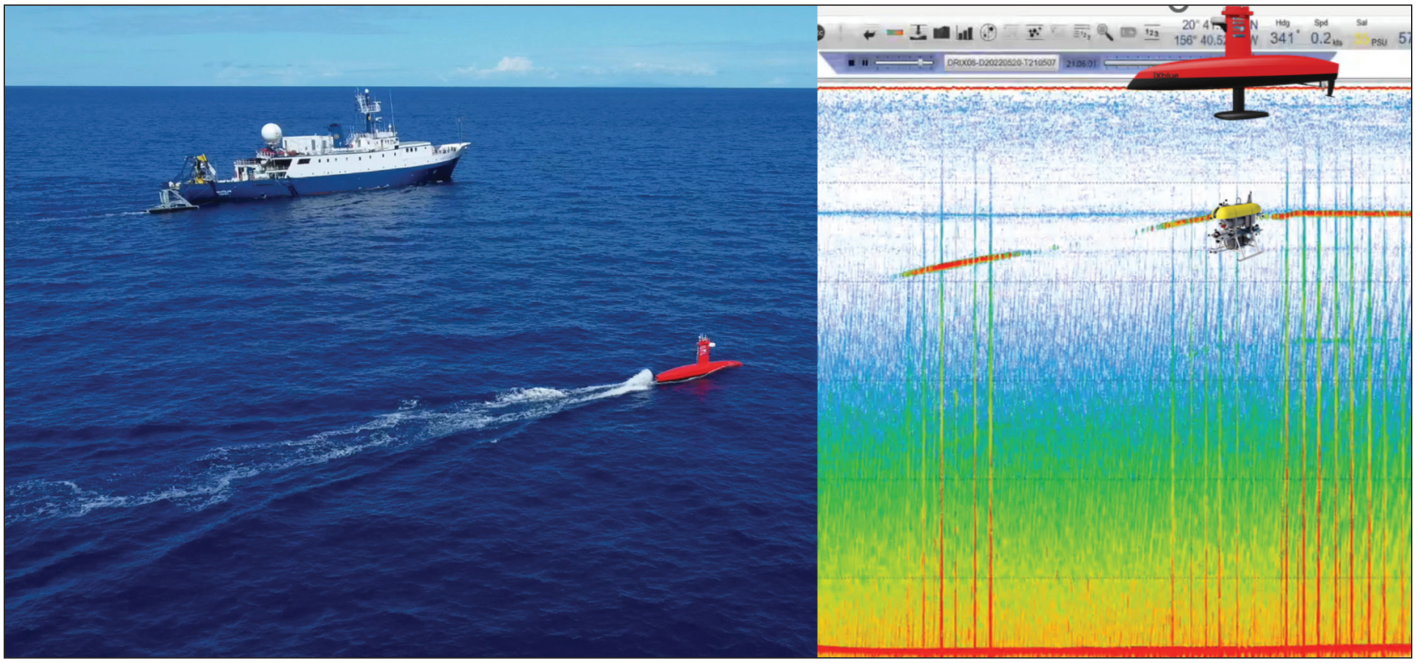


FIGURE 10 DriX, a 7.7 m long uncrewed mapping vessel capable of mapping to 3,000 m acting as force multiplier while operating in parallel with to the *E/V Nautilus* (left, photo courtesy of Ocean Exploration Trust). DriX is used to direct the Woods Hole Oceanographic Institution AUV Mesobot to a mid-water acoustic target and turn on video and eDNA samplers when it is verified that it is directly in the target layer (right).

for shallow water mapping (e.g., "Uncrewed vessels survey the seafloor," 2023), and medium-to-small USVs have proven remarkably valuable for expanding the footprint of ocean exploration by monitoring the activities of AUVs and, in real-time, directing these vehicles to specific targets in the water column. For example, recently in the mid-Pacific, a 7 m USV deployed from a mother ship was used to map mid-water acoustic targets (scattering layers) and was able to track and direct a small AUV (Mesobot) directly into the scattering layer before turning on eDNA samplers and high-resolution video, all while the mother ship was free to carry on other activities. This new approach to "Verified Directed Sampling" is already having important ramifications on estimates of biodiversity in the mesosphere and our understanding of the nature of mid-water scattering layers (Mayer, 2023; Govindarajan, 2025) (Figure 10). We are, however, still in the early days of development of USVs that are large enough and have the endurance to carry out long-range deep-ocean mapping missions. Challenges include operations in extreme environments, long-term reliability, and truly autonomous behaviors that include obstacle avoidance and dynamic decision making (Norazaruddin et al., 2024).

