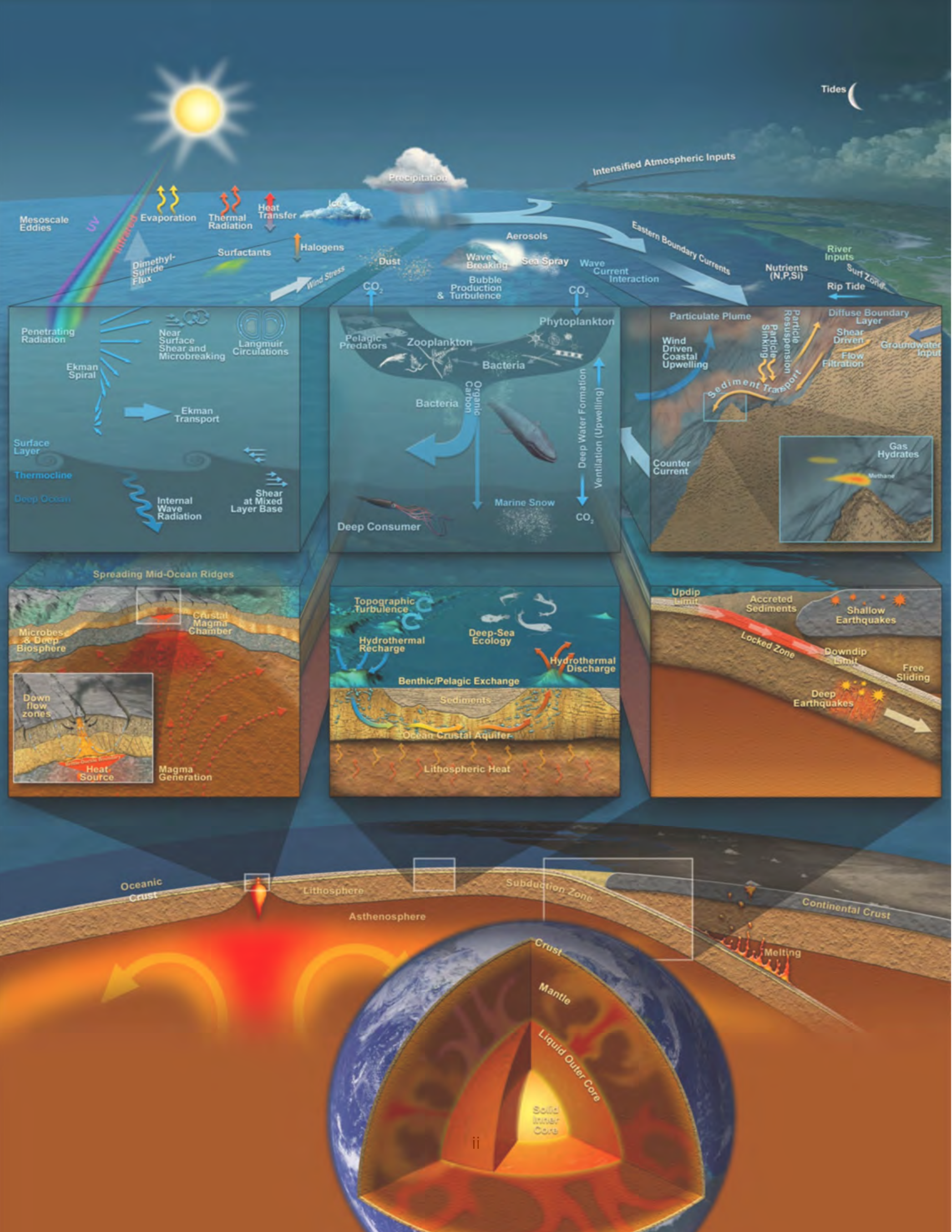
Developing Submergence Science for the Next Decade (DESCEND–2016)

Workshop Proceedings

January 14-15, 2016


Tides
Intensified Atmospheric Inputs
Precipitation
Mesoscale Eddies
UV
Infrared
Evaporation
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Heat Transfer
Ice
Dimethyl-Sulfide Flux
Surfactants
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EXECUTIVE SUMMARY

“How inappropriate it is to call this planet Earth when it is quite clearly Ocean.”
- Arthur C. Clarke

Over the last fifty years, our awareness of the role that the ocean plays in the Earth system has grown remarkably. During the 1960s, as the first commercial satellites were launched, plate tectonics progressed from being a dubious idea to a well-tested paradigm that explains hundreds of millions of years of seafloor and continental processes with important implications for deep-seated phenomena within Earth’s mantle. Coincident with the first personal computers being introduced in the late 1970s, marine scientists discovered hydrothermal vents and their astonishing biological communities, both of which re-shaped our notions of where life can flourish here on Earth and on other planets. Throughout the 1980s, as biotechnologies enabled DNA fingerprinting and the Human Genome Project, marine microbiologists discovered a tiny microbe that is the most abundant photosynthetic (oxygen-producing) organism on the planet. The 1990s saw advances in our understanding of the ocean carbon cycle, and signs of how our ocean might be responding to a changing world. The past twenty years have been a watershed for understanding geological, geochemical and biological phenomena and their linkages. Through this increased knowledge base, often driven by technological advances, scientists have discovered an entirely new class of hydrothermal vents, found countless new animal and microbial species, produced high-resolution bathymetric maps of the seafloor that rival or surpass those created for land, and advanced our understanding of methane cycling in the deep-sea. Recent advances in genomics have led to a massive surge in sequencing of microbes and animals alike, which has literally redefined humankind’s understanding of the origin and evolution of life on Earth.

In November 1999, in the midst of this scientific and technological revolution, marine scientists held a workshop called DEveloping Submergence SCiencE for the Next Decade (DESCEND) at the National Science Foundation in Arlington, Virginia. This meeting was prompted by a desire to define the primary scientific goals of the deep-sea research community, and to identify the technologies required for advancing deep-sea studies. To accomplish its goals, the DESCEND Workshop brought together scientists and technology experts to identify the most pressing questions in deep-sea research, the newest tools, and the most innovative technological approaches necessary to address those questions. The DESCEND Workshop helped set the stage for 21th Century deep-sea research, and the recommendations of the committee helped the community and the National Science Foundation (NSF) and other cognizant federal agencies (i.e., NOAA and ONR) better deploy their resources to greater effect.

In 2015, with support from the NSF, members of the Deep Submergence Science Committee (or DeSSC, which is a committee of the University National Oceanographic Laboratory System, or UNOLS), proposed a workshop in response to that recommendation. The DEveloping Submergence SCiencE for the Next Decade–2016 (DESCEND–2106) Workshop was held from January 14 to 15, 2016 in

Cambridge, Massachusetts. (See http://projects.iq.harvard.edu/descend2.) The workshop involved scientists and engineers from the deep-sea research community tasked with **A) identifying the technological and cultural innovations that will enable us to advance our understanding of the deep sea; and B) presenting guidelines that will facilitate government agencies, as well as industry and philanthropic partners, in developing new operational modes and funding opportunities, as appropriate, to advance deep-sea research.**

Key Findings

1) Federal agencies should promote joint programs that bring different communities together to advance technologies and address transdisciplinary questions, e.g. NASA astrobiology and NSF Ocean Sciences.

1A) Support advances and initiatives in robotics, automation, sensor development, and big data management/analyses that will foster new avenues for exploration and advance our understanding of geological, geochemical, and ecological processes in the ocean, on the seafloor, and within the Earth's interior.

1B) Increase attention to, and support for, exploring and studying underserved habitats such as the shallow shelf, midwater, sub-ice ocean, abyssal plains, and trenches. Including these regions will help us better understand the biotic and abiotic evolution of our ocean system, and assess its sensitivity to natural and anthropogenic change.

2) Federal agencies, philanthropic entities, and academic institutions that support Earth-Ocean research should actively collaborate to promote effective communication among all parties. Special attention should be paid to developing programs that incentivize established investigators to engage and mentor early career scientists. Agencies and entities should place a greater emphasis and recognition for public service and engagement.

2A) Enhance cooperation among governmental and philanthropic foundations to enable scientific pursuits that leverage public/private resources to greater effect than can be achieved through any one means of support.

2B) Develop programs to promote inclusivity and increase diversity in the ocean sciences. Studies have shown that diversity writ large improves the quality of research.

2C) Engage and train early-career scientists as a key to maintain a vigorous research community.

The resulting report addresses how existing technologies that can be better deployed to help address the science questions, which new technologies are needed to answer long-standing questions, how we might alleviate major logistical or financial constraints that can limit scientific exploration and studies, and how we might bring together government and nongovernment entities to facilitate collaborative sponsorship and provide new opportunities for advancing deep-sea research.

Advancing the Development and Use of Emerging Technologies: The DESCEND–2016 participants noted that recent advances in our understanding of the structure and function of ocean ecosystems has spawned a myriad of new questions, many of which require novel technologies. Here are highlights of the communities' suggestions (the details of which can be found in the breakout reports later in this document).

<u>*Robotics and automation*</u>: There was a broad recognition that advances in robotics and automation, including the development of more sophisticated autonomous vehicles, would enable scientific explorations in deep-sea environments. Advanced robotics / automation can enable more effective research of deep-submergence targets such as submarine volcanic, hydrothermal, and tectonics systems, including the sites of the Ocean Observatories Initiative (OOI). Moreover, despite growing awareness that the polar regions are very sensitive to anthropogenically influenced climate change, there are no robust, readily available deep-sea vehicles for under ice work. Several institutions, including Woods Hole Oceanographic Institution (WHOI), have been developing under-ice ROVs, yet their platform and many others would benefit for further "hardening" for frequent use in under-ice field campaigns. Finally, to date, there are no basin-scale navigation systems for long-range under-ice operations, which limits both the resolution and operational area of any under-ice vehicle. It is also recommended that there be greater investment in midwater tracking, sensing, and