Several vendors are bringing large uncrewed vessels to market that can carry deep-water sonars that may have the speed, range, and endurance to potentially provide a scalable and cost-effective alternative to traditional research vessels (e.g., https://www.exail.com/product/drix-o-16, https://oceaninfinity.com/news/ocean-infinity-completes-armada-fleet-milestone-with-delivery-of-final-vessel). Addressing the other major costs associated with traditional research vessels, large sail-powered uncrewed vessels have been developed and are currently collecting mapping data while exploring the trade-offs between slower rates of coverage and potentially extended endurance (Figure 11). There is still much to be learned about the best operational modes for these vessels and shore-based crewing requirements, and thus questions remain about the overall cost-effectiveness of their operation. As experience is gained and lessons are learned from operating these systems, their viability and the role they can play in the complete mapping of the global ocean will be better understood (Mayer, 2023).

Given the tremendous technological and safety concerns of operating USVs on the open ocean, Victor Vescovo, an individual who has led the collection and contribution to international databases of much new deep-sea mapping data in support of submersible diving operations to the world's deepest trenches, is constructing a small (24 m) minimally (one- or two-person) crewed vessel whose only purpose would be to map. Vescovo is constructing the first of these vehicles, which is estimated to be an order of magnitude cheaper to operate than a traditional ocean-going research vessel, and is challenging others to build similar vessels so that a fleet of these relatively inexpensive to operate vehicles can address the challenge of completely mapping the oceans (Dunn, 2025) (Figure 11).

OTHER INNOVATIONS

While the efforts described above have focused on decreasing the cost of collecting multibeam sonar data, deep-water multibeam sonars are inherently large and expensive. To supplement multibeam sonar data, others are looking at ways to increase the use simpler and cheaper single-beam sonars and to find ways to deploy them in remote areas of the ocean.

One approach to this is to engage the "crowd," the millions of recreational and commercial vessels that carry echosounders but do not commonly record the depth information. To address this, efforts are now underway to create very inexpensive devices that are easily attached to most any vessel's echosounder, perform internal calibrations, and even transmit that data to the national data archive (Calder et al., 2020). This approach has proven successful when applied to the commercial fishing sector (Novaczek et al., 2019), and its expansion to the broader community can add important new data to the global database.

Crowd-sourced bathymetry tends to focus on shallow water areas and regions that are well traveled by commercial vessels. To address the issue of collecting data in the most remote regions, specialized profiling floats have been designed that use the thermal difference in the upper part of the water column to supply power to drive a buoyancy engine and a narrow-beam echo-sounder. These floats can be deployed in the most remote regions of the ocean, drift around,

FIGURE 11 Left, 16 m long DriX O-16 long-endurance, deep mapping USV. Source: Exail (https://www.exail.com/product/drix-o-16); and right, 21 m long Saildrone Surveyor, sail-powered, deep-water mapping USV. Source: Saildrone (https://www.saildrone.com/tag/saildrone-surveyor).