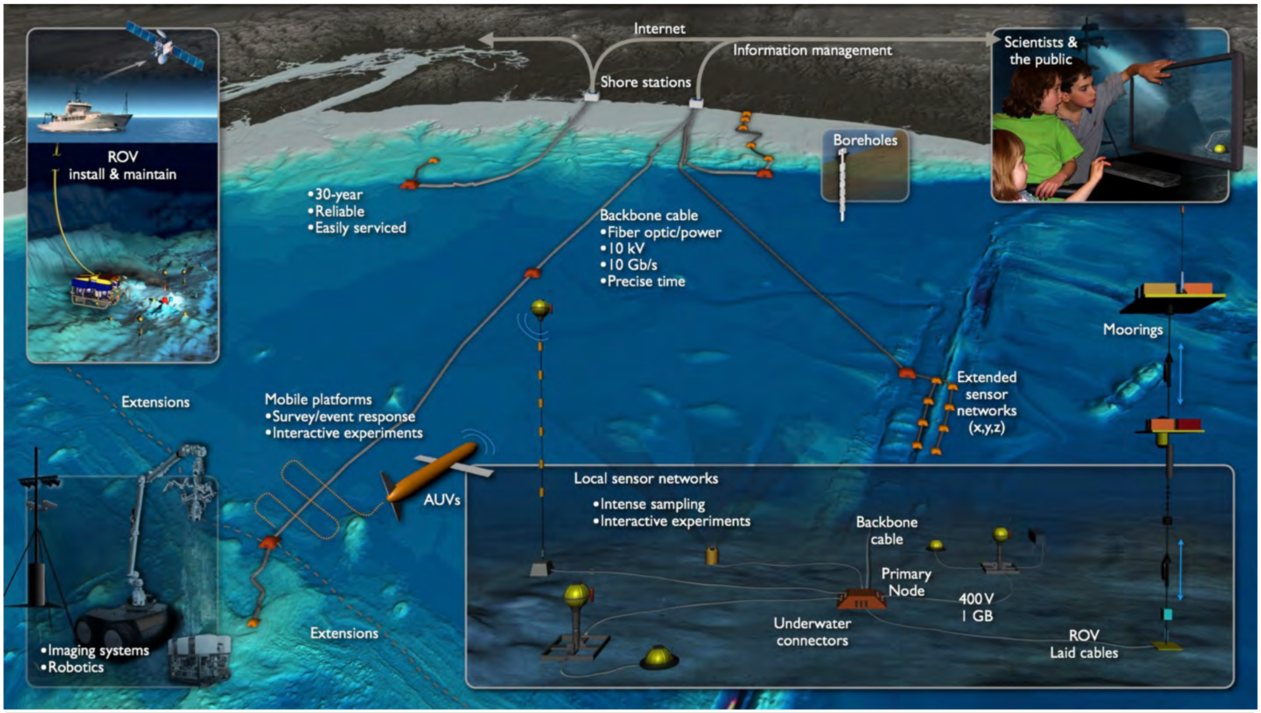


Fig. 1: A seafloor cabled observatory supporting networked autonomous vehicles and research vessels working together to understand the biological, geological, and geochemical linkages from the continental slope to a hydrothermal vent system. © CEV

sampling technologies. Midwater research has undergone a series of expansions and contractions during the last 40 years, and the growth of oxygen-minimum zones and heightened awareness of the role that midwater organisms play in biogeochemical cycles has led to renewed interest in this vast and biologically productive region in the global ocean. For example, autonomous vehicles designed for tracking and studying midwater organisms could examine the role of gelatinous zooplankton in carbon flux. Further development of lower-cost, user-friendly midwater sampling systems for finer-scale sampling would facilitate a new generation of water column studies.

It was broadly recognized that benthic vehicles, regardless of depth, have not progressed at the same rate as water column vehicles. While there are groups conducting exemplary work with benthic landers, samplers, and crawlers, these tools are often highly specialized or cost-prohibitive thereby complicating their widespread use. The consensus from geologists and geochemists to animal and microbial ecologists is that there needs to be an emphasis on the development of AUVs to enable autonomous georeferenced seafloor mapping and high-resolution photography, autonomous *in-situ* molecular biological analyses, as well as autonomous georeferenced animal tracking and sampling.

Moreover, the deployment of deep-sea observatories, cabled or otherwise, in both the Arctic and Antarctic would offer the capacity to conduct sustained studies of deep-sea processes without the need for frequent field campaigns in some of the most hostile weather regions on the planet. Such observatories benefit multiple nations engaged in polar research. A U.S.-led effort in polar seafloor observatories would ensure U.S. leadership in polar research, promote international science efforts, and could lead to distributed costs of operations and maintenance among international partners.

The hadal environments, trenches, and other areas of the seafloor below 6 km (~20,000 feet) are among the least-explored regions of our ocean. Only three people have been to the deepest spot on Earth by way of submersible (in contrast, a dozen men having walked on the moon). An equally small number of ROVs and samplers have reached these depths. Nevertheless, scientists are interested in the hadal regions because they may hold clues to the geological, geochemical, and biological evolution of our oceans. Despite growing interest in hadal research (i.e. the ~2% of the global seafloor that extends from ~7km to the full ocean depth of ~11 km), there are no U.S. research assets capable of working at these depths. In the US, WHOI's hybrid ROV *Nereus* was designed for such missions, but was unexpectedly lost in 2014. Further U.S. investment in hadal technologies would allow scientists frequent and dependable access to the hadal regions. A full-ocean depth ROV would enable the widest variety of operational regimes. It was also acknowledged that Japan, China, as well as philanthropic organizations may be engaged in building an 11 km vehicle, which in turn may afford the NSF an opportunity to lease this vehicle (with or without its host vessel). It was further recognized that developing other sensor and sampling systems, such as full-ocean depth water and sediment samplers, landers, or other standalone systems would address many of the scientific communities needs and potentially afford more frequent access to hadal regions for multidisciplinary research.

Sensor and sampler development: The lack of sensor technologies remains a major issue in deep-sea research, a shortcoming that was noted in the previous 1999 DESCEND report. One of the most resounding recommendations was to increase federal support for technology development and use of sensors, including but not limited to chemical sensors, sonars, and communication (data and navigation) systems. For a variety of reasons, the last decade has seen a decrease in the financial support available for developing technologies relevant to the deep sea. The Department of Defense (DoD) continues to lower its support for basic research in the deep sea. Concurrently, the NSF has not adequately supported programs, such as the Oceanographic Technology and Interdisciplinary Coordination (OTIC) program. While the National Oceanic and Atmospheric Administration (NOAA) has begun to support deep-sea technology development, their financial capacity in this regard remains limited. This is especially problematic because of the scarcity of robust, high-performance, and cost-effective sensors available to the broader deep-sea research community. Temperature, pressure, conductivity, absorbance, and fluorescence are the most common sensors. Eh and pH sensors are somewhat available, but suffer from limitations in durability or dynamic range. Individual investigators have developed *in-situ* laser raman and membrane inlet mass spectrometers and isotope analyzers, but they are largely impractical for widespread use because of the specialized nature of the instrumentation and preparation required for their operation. *In-situ* genomic molecular biological analyzers have also been fabricated and commercialized, but they too require a substantial commitment in both cost and time. Similarly, advanced mapping systems such as synthetic aperture sonars remain too costly for most investigators to procure. We therefore recommend that agencies and philanthropic foundations substantially increase their support of sensor and tool development, ideally with an emphasis on open-design and open-source codes to foster more rapid dissemination among the members of the community. Moreover, agencies and entities can work to provide a more advanced set of sensors on board research vessels and other platforms, ensuring that all those who would benefit from the data have access to it with little or no impediment.

*Data management and automated analyses:* Existing databases and management systems are lacking both in capacity, standardization, and accessibility. Today, users interested in comparing different data types (e.g., microbiological communities and geological samples) must navigate several databases with different interfaces, extract the required data, and manually align the data based on time or location. At a minimum, a graphical user interface that allows users to easily access, view, and collate data from different databases would be a major advance in data accessibility.

Long-term data storage and archiving is a massive concern. Some participants emphasized the value of storing data in the free public “cloud” (e.g., YouTube), while others suggested that this commitment would place our data at risk if there are future changes in policy or corporate ownership. Support for additional workshops and pilot projects were encouraged to address this issue.

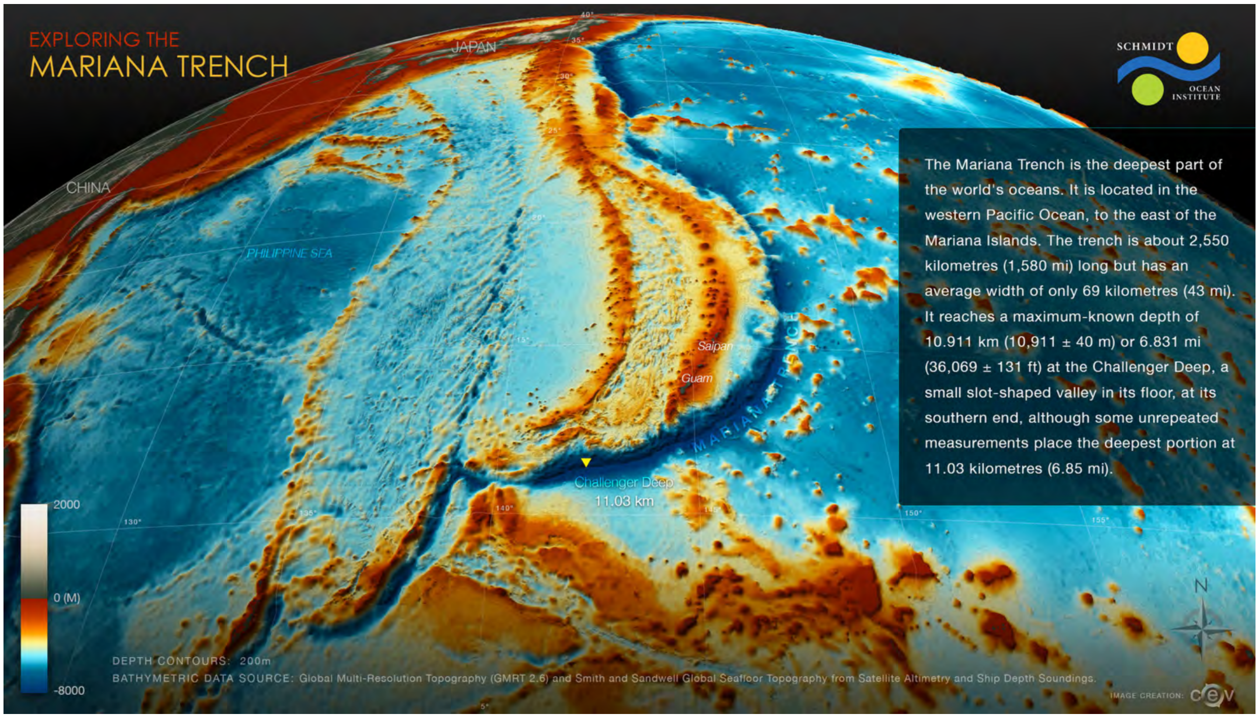
Capitalizing on advances in communications/coordination algorithms could enable synchronized, distributed data collection in the deep sea. To date, few systems exist that obtain and autonomously analyze detailed spatial and temporal data. Moreover, there are few cases of distributed sensor systems that enable effective high-resolution spatial and temporal analyses. Ultra-low power acoustic modems, as well as high-performance optical modems, provide key requirements for developing such distributed systems. Advances in machine learning and computer vision can facilitate autonomous underwater exploration and mapping, whereas automated analyses and high-performance computing may reduce the labor required to process and validate scientific data across a wide range of spatial and resolution scales (e.g. from multibeam sonar maps to image analyses of deep-sea animals for taxonomic identification). Finally, additional emphasis should be given to developing models for physical, chemical, and biological processes.

Advanced communications technologies can also put more humans “in the loop” from shore. The use of real-time broadband ship-to-shore communications in support of science and outreach—so-called telepresence—should be increased to promote greater engagement in seagoing expeditions. Telepresence affords scientists and engineers the opportunity to engage with the expertise of others not on the expedition, and importantly it provides a crucial opportunity to expose students and the lay public to the excitement of Earth-ocean exploration. Telepresence allows larger volumes of data to be moved to shore, where investigators can access more sophisticated tools for their analyses. Enabling telepresence will require investments in both hardware as well as financial support for satellite time. It is also reasonable to develop models where near real-time communications would reduce the number of support staff on a vessel. Finally, the ability to engage students and the public should not be underestimated. To maximize utility to the broader scientific community, telepresence-centric expeditions and shore-based facilities should be built (similar in scope to the Inner Space Center at the University of Rhode Island, MBARI’s microwave link to shore, and other locales around the U.S. and abroad).