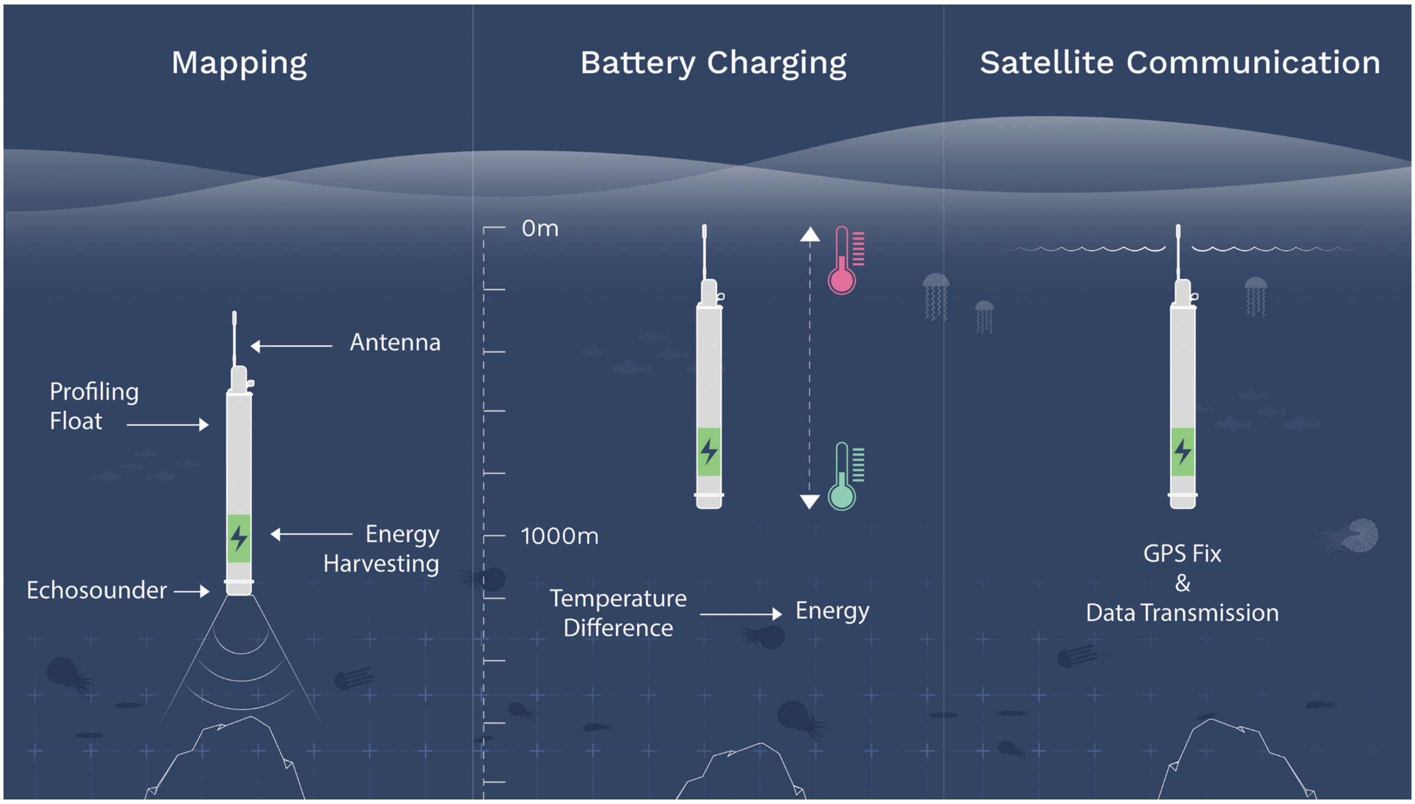


FIGURE 12 The concept of thermal energy harvesting buoyancy engine driven float with deepwater echo sounder. Image courtesy of Yi Chao, SeaTrec Inc.

and operate for many years, moving up and down the water column to harvest power while collecting several soundings a day, each time surfacing and sending data back to shore-based repositories via satellite (Mayer, 2023) (Figure 12).

Recently, researchers at MIT/Lincoln Labs have proposed a truly innovative way to address seafloor mapping. Their approach uses the concept of a sparse array where many small autonomous vessels move together to create a very large (e.g., 40 km x 40 km) array with some of the vessels sending out sonar pings that are then received by the rest of the vessels. Smaller prototypes have been built and tested, but, if working at full scale, the approach has the potential to achieve both much better resolution and greater coverage than a conventional multibeam sonar (Ryu et al., 2023). Together, these approaches suggest that complete mapping of the global ocean may be technically achievable within decades.

From Quest to Planetary Responsibility

For me, the pursuit of ocean mapping began as an adventure, driven by curiosity and the desire to explore. As the field has progressed to the point where we can, at relatively high-resolution, visualize the fine-scale features of the deep-sea floor, I have learned that the information provided by detailed ocean mapping represents a foundational requirement for managing the Earth system, and my adventure-driven quest has evolved into a quest to achieve something important. The remaining unmapped ~75 percent of the seafloor represents not merely unexplored territory but unresolved risks to navigation, climate prediction, hazard mitigation, resource exploration, environmental stewardship, and the potential for yet-unknown discoveries. The tools to complete a map of the global ocean now exist or are rapidly emerging. What remains is the need for a collective decision (and fiscal will) to recognize that the complete mapping of the ocean is essential to understanding—and responsibly managing—our planet. The quest continues.

References

Bell, K. L. C., Johannes, K. N., Kennedy, B. R. C., & Poulton, S. E. (2025). How little we've seen: A visual coverage estimate of the deep seafloor, *Science Advances, 11*(19). https://doi.org/10.1126/sciadv.adp8602

Billinghurst, M., & Thomas, B. (2016, August 9). *Lecture 3: Human perception (COMP4010—Virtual Reality)* [Lecture slides]. University of South Australia. https://www.slideshare.net/slideshow/comp-4010-lecture3-human-perception/64827753

Calder, B. R., Dijkstra, S. J., Hoy, S. K., Himschoot, K., & Schofield, A. P. (2020). A design for a trusted community bathymetry system. *Marine Geodesy, 43*, 327–358.

Colbo, K., Ross, T., Brown, C., & Weber, T. (2014). A review of oceanographic applications of water column data from multibeam echosounders. *Estuarine, Coastal and Shelf Science, 145*, 41–56. https://doi.org/10.1016/j.ecss.2014.04.002

Dunn, L. (2025, August). Victor Vescovo on enlisting Espen Øino to design a new $6M ocean-mapping vessel. *Boat International.* https://www.boatinternational.com/luxury-yacht-life/owners-experiences/victor-vescovo-mapping-ocean-floor-espen-oino

Gardner, J. V., Malik, M., & Walker, S. (2009). Plume 1400 meters high discovered at the seafloor off the northern California margin. *Eos, Transactions American Geophysical Union, 90.* https://doi.org/10.1029/2009EO320003

Govindarajan, A., Fahy, J., Hayden, E., Mayer, L., Roman, C., Schmidt, V., Yang, N., & Yoerger, D. (2025). Combining multi-vehicle operations, autonomous sampling, and environmental 'omics for surface to seafloor biodiversity assessments of the Geologists Seamounts, OS-51A-05, AGU Fall Annual Meeting, New Orleans, LA, 15–19 Dec 2025.

Hickman, S. H., Hsieh, P. A., Mooney, W. D., Enomoto, C. B., Nelson, P. H., Mayer, L. A., Weber, T. C., Moran, K., Flemings, P. B., & McNutt, M. K. (2013). Scientific basis for safely shutting in the Macondo well after the April 20, 2010 Deepwater Horizon blowout. *Proceedings of the National Academy of Sciences, 109*(50), 20268–20273. https://doi.org/10.1073/pnas.1115847109

Hughes Clarke, J. E., Mayer, L. A., & Wells, D. E. (1996). Shallow-water imaging multibeam sonars: A new tool for investigating seafloor processes in the coastal zone and on the continental shelf. *Marine Geophysical Researches, 18*, 607–629. https://doi.org/10.1007/BF00313877

Ma, D., Li, Y., Ma, T., & Pascoal, A. M. (2025). The state of the art in key technologies for autonomous underwater vehicles: A review. *Engineering.* https://doi.org/10.1016/j.eng.2025.08.002

Mayer, L. (2023). Uncrewed surface systems facilitating a new era of global ocean exploration. *International Hydrographic Review, 29*(1). https://ihr.iho.int/articles/uncrewed-surface-systems-facilitating-a-new-era-of-global-ocean-exploration/

Mayer, L. A., Jakobsson, M., Allen, G., Dorschel, B., Falconer, R., Ferrini, V., Lamarche, G., Snaith, H., & Weatherall, P. (2018). The Nippon Foundation—GEBCO Seabed 2030 Project: The quest to see the world's oceans completely mapped by 2030. *Geosciences, 8*(2), 63. https://doi.org/10.3390/geosciences8020063

Mayer, L. A., Li, Y., & Melvin, G. (2002). 3-D visualization for pelagic fisheries assessment and research. *ICES Journal of Marine Science, 59*, 216–225.