Promoting the Exploration and Study of Underexplored Habitats: There remain vast areas of the ocean that are very poorly studied, including large areas of the U.S. exclusive economic zone (EEZ). For example, recent expeditions off the Oregon and California coasts found expansive areas of hydrocarbon seepage, massive deep-sea seep ecosystems in or around the waters of the southern California borderland, and underwater canyons off the eastern United States. Given the growing interest in exploiting deep-sea biological and geological resources as well as the dearth of information on much of the U.S. EEZ, it is recommended that increased emphasis be placed on making deep-sea submergence assets more readily available in nearer shore environments. Smaller, lighter ROVs, HOVs, and AUVs that can be deployed from regional-class research vessels are suitable for studies in many of these environments, and are far more cost-effective than deploying current assets of global-class vessels.

Lower fuel and staffing costs and the proximity to shore offer financial and logistical benefits that are not available when working in more remote environments.

Much of the workshop's discussion compared the advances in the epipelagic zone to deeper marine realms. Research in the upper 200 meters (m) of the water column (= epipelagic zone) has been a mainstay of oceanography for decades. Approximately half the oxygen in our atmosphere comes from epipelagic algae and microbes, as does 20% of humankind's nutrition (specifically protein). Scientists and engineers working in this realm have developed numerous shipboard as well as *in-situ* tools and sensors to enable widespread monitoring and experimentation at a variety of temporal/spatial scales. There is no question that robotics and automation have expanded our understanding of epipelagic processes through the deployment of thousands of ARGO (Array of Real-Time Geostatic Oceanography) floats to ultra-low-powered AUVs and gliders, robotics and automation have expanded our understanding of epipelagic processes. In contrast, there are no comparable assets or technologies for studies below 200 m. The deep sea represents approximately 80% of Earth's habitable volume and is a critical component of the planet's carbon cycle, and hosting marine organisms that are responsible for fertilizing the upper ocean while sequestering carbon in deep-sea sediments. These waters play a disproportionate role in moderating Earth's temperature and atmosphere. Advancing our understanding of the midwater (200 m to 1,000 m) realm requires a sustained, automated presence comparable in scope to that in the epipelagic. Substantial investments are



The Mariana Trench is the deepest part of the world's oceans. It is located in the western Pacific Ocean, to the east of the Mariana Islands. The trench is about 2,550 kilometres (1,580 mi) long but has an average width of only 69 kilometres (43 mi). It reaches a maximum-known depth of 10.911 km (10,911 ± 40 m) or 6.831 mi (36,069 ± 131 ft) at the Challenger Deep, a small slot-shaped valley in its floor, at its southern end, although some unrepeated measurements place the deepest portion at 11.03 kilometres (6.85 mi).

DEPTH CONTOURS: 200m
BATHYMETRIC DATA SOURCE: Global Multi-Resolution Topography (GMRT 2.6) and Smith and Sandwell Global Seafloor Topography from Satellite Altimetry and Ship Depth Soundings.

Fig. 3: Only three people have ever visited the bottom of the Challenger Deep in the Mariana Trench, and only a handful of robotic vehicles have the capability to dive that deep. Hadal research remains limited by a lack of appropriate deep-diving technologies. © CEV

recommended to support ROV, AUV, and other robotic technologies capable of sustained, unobtrusive observation and sampling. In addition to sophisticated, monolithic vehicle platforms, efforts should be focused on developing low-cost, highly reliable systems comparable to the ARGO floats.

The last two decades have witnessed unprecedented changes in the polar regions including: thawing tundra in the Arctic, encroachment of warmer water marine species on polar seafloor communities, and receding ice sheets at both poles are just a few of the major changes. Nevertheless, deep submergence assets have spent little time in these regions because of a number of logistical, technological, and cultural factors. Notably, the recently commissioned *RV Sikuliaq* is an ice-capable research vessel that can deploy both ROVs and AUVs, and should afford U.S. scientists access to higher-latitude waters. That said, the lack of U.S. Coast Guard icebreakers is a major problem for polar research because it reduces opportunities for scientists to work in and around ice sheets and marginalizes the US interests in Polar research (when compared to Germany, Sweden, Russia, Korea and China).

Equally important is the development of robots that can work under ice. New hybrid ROVs, e.g. the WHOI *Nereid Under Ice* vehicle, the Georgia Tech *Icefin*, among others, afford scientists an opportunity to work under ice safely and effectively, collecting sensor-based data as well as physical samples. Continued investment in under ice vehicles is recognized as important, if not critical, to advancing polar research. It should be noted that the polar research community is not well acquainted with the deep submergence vehicles in the National Deep Submergence Facility (NDSF), and should be surveyed prior to any further developments so that any new assets meet their primary research needs. Ongoing efforts led by the Deep Submergence Science Committee (DeSSC), which includes continued education and engagement between the deep sea and the polar research community, will hopefully stimulate greater interest in the development and use of underwater robotic vehicles.

It was also recommended that the U.S. invest in technologies that enable scientists to work in the hadal regions. Hadal regions are very challenging as unique materials and technologies are needed to work at those depths. Thus, while ROVs and AUVs are optimal, developing simpler systems such as water-sampling rosettes or camera-guided corers, grabs, and traps would also be advantageous. It is also recommended that U.S. federal agencies formalize collaborative efforts with philanthropic organizations that may be interested in developing their own hadal technologies. If that is the case, there may be opportunities for U.S. federal agencies to support hadal research by way of supporting the personnel and material costs, thereby leaving the vehicle development to the foundations.

Alleviating financial, logistical, and cultural impediments: There was broad support for developing programs that foster a greater degree of interactions among different oceanographic communities. Historically, programs like RIDGE, RIDGE-2000, MARGINS, and GeoPRISM within the NSF-promoted coordinated field campaigns and interdisciplinary efforts. They were critical for the maturation of hydrothermal vent research, thereby enabling investigators to propose interdisciplinary and higher-risk projects that would have faced disproportionate scrutiny in the core programs. These programs also had the effect of building a well-networked community of scientists and served to develop the technologies and research questions that spawned new initiatives (e.g., OOI, C-DEBI, among others).

Today, there is a strong desire on the part of the research community to see federal agencies, foundations and commercial entities work together to promote exploration and hypothesis-driven research in the global ocean, and also foster the application of these data to societally-relevant science and engineering problems. NOAA provides the scientific community with opportunities to engage in deep-sea exploration, typically focusing on areas that have not been well studied. The NSF supports hypothesis-driven research, but conversely does not typically support pure exploratory activities. At this meeting, it was widely recognized that more coordination between NOAA and the NSF is essential to increasing opportunities for advancing deep-sea research. It was strongly recommended that the agencies develop, for example, cooperative agreements that allow investigators to participate in exploration-driven field campaigns that afford a degree of data collection and sampling that would be directly relevant to a hypothesis-driven proposal to the NSF. It was also recommended that the agencies provide support for workshops that provide guidance on the development of such initiatives/programs. This recommendation also applies to fostering further interactions with the United States Geological Survey (USGS), which has an interest in deep-sea mineralogical resources; the Bureau of Ocean Energy Management (BOEM), which oversees the development of deep-sea energy and mineral resources; and the Office of Naval Research (ONR), which oversees the science and technology programs of both the United States Navy and Marine Corps.

There was also widespread agreement that the federal agencies should more proactively engage with the philanthropic entities, e.g. the Schmidt Ocean Institute (SOI) and the Ocean Exploration Trust (OET). These entities and others operate ships and deep-sea vehicles for exploration and hypothesis-driven science. Members of the U.S. and international scientific community participate in these expeditions but are typically required to provide their own support for salaries, supplies, shipping, and transportation. Such resources could be provided by federal agencies (so long as memorandums of understanding are made to ensure that all parties are aware of their respective responsibilities). This option is made more germane by the recent retirement of global-class vessels and the forthcoming refits of the remaining AGOR-24 vessels. Finally, there was interest in seeing federal agencies engage with both domestic and foreign research organizations and commercial operators as well (e.g., GEOMAR/MARUM Germany, CAGE-UiT and Bergen Groups – Norway, NERC- UK, IFREMER – France, CSIRO-Australia, GNS – New Zealand, the Remotely Operated Platform for Ocean Sciences [ROPOS] group in Canada, Kongsberg, and Fugro Offshore) to provide opportunities for working in areas that are otherwise inaccessible because of logistical or operational constraints.

Finally, it was noted that there was a paucity of opportunities for engaging small business in deep sea science, and it was further suggested that Federal Agencies could use existing models, such as the Small Business Innovation Research (SBIR) program to promote the engagement of small businesses with researchers, e.g. to facilitate job opportunities for young scientists and promote technological developments.

Increasing the training and diversity of the next-generation of deep-ocean scientists: There was resounding support for the continued development of programs that increase diversity and to enhance the training of future deep-sea scientists and engineers. In 2010, DeSSC and NSF launched a New User Program that has been highly effective in entraining younger scientists in DeSSC activities that were previously dominated by senior colleagues (e.g. the DeSSC Town Hall meeting at the Fall American Geophysical Union Meeting). This program became a template for at least 4 additional programs in ocean sciences, all of which have encouraged new users to be engaged with their respective programs.

Nevertheless, promoting diversity within ocean sciences continues to be a long-standing issue. We recommend that the federal agencies consider developing further funding opportunities to provide training and experience for those from under-represented groups in ocean sciences, including women and people of color. Notably, a postdoctoral program for women in marine engineering could serve to encourage a greater number of women to pursue careers in marine engineering and research. Also, a pre-graduate fellowship program for minorities and other under-represented groups could also provide a means for students to pursue degrees in fields they might otherwise dismiss. Current efforts such as early career training programs have been well-received by the early career scientists; and as such, our community will continue to advocate for those programs. Nevertheless, these programs fall short of providing Under Represented Minority (URM) students and women with a sustained opportunity to remain in ocean science. Finally, to ensure that such programs are well-supported and coordinated, we recommend that the federal agencies provide additional support to UNOLS to hire a coordinator who would oversee and promote early career activities for the broader community.

Increased societal engagement: The deep-sea provides many valuable services for humankind, yet few of these are known to the broader public (as well as other scientists for that matter). Few in the public understand the role of the deep-sea in supporting commercial fisheries, or the connectivity of the ocean to terrestrial processes (e.g., the hydrologic cycle); fewer yet recognize that the deep-ocean harbors resources of commercial value. As such, there was strong agreement that our community should continue to engage with students and the broader public, sharing the excitement of research while also emphasizing the societal relevance of deep-ocean processes. It was specifically recommended that the federal agencies and philanthropic agencies continue to support such efforts by formally recognizing their value and awarding additional support to those actively engaged with the broader public. We also recognize that we must develop new modalities for how to best portray and educate the global citizen of the critical importance of studying and better understand Earth-ocean phenomena, as they are key determining factors of how and whether humans can sustain their presence on planet Earth.

BENTHIC ECOSYSTEMS

By

Ken Rubin and Cindy Van Dover

Overview

The deep seafloor remains underexplored. This ecosystem includes diverse settings: isolated volcanic seamounts, sedimented abyssal plains, volcanic ridges, plateaus, tectonic windows into the deep-ocean crust/upper mantle, continental margins, slopes and canyon environments, and trenches at hadal depths, among others. Within these settings are processes that link ocean crust to underlying mantle at active volcanoes, and benthic habitats to the deep biosphere and overlying water column. Natural change at the seafloor occurs on temporal scales of eons (e.g., seafloor spreading, subduction) to moments (e.g., earthquakes, volcanic eruptions, changes in hydrothermal discharge, and mass wasting events) (Baker *et al.,* 2012; Rubin *et al.,* 2012). Anthropogenic change, including ocean acidification (Woosley *et al.,* 2016) and resource extraction (Mengerink *et al.,* 2014; Van Dover, 2014) add new imperatives to understanding systems as they currently exist and to inform predictions of what the future ocean will be like (Glover and Smith, 2003). We know now that even in just one of these systems—active submarine volcanoes—there are conditions and characteristics that change rapidly from volcanic edifice construction resulting from explosive and effusive eruption styles, and by hydrothermal discharge and precipitation, to development and succession of associated communities in response to perturbation (Delaney *et al.,* 1997; Fornari *et al.,* 2012; Box 1); yet each site studied so far differs greatly from the others. We know that the seafloor and its ecosystems are heterogeneous; but, we have not captured even a fraction of the variety or consequence of this heterogeneity (Danovaro *et al.,* 2014; Ramirez-Llodra *et al.,* 2010). And, we know that linkages between seafloor processes and the overlying water column are critical to physical (Piecuch *et al.,* 2015), chemical (Hansell and Carlson, 2013; Hawkes *et al.,* 2015), and biological systems (Tecchio *et al.,* 2013; Thorrold *et al.,* 2014) in the ocean.

Box 1. Examples of acute and chronic disturbances (natural and anthropogenic) that motivate interest in understanding and predicting responses of deep-ocean systems to change.

	Natural Disturbance	**Anthropogenic Disturbance**
Acute	Earthquakes, tsunamis, mass wasting, volcanic eruptions	Pollution, mineral extraction, oil spills, artificial islands/reefs
Chronic	Seafloor vents	Climate change (increased temperatures, increased acidity), fishing

Change (and baselines against which change can be measured across the full range and geographic spread of benthic environments), heterogeneity, and linkages motivate the frontier of hypothesis-driven, quantitative research that will inform society of the role the deep ocean plays in delivering ecosystem services (Armstrong, 2012; Thurber *et al.,* 2014); and bolster the emergent field of deep-sea environmental management and conservation (Van Dover, 2012; Wedding *et al.,* 2013).

In this report, we highlight a set of priorities for deep-ocean research and technology, and make recommendations on how to advance these priorities.

Priorities for Deep-Ocean Research and Technology

Natural and Anthropogenic Change, and the Importance of Baseline Studies and Monitoring: Given the reality of rapid contemporary and future global ocean environmental change (Levitus *et al.,* 2012), a mechanistic understanding of how such alterations are absorbed by and reflected in benthic systems is imperative (Smith Jr. *et al.,* 2013). Before any process-based conclusions can be drawn, however, a thorough understanding of the baseline state—the "before snapshot"—must be acquired. Such "snapshots" include time-series studies to understand the magnitude and time-constants of variations by way of temporal forcing mechanisms like tidal forcing, seasonality in particle inputs, or far-field tectonic and volcanic event responses. With reliable baseline data, research efforts can focus on the process and impact of physical, chemical, and biological changes to yield a predictive understanding of causal relationships. Specific agents of acute and chronic change include natural and anthropogenic phenomena. When applicable, baseline and change-oriented studies should be pre-emptive, in advance of expected interventions, such as mining, high-risk drilling, and island building.

Ecosystem Services: The formal definition of ecosystem services is evolving; but in essence, ecosystem services emphasize contributions of ecosystems to human well-being (Braat and de Groot, 2012). They include provisioning services (products sourced directly from the ecosystem for human use), regulating services (benefits that arise through the regulation of ecosystem function), cultural services (nonmaterial benefits that enhance societal well-being), and supporting services (functions that sustain other ecosystem services) (Millennium Ecosystem Assessment; Armstrong *et al.,* 2012; Thurber *et al.,* 2013; Box 2). There is a need to quantify these services in the deep ocean, especially where they may be of particular value to society (e.g., mineral resources) or threatened by anthropogenic activities (e.g., mineral extraction).

Box 2: Examples of ecosystem services provided by the deep sea.

Ecosystem Services	Relevant Examples in Benthic Environments
Provisioning	Fisheries, oil and gas, minerals, waste disposal, and (bio)chemical compounds
Regulating	Climate regulation, carbon capture and storage, and detoxification
Cultural	Education, research, entertainment, tourism, literature, and art
Supporting	Biodiversity, resilience, and biogeochemical cycling

Systems-Based Investigations: Because of the complexity, time, and expense involved in deep-ocean research, typical systems-based investigations target condition-specific (e.g., vent, seep, high-temperature, diffuse flow, hadal, soft sediment, and hard substratum) or site-specific questions. Discoveries across a range of natural systems continue to demonstrate the value of exploring interconnectedness (Fornari *et al.,* 2012; Follett *et al.,* 2014; Hansell and Carlson, 2013; Thorrold *et al.,* 2014). This governing system's principle warrants more explicit inclusion in deep-ocean research. For example, how do tectonic systems and heat flow processes facilitate and mediate chemosynthetic ecologies? How do fluids circulate through the shallow subsurface, and which chemical and biological constituents are gained and lost along the way? What roles do deep-ocean ecosystems play in delivering global ocean ecosystem services? Viewing the deep ocean as an integrated system connected by geology, chemistry, biology, economics, history, and cultural heritage may yield important insights and bridge cultural divides in the years to come.

Integrating Spatial and Temporal Scales in Systems Studies: The degree to which localized data—mineralogy, heat flow, chemical fluxes, biological load, and community structure—extends to broader scales remains an important and largely unresolved question. Developing analytical proxies that faithfully capture relevant parameters and enable scalable investigations would enable benthic science to progress from a discipline focused on selected sites (which are generally unrepresentative of broader function) to a more integrated view of seafloor systems. The seafloor also represents a unique interface from a geological and geobiological perspective, a site where biotic and abiotic products alike enter the rock record. Understanding the processing and selective incorporation of particular biomarkers, chemical proxies, or isotopic signatures is an important line of inquiry for the interpretation of ancient deposits and the reconstruction of past environmental conditions (Thiel *et al.,* 1999; Knoll *et al.,* 2007).

Event Detection and Response: Perturbation and responses in natural systems are cornerstones of understanding environments and ecosystems. The remoteness of marine benthic environments makes detection of perturbations difficult and responses even more so. Despite this challenge, the past decades have seen major advances in benthic event detection and scientific community response, primarily as focused efforts from the National Science Foundation (NSF)–RIDGE and successor Ridge 2000 programs, and through partners at National Oceanic and Atmospheric Administration (NOAA) and elsewhere. Earthquake detection has been a major part of the advance (Dziak *et al.,* 2011), as has the advent of focused study sites and seafloor observatories (Fornari *et al.,* 2012, Chadwick *et al.,* 2012; Kelley *et al.,* 2014). Although the focus of such studies has been on submarine eruptions (reviewed in Rubin *et al.,* 2012), especially at mid-ocean ridges (Delaney *et al.,* 1997), megaplume discharges (reviewed in Baker *et al.,* 2012), hydrothermal system impacts (Von Damm *et al.,* 2004) and ecosystem responses (Shank *et al.,* 1998); other events and responses, such as tectonic ones have also been studied (Sohn *et al.,* 1998). Collectively, they inform about the types and magnitudes of changes that occur over a range of spatial and temporal scales, and their impacts on community development, diversity, and structure. These types of studies require rapid resource mobilization, juggling of preassigned asset and personnel calendars, and significant expense; yet, the results have been both scientifically rewarding and very engaging for the public (Embley *et al.,* 2006; Resing *et al.,* 2011). Such studies will remain an important part of continued discovery of activity and responses at benthic environments and habitats, and will hopefully expand to a wider variety of geological settings in the coming years as event detection methods, and advanced robotics and autonomous capabilities for responses continue to improve.

Exploration: *An Enhanced Commitment to Exploratory Studies in the Deep Sea*. Exploration of the deep ocean has led to paradigm-shifting, foundational discoveries; but, proponents and reviewers are now often challenged to frame exploration in terms of hypothesis-driven research. There is scope for the scientific community and the NSF to work together to make the scientific case for exploration priorities.

A Comprehensive Database. Despite decades of deep-sea research, there is no centralized repository of our collective efforts, thereby making it difficult for scientists to acquire full contextual knowledge or develop optimal plans of study. A database compiling the dates, locations, and participants of benthic studies would not only provide a retrospective view to enable improved collaboration and avoid duplication of effort; but, it would also offer a forward-looking vantage, exposing high-priority regions or features that remain underexplored.

Examples of Specific Geographies of Interest

Global Mapping. The entire seafloor has recently been mapped to an x-y resolution of 5 kilometers (km) using gravity models and satellite-based altimetry (Sandwell *et al.,* 2014); yet, this resolution identifies merely the largest scale features. Even major bathymetric features remain unseen—features that may be indicative of novel tectonic processes or biologically mediated landscape perturbations (e.g., authigenic carbonate mound formations [Brothers *et al.,* 2013]). The types of features that exist at spatial scales relevant to geological and ecological studies on land (e.g., individual lava flows, faults, fissures, and seabed textures/rugosities at submarine volcanoes) are known from only a small number of sites (Sinton *et al.,* 2002; Fundis *et al.,* 2010; Colman *et al.,* 2012; Clague *et al.,* 2011, 2014). Generating higher-resolution (1-meter [m] vertical) maps of the seafloor is an important priority, but one that is currently limited by the number of mapping systems (e.g., autonomous underwater vehicles [AUVs]) and the speed with which they can map; enhancements to capabilities to map more broadly at this scale were recently encouraged through the Shell Ocean Discovery Xprize. Exploratory, descriptive, and experimental ocean sciences benefit from an enhanced understanding of the regional and local seabed geomorphology.

Slope, Bathyal, and Abyssal Plains. Much recent research has targeted dynamic, visually compelling sites on the seafloor and study of a diversity ("full range") of geologic or biologic settings and processes. However, such locations are not representative of the "average" or "typical" deep-ocean benthic environment, resulting in knowledge gaps regarding spatially dominant processes. A modern, integrated program of quantitative assessments of ecosystem functions and services (Thurber *et al.,* 2014) of slope, bathyal, and abyssal plain ecosystems would provide scalable data on a wide range of parameters (e.g., respiration rates, burial rates, redox profiles) of an "average" sediment-hosted community, etc.) for global estimates and enhanced predictive models (Jones *et al.,* 2014).