Norazaruddin, M. A., Abidin, Z. Z., & Hamza, M. I. (2024). Unmanned surface vessels in hydrographic surveying: Exploring technological progressions and development challenges. *Indian Journal of Geo-Marine Sciences, 53*(7). https://doi.org/10.56042/ijms.v53i07.10419

NOAA (National Oceanic and Atmospheric Administration). n.d.-a. NOAA Digital Collections. https://www.noaa.gov/digital-collections/photo-library/map00002jpg (Accessed February 24, 2026)

NOAA (National Oceanic and Atmospheric Administration), n.d. "History: Timeline: NOAA Office of Ocean Exploration and Research." NOAA Ocean Exploration. https://oceanexplorer.noaa.gov/history/timeline-the-breakthrough-years-1866-1922/ (Accessed February 20, 2026)

Novaczek, E., Devillers, R., & Edinger, E. (2019). Generating higher resolution regional seafloor maps from crowd-sourced bathymetry. *PLOS ONE, 14*(6), e0216792.

Ruppel, C. D., Skarke, A. D., Miller, N. C., Kidiwela, M. W., Kluesner, J., & Baldwin, W. (2024). Methane seeps on the U.S. Atlantic margin: An updated inventory and interpretative framework. *Marine Geology, 471*, 107287. https://doi.org/10.1016/j.margeo.2024.107287

Ryu, P., March, A., Kindler, D., et al. (2023). A wide-area deep ocean floor mapping system: Design and sea tests. *Geomatics, 3*. https://doi.org/10.3390/geomatics3010005

Sandwell, D. T., Phrampus, B. J., Salajegheh, F., et al. (2025, November 17). *Bathymetry prediction with SWOT gravity anomaly using machine learning methods: Paper 1—Model development.* ESS Open Archive.

Scholin, C. (2025). 26th Annual Roger Revelle Commemorative Lecture: Oceanography in the Age of Intelligent Robots and a Changing Climate. Lecture. May 1, 2025. Washington, D.C. https://www.nationalacademies.org/projects/DELS-OSB-19-P-169/event/44800

Seabed 2030. (2025). Seabed 2030 announces millions of square kilometers of new seafloor data on World Hydrography Day. https://seabed2030.org/2025/06/21/seabed-2030-announces-millions-of-square-kilometers-of-new-seafloor-data-on-world-hydrography-day/ (Accessed February 18, 2026)

Smith, W. H. F., & Sandwell, D. T. (1997). Global sea floor topography from satellite altimetry and ship depth soundings. *Science, 277*(5334), 1956–1962. https://www.star.nesdis.noaa.gov/socd/lsa/AltBathy/index.php (Accessed February 18, 2026).

Soria, M., Fréon, P., & Gerlotto, F. (1996). Analysis of vessel influence on spatial behaviour of fish schools using a multi-beam sonar and consequences for biomass estimates by echo-sounder. *ICES Journal of Marine Science, 53*(2), 453–458. https://doi.org/10.1006/jmsc.1996.0064

Stranne, C., Mayer, L., Jakobsson, M., Weidner, E., Jerram, K., Weber, T. C., Anderson, L. G., Nilsson, J., Björk, G., & Gårdfeldt, K. (2018). Acoustic mapping of mixed layer depth. *Ocean Science, 14*, 503–514. https://doi.org/10.5194/os-14-503-2018

Stranne, C., Mayer, L. A., Weber, T. C., Ruddick, B. R., Jakobsson, M. J., Jerram, K., Weidner, E., Nilsson, J., & Gårdfeldt, K. (2017). Acoustic mapping of thermohaline staircases in the Arctic Ocean. *Scientific Reports, 7*, 15192. https://doi.org/10.1038/s41598-017-15486-3

Uncrewed vessels survey the seafloor. (2023). *Journal of Petroleum Technology*. https://jpt.spe.org/uncrewed-vessels-survey-the-seafloor

Weber, T. C., Mayer, L. A., Beaudoin, J., Jerram, K., Shedd, W., & Rice, G. (2012). Mapping gas seeps with the deepwater multibeam echosounder on *Okeanos Explorer. Oceanography, 25*(1), Supplement.

Weidner, E., Stranne, C., Sundberg, J., Weber, T., Mayer, L., & Jakobsson, M. (2020). Tracking the spatiotemporal variability of the oxic–anoxic interface in the Baltic Sea with broadband acoustics. *ICES Journal of Marine Science*, fsaa153. https://doi.org/10.1093/icesjms/fsaa153

Wynn, R. B., Huvenne, V. A. I., Le Bas, T. P., Murton, B. J., Connelly, D. P., Bett, B. J., Ruhl, H. A., Morris, K. J., Peakall, J., Parsons, D. R., Sumner, E. J., Darby, S. E., Dorrell, R. M., & Hunt, J. E. (2014). Autonomous underwater vehicles (AUVs): Their past, present and future contributions to the advancement of marine geoscience. *Marine Geology, 352*, 451–468. https://doi.org/10.1016/j.margeo.2014.03.012

Zurek, R., Tamppari, L., Johnston, M. D., Murchie, S., McEwen, A., Byrne, S., Seu, R., Putzig, N., Kass, D., Malin, M., & Cantor, B. (2024). MRO overview: Sixteen years in Mars orbit. *Icarus, 419*, 116102. https://doi.org/10.1016/j.icarus.2024.116102

Revelle Alumni

Peter Brewer
1999

Shirley Pomponi
2000

Marcia McNutt
2001

Michael Orbach
2002

James Watkins
2003

Richard Alley
2004

Roger Pielke, Jr.
2006

Ken Caldeira
2007

Michael Freilich
2008

Paul Falkowski
2009

Jane Lubchenco
2010

Nancy Rabalais
2011

Eddie Bernard
2012

John Walsh
2013

David Karl
2014

Susan Lozier
2015

Philip Clapham
2016

Dawn Wright
2017

Jeffrey Bolster
2018

Lisa Levin
2019

Chelsea Rochman
2020

Harriet Harden-Davies and Alfredo Giron
2021

John Dabiri
2022

Kathryn Sullivan and Margaret Leinen
2023

Kim Cobb
2024

Chris Scholin
2025

The National Academy of Sciences

was established in 1863 by an Act of Congress, signed by President Lincoln, as a private, nongovernmental institution to advise the nation on issues related to science and technology. Members are elected by their peers for outstanding contributions to research. Dr. Marcia McNutt is president.

The **National Academy of Engineering** was established in 1964 under the charter of the National Academy of Sciences to bring the practices of engineering to advising the nation. Members are elected by their peers for extraordinary contributions to engineering. Dr. Tsu-Jae Liu is president.

The **National Academy of Medicine** (formerly the Institute of Medicine) was established in 1970 under the charter of the National Academy of Sciences to advise the nation on medical and health issues. Members are elected by their peers for distinguished contributions to medicine and health. Dr. Victor J. Dzau is president.

The three Academies work together as the **National Academies of Sciences, Engineering, and Medicine** to provide independent, objective analysis and advice to the nation and conduct other activities to solve complex problems and inform public policy decisions. The National Academies also encourage education and research, recognize outstanding contributions to knowledge, and increase public understanding in matters of science, engineering, and medicine.

Learn more about the National Academies of Sciences, Engineering, and Medicine at **www.nationalacademies.org**.

NATIONAL ACADEMIES *Sciences Engineering Medicine*

The National Academies provide independent, trustworthy advice that advances solutions to society's most complex challenges.

www.nationalacademies.org