Seamounts. There are thousands of seamounts in the world's oceans (Kim and Wessel, 2011). Some small (unknown) fraction are active or recently active volcanoes like Loihi and Vailulu'u Seamounts (Staudigel and Clague, 2010) with potentially unstable flanks (Smith and Wessel, 2000). Seamounts and knolls represent ~20% of the global seafloor habitat (Yesson *et al.,* 2011); they can be hotspots of pelagic (Morato *et al.,* 2010) and benthic biodiversity (Rowden et al., 2010), or may host more modest biological assemblages (Morato *et al.,* 2015). As in other deep-sea ecosystems, and as Rowden *et al.* (2010) note, there exist a number of plausible paradigms about their ecology, including biodiversity, source-sink dynamics, refugia role, and vulnerability, that remain to be tested with quantitative studies. Seamount ecosystems are subject to bottom-trawling pressures (Pusceddu *et al.,* 2014); and, in some regions of the world's oceans are of interest for their cobalt crusts (Schlacher *et al.,* 2014).

Hadal Systems. The deepest reaches of the ocean—the hadal zones—are easily the most challenging regions on Earth to access. Hadal systems and linkages to abyssal and bathyal systems are now being studied using new submersible assets

(Jamieson, 2015); but, much remains to be understood about these ecosystems, including habitat diversity; biodiversity; as well as geology and geophysics, hydrography, and geochemistry.

Technical Enhancements

Telepresence. Deep-ocean exploration has engaged the public through telepresence (Scowcroft *et al.,* 2015), an approach that also has tremendous untapped potential for training and research (Delaney *et al.,* 2013; German *et al.,* 2014). This platform remains an emergent approach with tremendous scope for technical enhancements and improved models of engagement with the research community, including hypothesis-driven as well as exploratory and descriptive science.

Full-Ocean Depth Remotely Operated Vehicle/Autonomous Underwater Vehicle. With the loss of the *Nereus* hybrid remotely operated vehicle (HROV), millions of square kilometers of the deep ocean are currently inaccessible by U.S. National Deep Submergence Facility (NDSF) assets, and there are no generally available alternates. Best practices for exploration and research suggest that mapping/survey capabilities of an AUV are essential for both reconnaissance and process-oriented studies, while remotely operated vehicles (ROVs) are critical for observation, experimentation, and sampling on the seafloor. There is thus an imperative to replace the *Nereus* capabilities if we are to build our understanding of the deepest regions of the oceans and the role they play in providing ecosystem services.

Increased Automation. Human involvement is the most time-consuming and costly limitation of deep-sea research. While improvements in automation have been made—most notably in glider endurance, robustness, and reliability—there is substantial room for improvement. The development of “smart” platforms that could conduct initial analysis, survey the seafloor in an adaptive fashion, and strategically collect samples—all without the onsite guidance of a human operator—would vastly expand the rate of analysis and lower the barrier to entry for many researchers.

Improved In-Situ Analysis and Collection. The depth of benthic environments has always been problematic for researchers who seek to understand *in-situ* processes. During extended transit from sampling sites—which is accompanied by varying degrees of depressurization—biological activity can be irrevocably altered, gases can exsolve, mineral phases can change, and the intervening water column can cause contamination headaches. Enhanced collection and analytical/sensor capabilities and calibrations, as well as battery improvements, would provide a more widely deployed, higher precision and faithful representation of seafloor/subseafloor processes.

Communication and Navigation. There is a need to spur development and implementation of latest-generation technologies for communication, navigation, remote control, and remote data transfer to and from long- and short-term deployed infrastructure, such as using latest generation optical/acoustic transmission methods.

Standardization. Cross-platform standardization of pressure housings, power sources, software, data management, and reporting, etc., is a continuing challenge in deep-ocean systems, even within the same institution. There should be continual effort to upgrade all systems to the best available standard—especially for operational platforms that belong to national facilities.

Resources, Repositories, and Facilities

Diversity and nurturing of the next generation of deep-ocean scientists. Like the geosciences in general, the deep-ocean scientific community is not ethnically diverse. As a community, there is a need to participate in diversity initiatives led by the NSF Geosciences and other programs to build a bold, innovative, and relevant future for a diverse community of deep-ocean scientists. Activities that contribute to the engagement and training of the next generation of deep-ocean scientists are critical to this effort.

Education and Public Outreach Professionalization. Public understanding/ perception of the deep sea was identified as a problematic weakness with a negative feedback effect on the ability to conduct science and promote sustainable stewardship of the oceans. While funding agencies have proactively built education and public outreach (EPO) components into proposal requirements, the resulting efforts are almost invariably small-scale, one-off, laboratory-based initiatives that promote engagement with a broader community but fail to achieve a scalable impact. To many participants, deep-sea EPO efforts compare unfavorably to those of the National Aeronautics and Space Administration (NASA) despite overlapping themes, such as high-tech exploration, scientific mystery, and large temporal and spatial scales. A potential remedy could include a centralized facility (similar in concept to NASA's EPO office) that is pool-funded by individual researchers in fulfillment of agency-mandated EPO activities. This option would remove the burden on overcommitted, undertrained scientists and enable professional educators and communicators to more effectively disseminate scientific findings.

Centralization of Common Resources. Resources (meaning web-based facilitation, teleconferencing coordination, financial support, or any means by which these efforts can be enhanced) are needed to connect scientists to engineers in order to further infrastructure and vehicle developments. Moreover, resources are also needed to help scientists connect to other scientists *vis a vis* equipment sharing, improved data access and reuse, physical sample curation and sharing, education and outreach efforts, international collaboration, and information about potential industry and philanthropic partners. This community should take advantage of the NSF EarthCube to employ the latest emerging cyber-infrastrucutre capabilities for cross-disciplinary data discovery, modeling and visualization.

Recommendations

Workshop 5-year priorities:

- Explore (through a workshop) the potential for a national initiative to identify and quantify ecosystem services (especially supporting and regulatory services) of the deep ocean. This workshop would establish the importance and rationale for this work, identify knowledge gaps, recommend approaches to advance our understanding of these services and their societal value, and consider the potential for disruption of these services by human activities, including climate change.

- Explore (through a workshop) how to continue rapid response capabilities for time-critical event response in benthic environments and how to build from focused efforts and protocols developed during the RIDGE program and refined during Ridge 2000 (http://www.ridge2000.org/science/tcs/). The relatively small community of active event-response scientists and their connectivity has dwindled significantly since the end of the Ridge 2000 program because of a lack of centralized support and retirement of some senior personnel. A new effort to reinvigorate this capability is important to gain the most from future response efforts.
- Explore (through a workshop) new priorities for and approaches to science-motivated and hypothesis-driven deep-ocean exploration.
- Facilitate discipline-specific discussions to identify relevant proxies for parameters of interest to better integrate across spatial scales, and promote opportunistic data collection among the international oceanographic community.
- Undertake a National Research Council (NRC) review of the need for baseline studies in the deep ocean and the role the NSF should play in this work.
- Elaborate a plan for an effective ocean EPO office in support of broader impacts in the ocean sciences and to engage the public.
- Charge the Biological and Chemical Oceanography Data Management Office (BCO-DMO), Interdisciplinary Earth Data Alliance (IEDA) and/or other groups with developing either a centralized, federated repository of benthic data or a search portal that effectively centralizes distributed resources. This effort should take advantage of related efforts by way of the NSF EarthCube to employ the latest emerging cyber-infrastructure capabilities for cross-disciplinary data discovery, modeling, and visualization.
- Charge the NDSF with developing and implementing a policy and strategy of standardization, and a centralized hub for managing increased access to community resources.
- Ensure deep-ocean science is strongly represented in the NSF Geosciences diversity initiatives.
- Continue to engage and train the next generation of deep-ocean scientists through early-career training and mentoring activities of Deep-Submergence Science Committee (DeSSC) and the deep-submergence community.
- Enhance education and public engagement about Earth's "Largely Uncharted Last Frontier."

Longer-term objectives during the next decade include the following:

- Implement a deep-ocean ecosystems services initiative in the NSF Geosciences.
- Implement a coordinated event detection and response initiative through the NSF Geosciences.
- Implement a deep-ocean exploration, baseline, and monitoring program in the NSF Geosciences, targeting specific geological/biological provinces of interest.
- Foster cross-disciplinary studies in the deep ocean through some form of NSF-initiated coordination that existed when under NSF programs, such as Ridge 2000.
- Develop capabilities for easy-to-deploy, inexpensive tools to study environments beneath the seabed.
- Add a full-ocean-depth-capable ROV and AUV to the NSDF.
- Drive additional development of deep-sea research tools, sensors, vehicles, platforms, communication systems, and navigation capabilities to support the next generation of benthic studies.
- Increase access to and number of autonomous and robotic platforms for deep-sea studies, as well as maintain current HOV capabilities.
- Establish an ocean EPO office that includes an engagement and training program for early career scientists.

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* (Photo by Hanu Singh, Yogesh Girdhar, Jeff Anderson, Woods Hole Oceanographic Institution) – See more at: http://www.whoi.edu/news-release/swarming-red-crabs#sthash.Ru8p77iQ.dpuf.

COASTAL ECOSYSTEMS

By

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Overview

The coastal ocean provides a range of ecosystem services and is essential to the economic, cultural, and recreational well-being of numerous maritime communities. Coastal environments can be defined broadly as any environment directly influenced by terrestrial systems. In this context, the coastal ocean could include an estuary impacted by anthropogenic nitrogen, a continental shelf influenced by subterranean groundwater flows, or an upwelling region driven by eastern boundary currents. Of course, coastal ecosystems also interact strongly with the open ocean. Thus, the continental margin spanning from lagoons and estuaries to the continental shelves, ocean slopes, and adjacent seas is a familiar definition that fits well herein.

These regions include benthic hotspots of biological diversity and biogeochemical cycling (e.g., coral reefs, estuarine/shelf sediments, etc.) (Codispoti *et al.,* 2007 Levin and Sibuet 2012). Globally, the shelf-to-slope break is only 8% of the surface area of the global ocean but may account for more than 20% of the total marine productivity (Huettel *et al.,* 2014) and may supply 50% of the carbon transferred by the biological pump to the deep ocean (Jahnke 2010). The coastal ocean is also responsible for removing significant amounts of reactive nitrogen through denitrification. In particular, continental shelf sediments account for roughly 70% to 85% of the total nitrogen removed globally by ocean sediments (Devol 2015). Although given the paucity of directly measured sediment denitrification rates, this estimate should be taken with caution.

Unfortunately, coastal ecosystems are under increased stress from anthropogenic activities. Presently, ~40% of the world's population lives within 100 kilometers (km) of the coast, and 16 of the world's 23 megacities are coastal (Blackburn and Pelling 2013; UN–DESA 2012). As human coastal populations rise and land use practices change, industrial, agricultural, and municipal wastes are discharged in coastal ecosystems leading to a series of negative consequences. On top of these more local and regional changes are large-scale forcings, such as the ongoing secular warming trend (Levitus *et al.,* 2000).

Regrettably, our ability to detect and understand both natural and anthropogenic changes in the coastal ocean is undermined by a lack of systematic baseline data. For example, despite the importance of coastal systems in carbon cycling, continental shelf CO_2 gas exchange fluxes carry a 50% uncertainty with them (Bauer *et al.,* 2013). A systematic effort focused on coastal environments is needed to address the large uncertainties in key biogeochemical rate processes and biodiversity assessments. A focus on coastal environments is timely as numerous coastal observatories are established and supplying easily accessible online data. For example, the National Science Foundation (NSF)-funded Ocean Observatories Initiative (OOI) recently commissioned two coastal observatories, and there are other active coastal platforms (e.g., Northeastern Regional Association of Coastal and Ocean Observing Systems [NERACOOS], Channel Coastal Observatory [CCO], etc.) with long-term and publicly available data. Such systems provide essential water column data (e.g., temperature, pH, salinity, etc.) that can help inform process rate studies.

Key Questions in the Coastal Ocean

The overarching question we identified as the driver for coastal ocean research during the next decade was: **What are the short- and long-term effects of natural and anthropogenic phenomena on coastal environments?**

From this primary question, we also identified the following three subquestions:

- How do physics, biology, and chemistry interact to alter the coastal environment?
- How do we best characterize the temporal and spatial baseline of the coastal environment?
- How do we predict change and mitigate impacts on ecosystem services and society?

The latter question is especially relevant as human coastal population rises and our footprint expands.

Recommendations

With ongoing developments in robotic vehicles and *in-situ* sensor technology comes exciting new opportunities for addressing key questions in coastal environments, but there is a need to increase awareness of available assets and their technical capabilities. Fostering communication through educational opportunities (e.g., webinars, training, etc.) and community workshops is critical to enabling scientific use of technical developments and to developing the use cases necessary to advance technology. The need for establishing workflows and protocols for efficiently managing data produced by individual researchers continues to grow and will be critical to enabling the community to take, develop, and share baseline environmental observations; and take advantage of ongoing developments in cyberinfrastructure.

We identified the following short-term and long-term goals:

Short-term recommendations

- *Promote the use of coastal environments as natural laboratories for technology testing and scientific capitalization.* This action can be achieved, for example, by coordinating efforts with OOI cruises to coastal arrays, and coordinating with groups “testing” technology in shallow systems to answer science questions.
- *Improve data awareness and data management processes.* This activity includes breaking down barriers between data acquired through federal, state, and locally funded research, thereby ensuring that the tools necessary for documenting and preserving long-tail and “dark” (offline) data, workflows, and software are available.

- *Increase student involvement and expand public outreach*. Student training opportunities are critical for not only inspiring the next generation of scientists, but for raising public awareness about the ocean and the importance of ocean science research. Effective public outreach takes considerable effort, and only a subset of our community has been very successful with it. We should evolve the way we approach broader impacts, and seek to develop partnerships between individual researchers and larger outreach-focused groups to improve our impact.
- *Breakdown funding stove pipes.* We note that coastal research is inherently interdisciplinary, which can make it difficult to identify appropriate funding mechanisms for research proposals. There is a need to work with funding agencies to identify mechanisms and guidelines for funding interdisciplinary coastal research.

Long-term recommendations

- *Develop new technology/assets that uniquely serve the coastal environment.* This commitment should involve community input to understand the current status (e.g., Integrated Ocean Observing System [IOOS]), perceive needs, and develop use cases for expanding this capability to benthic environments. Potential new technology includes the following:
    - Rapidly mobilized, multiplatform operations that enable temporal/spatial understanding of coupled C and N cycling in the coastal environment.
    - Benthic rovers that can traverse the seafloor, and conduct *in-situ* sensing, and acquire physical samples. In fact, many of the technologies exist and need only to be brought from the deep-sea research community into shallow systems.
- *Develop new CyberInfrastructure for real-time data integration, visualization, and modeling that can be accessed on a variety of platforms (e.g., desktop, mobile, etc.) by scientists and the public.* This process depends, in part, on data routinely and consistently being documented and made available, and includes developing new mechanisms to share knowledge with the goal of improving data value. We should also aspire to improve international data sharing (e.g., access to international data).
- *Expand Education and Outreach Efforts.* Consider ways we can more effectively reach out to the broader public (e.g., Aquarium Programs, Telepresence, Web Technology). Seek to develop projects and collaborations that bring emerging technologies developed in the U.S. to the coastal waters of developing countries, thereby scientifically bridging local and global issues.

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PELAGIC ECOSYSTEMS

By

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Overview

Deep-sea habitats are the largest living volumes on Earth, but have been sparsely surveyed from surface ships and infrequently accessed for direct observation or sampling with submersible vehicles. The biological diversity and geochemical cycles within them remain mysterious. Yet, in the last two decades technological advancements in the capability and maneuverability of undersea vehicles, new sensor capabilities, improved digital imaging, and greater computer capacities have provided more and better direct evidence about the pelagic environment and how deep-sea organisms survive. A broader understanding of natural histories and anthropogenic disturbances in pelagic regimes requires persistent investigation of community compositions on many temporal and spatial scales.

Although this realm is accessible with an array of sensors, tools, and platforms, their utilization is limited, largely because of the high cost to build, maintain and deploy them. It is likely that future research in the pelagic will utilize telepresence and cognitive robotics, and more cost-effective and productive technologies than human-based excursions. However, in the near term—at least the next decade—exploring, surveying, and sampling will rely primarily on currently available assets (human occupied vehicle [HOV], remotely operated vehicle [ROV], and autonomous underwater vehicle [AUV]), augmented where possible with more focused approaches described subsequently.

Recognizing that the open-ocean and deep-sea pelagic are far too vast to explore and survey fully, we recommend that future investigations in deep water should focus on targeted scrutiny of interface regions in the water column—where biomass, diversity, and activity are higher—together with *in-situ* biological process studies at those locations. These approaches can provide data suitable for input to models addressing community function and resilience. Despite seeming homogeneous, the water column is a dynamic, multidimensional arena, circulating and stratified. Even if subtle, there are recognizable discontinuities and boundaries caused by upwelling and downwelling, clines of temperature, density and/or oxygen, plumes, fronts, gyres, internal waves, and isolumes; as well as concentrations of biomass resulting from growth dynamics or diel behavior. Attention to such regions should maximize the ability to define response patterns, acclimation, and adaptation among species and trophic levels. Furthermore, models are crucial to expand results from field observations and manipulative experiments to predict ecosystem changes on regional and global scales.

The questions and priorities from the 1999 DESCEND report are still relevant.

Primary Questions:

1. What are the temporal and spatial patterns of the physical and chemical structure of the pelagic environment, and how does this structure determine the diversity, distribution, and behavior of pelagic organisms? How may these

patterns be altered by global climate changes and/or anthropogenic forces? What key species could be studied to trace and quantify trophic relationships and community metabolism in the pelagial?

   A. Are mesopelagic and bathypelagic communities stable and cosmopolitan? To what extent are episodic, biogeochemical disturbances likely to alter trophic pathways?
   B. Can bottom-up and top-down regulation of biodiversity be modeled with specific target species, e.g., by way of extinctions of common species or invasions of exotic species? Are coupled individual-based and physical models more informative predictors of consequences? Can trait-based models link community structure and function to predict the influence of different environmental conditions? Can end-to-end models distinguish natural variability and anthropogenically induced changes?

2. What is the contribution of the pelagic biota to fluxes and transformations of C, N, and nutrients within the water column and net transport between the surface and the benthos?
   A. What mechanisms alter the biological pump and affect the vertical transport of organic matter by microbes packaged within aggregates and fecal pellets?
   B. Can investigation of large suspended marine snow aggregates resolve the imbalance between production and utilization of prokaryote biomass?
3. What insights do the pelagic biota provide into the evolution of organisms in a multidimensional environment? What genetic and behavioral characters enable survival in stable and perturbed deep-sea environments?
4. What enabling technologies are required for future research to address these questions?

Logistical Challenges:

1. The questions require integration of data covering an array of spatial and temporal scales with process and mechanism data from the level of specific regions and individual organisms.
2. Survey and surveillance from moored and towed instruments or samplers are limited in extent and biased in their capabilities.
3. *In-situ* collections of reliable observational and experimental data using currently available HOVs, ROVs, or AUVs are time-consuming and expensive.

Cultural Impediments:

1. There has been a reduction in interest, activity, and facilities for deep pelagic research during the last 20 years. The community of scientists currently active in this environment is small.
2. The importance of oceanic and deep-sea pelagic communities needs to be presented in the context of ecosystem function and ecosystem services on regional and global scales, with emphasis on biodiversity, dynamics, and evolution.
3. Better communication between scientists and engineers will promote solutions to technological challenges.

Technological Needs:

1. Collections of data on multiple scales that have relevant spatial, temporal, and taxonomic resolution.
2. Determination of process rates *in-situ*. Proxies for rates are not adequate nor are laboratory measurements.
3. Efficient (rapid) analysis and integration of disparate data types (i.e., genetic, physiological, numerical, imagery) to facilitate physical/chemical context and provide data that can be modeled to extend observations.

Recommendations for Science and Technology Priorities:

1. A federally sponsored initiative to match science problems with appropriate technologies in the pelagial would energize a renewed and productive emphasis on understanding the evolution of the water column in our planet. More technical capabilities are available than ever before for pelagic research, but financial resources are needed to adapt and apply them.
2. Given the limited extent of opportunities for direct, submersible-based observations in the pelagial, efforts should be made, when feasible, to augment such operations with existing at-sea programs (i.e., ship transits, acoustic surveys, glider profiles) or instrument installations (i.e., satellites and moored arrays).
3. *In-situ* and process-oriented submersible investigations should be focused in habitats that are likely to support contrasting levels of density, diversity, and/or activity. Technologies and methods developed for these situations should be used to guide the deployment of undersea vehicles. Red and blue light should be utilized to document natural behaviors.
4. Improved survey technologies—incorporating acoustic and imaging capability with environmental sensors—could be deployed from ships or AUVs for more extensive representations of pelagic communities.
5. As autonomous underwater vehicles become smaller, cheaper, and more capable of extended, unattended operation, they can increasingly provide close-up tracking of pelagic organisms to delineate behavioral repertoires and small-scale distribution patterns.

POLAR SYSTEMS

By

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Overview

Work in the Polar oceans represents a major frontier area of research within the ocean sciences. Notably, it was not well addressed at the first DESCEND meeting—presumably because there was little to no underwater technologies available to investigate the ocean or seafloor beneath oceanic ice cover (The notable exception was the Submarine Arctic Science Program [SCICEX] in collaboration with United States Navy [USN] that equipped submarines operating in the Arctic with geophysical remote sensing sonars as they patrolled beneath the ice.) Fifteen years later, technological (robotic) capabilities have improved considerably and societally relevant scientific issues pertinent to the polar oceans have come into increasing focus—both in the ocean science community and in society as a whole. Even so, Deep Submergence Scientific Committee (DeSSC)-related science in polar regions remains in its infancy, which was reflected quite clearly within the structure of the DESCEND2 Polar working group. The working group was composed primarily with deep submergence engineers at the cutting edge of providing enabling capabilities for under-ice ocean and seafloor investigations together with a smaller number of scientists with expertise, primarily in seafloor investigations: areas of scientific expertise that, for the polar oceans, are comparable to traditional DeSSC studies in the "blue-water" deep ocean.

Discussions within the group followed four primary tracks:

- Identification of how studies in the polar oceans map directly to the recent decadal review of the National Science Foundation (NSF) Ocean Sciences (*Sea Change: 2015-2025 Decadal Survey of Ocean Sciences* report) activities
- Identification of key scientific issues in the polar oceans (both those relevant to the priorities identified by *Sea Change* and better reflect other entities' priorities)
- Identification of technical responses required to achieve the identified science goals
- Identification of other pertinent challenges and opportunities
- Identification of 3-year to 5-year and ~10-year recommendations on how to address the science questions.

Within the scope of these discussions, we chose not to emphasize the "Deep" in Deep Submergence for our *Polar* deliberations; and, instead, focused more on the areas of expertise that were unique to the DeSSC research community (both in science and engineering), particularly in terms of the capabilities and expertise we possess in the use of *submerged* assets to conduct relevant scientific investigations in polar oceans at any ocean depth.

Polar ocean science priorities in the context of the Sea Change report.

Our break-out group identified that polar deep submergence science had important contributions to make in responding to four of the eight priority science questions identified in the National Academy of Science (NAS) Sea Change: 2015–2025 Decadal Survey of Ocean Sciences, as follows:

- How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change during the next century?

The warming effects of Earth's oceans are particularly apparent in polar regions with the retreat of ice cover—formed as a floating sea-ice retreat in the Arctic, in receding glaciers off Greenland, and in the calving of enormous volumes of ice-shelf into the ocean in Antarctica. It is increasingly urgent that we begin to better constrain what the natural and unperturbed system used to be like, as best we can in what is clearly already a nonpristine state, if we are to predict how the system will continue to change during the next-century time scale as shown in the following examples:

- Very little is known about the temperature and salinity characteristics associated with ice-water interactions in the oceans, at the underside of attached, or either continent-attached (e.g., Antarctica, Greenland) or floating (e.g., Arctic) sea-ice. However, what can be concluded, from first principles, is that at this lower-bound ice-water interface, the heat exchange leading to melting of the ice is most efficient, particularly when compared to the overlying ice-atmosphere interface. Traditional autonomous underwater vehicles (AUVs) and gliders that do operate beneath ice cannot collect data in the difficult terrain associated with this critical interface, and ice-tethered profilers (ITPs) cannot penetrate through the thick ice associated with glaciers (e.g., Greenland) and ice-shelves (e.g., Antarctica). Even in the case of floating sea-ice in the Arctic, ITPs can only be deployed in regions where the sea-ice is sufficiently thick; therefore strong, to sustain on-ice equipment deployment operations. Critically, this situation eliminates opportunities to collect data closest to the thinnest ice cover at the marginal ice-zone where new observations would be most instructive. The new Nereid Under Ice (NUI) vehicle (shown subsequently) provides opportunities to address all the previously described challenges.
- The first deployments of the NUI vehicle in the Arctic, approximately 200-kilometers (km) north of Greenland in July 2014, revealed a whole ecosystem of gelatinous organisms in a complex food chain, driven by through-ice photosynthesis that, because they lacked prior visual observations, had never been anticipated. Consequently, no hypotheses had previously been put forward as to how that part of the ocean ecosystem contributes to or will respond to climate change, because it was not known to exist. But now that it is known, and because the ecosystem is apparently specific to the physical environmental conditions found in a sunlit ice-covered ocean, it will presumably be destined to be perturbed as the ice melts and the sea-ice cover is removed. For example, one possibility is that this ecosystem has been overlooked

because the dominant fauna lacks exoskeletons (i.e., protection against predators); therefore ballast, which is why their presence was not recorded in sediment traps or sediment cores. But, with an absence of settling flux, we now know from four preliminary NUI dives, each of 4-hour duration (maximum), that it does not necessarily reflect an absence of primary productivity in the overlying Arctic as previously assumed.

- Some of the largest submarine gas hydrates sit at a relatively shallow ocean depth around the Arctic margin. These sediment-hosted systems are susceptible to physical destabilization if the overlying ocean temperature rises by only 1°C to 2°C. Because of the methane strength as a greenhouse gas, and because gases released from the seafloor at shallow margin depths will likely rise all the way to the ocean surface, we consider the fate of these shallow gas hydrates to be a particularly critical area of seafloor research where the DeSSC/DESCEND2 community has a potentially pivotal role to play.
- What is the role of biodiversity in the resilience of marine ecosystems, and how will it be affected by natural and anthropogenic changes?

Our working group lacked expertise from biologists to address this problem in great depth; but, key examples of issues of which we were aware (i.e., beyond the upper-ocean through-ice photosynthesis previously alluded) include the following:

- Arctic: We lack almost ANY data about the diversity, abundances, and distributions of benthic fauna, including microbiota, across the whole of the Arctic Ocean basin. The possible exception might be the in-fauna, including microbiota, recovered from sediment cores. It is hard to predict what the impact of natural and anthropogenic changes will be on a marine ecosystem that remains almost completely unstudied to this point; but, the fact that we expect ice cover to be removed completely from the Arctic in the future means it appears safe to assume there will also be an impact on the underlying seafloor. The same logic presumably also holds true for pelagic fauna within the deep ocean interior.
- Antarctic: One case study in which members of our break-out group was aware involved the case of invasive crab species in Antarctica. For the past 30 million years, circumpolar waters have been too cold for crabs and lobsters to survive, and an entire benthic ecosystem has evolved that has no protection against hard-shell crushing predators. Yet, in the past few years, it has been reported that large numbers of crabs were migrating onto the warming Antarctic shelf, thereby placing the entire pristine ecosystem at risk.

What are the processes that control the formation and evolution of ocean basins?

Mid-Ocean Ridge Systems:

- Ocean basins are formed at mid-ocean ridges that span ~55,000 kilometers (km) of continuous plate-boundary that encircles the globe. Approximately 25% of the cumulative length of that ridge system (14,800 km) generates ocean crust at ultraslow spreading rates (0 centimeter [cm] to 20 cm/year full spreading rate), thereby giving rise to both geological processes and hydrothermal systems that are more diverse than, and often fundamentally different from, those observed along all other ridge crests. Thus, understanding processes active at ultraslow ridges is essential to our understanding of the Earth system as a whole, and in particular, how Earth's ocean basins are formed and evolve.

- Unfortunately, despite their great cumulative length, Earth's ultraslow speading ridges are almost entirely remote and difficult to access with a ~50:50 split between the Arctic and the southwestern Indian Ocean. Thus, while one might consider the Arctic mid-ocean ridges to be a particularly inaccessible region that is difficult to study, it can equally be argued that the Southwest Indian Ridge (SWIR) is comparably problematic for the quite different reason that it is situated at rather high latitudes (30°S to 50°S) in the southern hemisphere where the "infinite fetch" of circumpolar currents can lead to very arduous sea states and nonpromising working conditions. By contrast, significant wave height in the Arctic is not anticipated to become a problem until the ice melts.
- From a hydrothermal perspective, an increasing impetus to pursue research on ultraslow ridges in the Arctic comes from recent work at the Mid-Cayman Rise (MCR) that may be representative of all ultraslow ridges. First, ultramafic-influenced vents, such as ones found on the MCR, may provide novel geochemical settings; which, in turn, might be particularly conducive to biogeochemical reactions relevant to understanding the origins of life. Second, the seafloor massive sulfide deposits found at the MCR, as well as at the first vent site found at each of the SWIR and in the Arctic, are also much larger than would have been predicted from the spreading rate, and also much richer in copper and gold than their faster-spreading ridge, basalt-hosted counterparts.

Rift systems:

- Rifts fundamentally shape Earth's planetary surface and form part of the global cycle in the transfer of heat, mass, and chemicals between the solid earth, continents, oceans, and atmosphere. The West Antarctic Rift System (WARS) is one of the world's largest rift zones and is the only rift system covered by a continental scale ice sheet—the West Antarctic Ice Sheet. Understanding the WARS evolution is key, as it has important implications for the evolution of the Antarctic continent, and further constrains the global circuit of plate motions. Unfortunately, the offshore portion of the WARS is located under ice (the Ross Sea ice shelf and moving ice in the Ross Sea), and it has never been accessed or directly sampled in real-time with the precision that open-water deep submergence technology provides.
- Finally, moving from ocean-basin formation to ocean-basin evolution, it is also the case that there are unique processes to be studied at both the Arctic and Antarctic seafloor—not only to characterize the unperturbed processes of sediment deposition in these unusual geologic settings but also to investigate

for evidence of enhanced glacial margin sediment inputs associated with global climate change.

- How can risk be better characterized and the ability to forecast geohazards like mega-earthquakes, tsunamis, undersea landslides, and volcanic eruptions be improved?
- As discussed previously, there are large reserves of methane trapped in gas hydrates that pervade the Arctic Ocean margin environment. Presently, as that methane is released into the ocean, it undoubtedly provides a major nutrient flux. But, it should also be considered from the perspective of a large and untapped energy resource; and, if released extensively to the atmosphere (as a major greenhouse gas) or suddenly (to the extent that it destabilizes the continental margin sediments), then the entire system should also be treated as a potential geohazard.

Identification of key scientific questions

Following our initial discussions, the second session of our polar ocean break-out group began by identifying the following key scientific themes—specific to the deep submergence research community—that it would be important to tackle in the coming decade:

1. Gas hydrates (particularly in the Arctic): Their distributions; investigation of their stability in the face of ocean warming and climate change; contributions to the ocean biogeochemical cycle (e.g., as an important nutrient); potential as an “until-now” untapped energy source; and potential as a future geohazard.
2. Ultraslow spreading ridges (particularly in the Arctic): Studies of MCR processes in the Arctic, as at all mid-ocean ridges (MORs), can be done using remote sensing and sampling from conventional research ships. However, there is great value in using ice-breakers to further arctic research (see the successes of the Arctic Mid-Ocean Ridge Exploration [AMORE] program in 2002). There are particularly interesting questions related to hydrothermal activity along the arctic ridges that range from formation of the world’s largest and highest grade seafloor massive sulfide deposits to the abiotic synthesis of organic molecules that might provide insights into the origin of life. These systems are also ripe for new studies of vent site biogeography, including which mega-fauna, if any, have colonized vent-systems in an ice-covered ocean basin.
3. Geosphere/cryosphere system response (e.g., Ross Sea and the Ross Sea oceanic lithosphere formation and evolution by WARS): While many studies of rift processes on Earth have been conducted; ultrahigh-resolution geological, biological, chemical, and physical oceanographic observations by underwater vehicles have yet to be undertaken. Understanding how processes of the offshore extension of WARS (the largest rift system on Earth) occur and evolve through time is a key to advancing our knowledge about the mechanisms involved in Earth’s planetary evolution, such as plate tectonics (i.e., the overall Wilson cycle), magmatism, and their impact on cryosphere (i.e., glaciers, ice-shelf, and floating ices), ocean currents, and climate change as a whole. As mentioned, undiscovered hydrothermal fields in the Ross

Sea basins could only be revealed by utilizing deep submergence technologies *under ice*.

4. Other research areas include Paleoclimate, paleoglaciation, and paleoceanography, physics of the water column, including ocean circulation, heat flux, water column biology, and biogeochemistry (primary production), ocean acoustics, and water-ice-atmosphere interactions (e.g., the evolution of the marginal zone ice).

Technological Responses

In the polar oceans, various oceanographic technologies and deep submergence vehicles have now been deployed successfully to conduct scientific research. It is important, when considering the polar oceans, to remember that not all these oceans are ice covered all the time or even at all. Conversely, however, it is also the case that some technologies can only access parts of the polar oceans when ice cover is NOT present; whereas, some of the most compelling scientific problems identified previously require year-round studies to investigate interseasonal as well as year-on-year variations.

The Current State of the Art

Drawing on the strengths of our polar oceans break-out group's team membership, we devoted significant time to identifying what technologies we did already know of as being suitable for polar investigations and also noted any important caveats and/or limitations associated with each identified technology. Some examples identified during these discussions included heat flow measurements carried out by deep-towed vehicles (e.g., TowCam), rock sampling by conventional shipboard dredging; sampling and observations accomplished by remotely operated vehicles (ROVs) (e.g., remotely operated platform for ocean science, or ROPOS) which have routinely been conducted to depths of up to 1,000 meters (m) but not deeper; long-range oceanographic investigations conducted by AUVs (e.g., AUTOSUB Under Ice, Remus vehicles, Monterey Bay Aquarium's [MBARI's] AUVs) and Sea Gliders; and, most recently, the first science-verification dives (to ≤30 m depth but out to ~1 km laterally from the ship while operating close to the underside of sea ice) the 2,000-m depth-rated, hybrid remotely operated vehicle (HROV) NUI. Our discussions also noted that –in theory- it is possible to gain access for deep submergence science in polar regions by any of the National Deep Submergence Facility (NDSF) vehicles: AUV *Sentry*, ROV *Jason,* and even HOV *Alvin* for locations that are suitable for the R/V *Atlantis* to also operate. However, in many cases, these scientific operations at high latitudes might also come with an associated risk of loss of the vehicle (in the case of *Jason* and *Sentry*—no such risks could even be contemplated in the case of *Alvin* dives). More pragmatically, because of the remote nature of the high latitudes at which polar ocean research is conducted, the shipping logistics to deliver these NDSF assets to suitable ships could probably only be achieved by taking the same vehicles away from their regular sphere of operations at lower latitudes for extensive periods in any given year—at significant cost to the remainder of the national deep submergence research program.

Future Technology Needs

In our third and final session, our break-out group sought to address each of the key scientific drivers identified in the polar oceans science session. In these discussions, we identified both conventional deep submergence approaches that could already be employed and also novel technologies that would need to be developed to provide solutions to some key challenges unique to polar-ocean deep submergence science.

Key Science Questions

(a) Some key science questions identified for the Polar oceans that can be tackled using conventional deep submergence assets include *some (but **not** all)* aspects of: (1) gas hydrates, (2) ultraslow spreading ridges, and (3) benthic biology (see preceding section). Technological developments required to advance these areas of research include the following:

- Deploying temperature resilience of any sensors from deep submergence platforms (entire systems routinely have to withstand below-freezing conditions on deck prior to deployment; and also to remain within specifications and calibration at depth where, unlike the rest of the global ocean, temperatures can routinely fall below 2°C: many ocean sensors are not designed for such temperatures).
- Multiscale navigating in both under-ice environments and mixed/transient conditions at the marginal ice zone.
- Resolving magnetic heading problems experienced at high latitudes.
- Establishing long-range (>1,000 km) methods for under-ice vehicle navigation.
- Equipping vehicles with full mapping and imaging capabilities to be effective in the harsh environments anticipated that, in addition to low temperatures, are also likely to include high bottom currents and very poor visibility caused by sediment resuspension.
- Deploying water column acoustic and *in-situ* chemical sensors.
- Determining fluxes using acoustic techniques.
- Sampling rocks (e.g., carbonate, hydrate, igneous rocks) and sediment (e.g., push-coring).
- Developing and deploying *in-situ* rock drilling techniques to investigate sub-seafloor.

(b) Some key science questions identified for the polar oceans that could ***not*** be tackled using traditional deep submergence assets include: (1) geosphere/cryosphere interactions; (2) paleoclimate, paleoglaciation, and paleoceanography; (3) physical oceanography studies of the water column; and (4) ocean acoustics. Some examples of key technological developments required to address these questions, *in addition to* those identified in (a) previously include the following:

- The capability of conducting investigations, laterally, for tens of kilometers away from any support ship—allowing assets to be launched from open water beyond the marginal ice zone to conduct investigations of the ocean water column and underlying seafloor in regions beneath thick ice cover (e.g., the Antarctic ice shelf). One possible solution for this would be to couple the endurance of the NUI vehicle with an extended lateral range achieved either through tetherless communications or daisy-chaining together multiple packs of the currently used light-fiber tether in series.
- The capability to dive all the way to the sea floor in all polar ocean settings (i.e., up to and beyond 5,000 m in the case of the Arctic Ocean basin). One possible solution for this would be to upgrade the existing NUI vehicle to extend its depth capabilities beyond the current 2,000-m limitations. Without that solution, for example, the newly discovered vent sites that have already been imaged from deep-tow operations at the Aurora Field on the Gakkel Ridge remain frustratingly out of reach.
- The capability to develop through-ice navigation systems (which could be coupled with untethered ROVs, launched from beyond the marginal ice zone) to achieve precisely navigated (and even acoustically controlled) deep submergence.

We note that this list is certainly not exhaustive. Rather, it was limited by the breadth of scientific expertise participating in our break-out group. We anticipate that further technological developments will also be required for additional paleoceanographic, biological, and physical oceanographic studies.

Other pertinent challenges and opportunities

During our discussions, the following three other themes came up that were not already reported in the preceding sections:

1. International collaborations are likely to be particularly valuable in the development of polar ocean deep submergence science, particularly when it comes to long-range expeditionary planning (e.g., using more than one ship, or even only deploying assets from one nation aboard icebreakers to another nation as was done with the NUI aboard *PolarStern* in 2014 and 2016). The advantages to such approaches are obvious (e.g., access to a much wider range of the polar oceans than any one nation can routinely reach). But, to do this effectively will require a much greater ability to commit resources in

advance and to dovetail with other nations' planning than has typically been the case until now.

2. There should be an increasing effort to partner among diverse federal agencies' programs (e.g., NSF, Ocean Color Experiment [OCE], Office of Polar Programs [OPP], National Oceanic and Atmospheric Administration [NOAA], and National Aeronautics and Space Administration [NASA]) to offset the added costs to operations at high latitude.
3. We should encourage more private-public partnerships (e.g., in the case of gas hydrates).

Recommendations: Polar Oceans – Science-enabling Technologies

Three years to five years (3 years to 5 years): We require the following technical developments (leading to operations as a facility):

- Novel ice-relative navigation systems, in addition to extant seafloor navigation methods.
- An improved lateral range *and* depth range to the current NUI vehicle: We require one or more lightly/virtually tethered vehicles that can conduct research out to >20-km laterally, away from a support ship (e.g., to investigate under Antarctic ice sheets and Greenland glaciers) and also dive (same vehicle) to full ocean depths, not just 2,000 m (to facilitate seafloor operations at the sub-ice shelf Antarctic seafloor, as well as the ridge axis and abyssal plains of the Arctic Basin).
- An ability to operate in ROV mode in hazardous areas (e.g., those associated with the marginal ice zone, where a mix of open water and floating ice blocks (as opposed to continuous ice cover) can present a particular hazard to conventionally tethered deep submergence assets.

Ten years to fifteen years (10 years to 15 years): We require the following technical developments:

- Basin-scale navigation systems for long-range, under-ice operations.
- Establishment of both Arctic and Antarctic cabled observatories. (Colleagues in the polar oceans research community have already identified where the highest priorities for such future observatory activities should be located, together with scientific justifications for those locations.)
- Mobile seasonal-scale installations (i.e., seafloor and fixed-to-ice) that can be relocated throughout the polar oceans and operated as a facility (i.e., not only owned "privately" because they are funded by, but therefore linked to, a single PI-led grant-based investigation.
- AUVs and ROVs provided as standard for an "increasingly science-capable"* next generation of U.S. ice breakers (i.e., new ice breakers that match to current

standard University National Oceanographic Laboratory System [UNOLS] capabilities, a level of service that current United States Coast Guard [USCG] vessels fail to reach).

Breaking down barriers: We identified three key issues specific to our discussions as follows:

- In developing our priorities for the next decade, it will be essential to consult with a much broader range of polar-aware sea-going scientists, who are not (yet) regular participants in deep submergence meetings and discussions because the DeSSC did not previously have much in the way of polar-capability technologies to attract their attention or interest. The UNOLS is well positioned to play an active and important role in this regard by fostering stronger links through and between the appropriate committees and agencies.
- It will be important to recognize that there will be a need for prioritized (but not exclusive) assets for polar oceans deep submergence science. Because of logistics demands, it would not be feasible to draw conventional assets away from the NDSF pool without harming the rest of the national deep submergence science community. But, both the vehicle and sensor developments that we hope this interest in polar ocean studies will stimulate would undoubtedly also be of benefit and should be pursued in coordination with the “blue water” ocean science community. Anything that can work at the bottom of the deep, cold Arctic should also be able to work anywhere else in the oceans!
- To maximize returns for hard-won access to public (i.e., tax-payer) dollars, the U.S. research community should continue to make use of excellent opportunities that exist in polar research through international collaborations. To optimize this effort will require an ever-improving approach to long-range planning in the U.S., ideally out to ~5 years in advance. Such long-range planning and vision will be particularly important for multiship polar ocean expeditions.

BIOGEOCHEMISTRY

By

Colleen Hansel, George Luther, Brandy Toner, and Scott Wankel

Overview

Biogeochemistry encompasses three major scientific disciplines necessary for understanding processes governing the functioning and health of the ocean, including the deep ocean. These biogeochemical processes are underscored by geophysical controls on fluid flow and particle dispersal. Within the deep sea, in particular, geophysical processes provide myriad chemicals to macro- and micro-organisms allowing them to thrive within focused and diffuse flow systems. The previous Ridge 2000 program had a significant major impact on our understanding of focused flow and diffuse flow systems, with direct bearing on understanding deep-sea biogeochemistry. In particular, the Ridge 2000 program focused scientific inquiry at specific locations in the deep ocean, which led to a greatly improved understanding of biogeochemical processes at mid-ocean ridges (e.g., East Pacific Rise 9–10 N) and to a lesser extent back-arc subduction zones (e.g., Lau Basin). The outcome of the Ridge 2000 program highlights the value of targeted initiatives in making large-scale advances in marine science. For instance, by coupling Ridge 2000 data with prior research at the East Pacific Rise, datasets of sufficient density and extent were acquired to allow for the development of a robust regional carbon model (German *et al.,* 2015). Since the Ridge program has ended, however, there has not been a concerted, targeted effort by the community to explore biogeochemical processes within the ocean.

During the past decade, the complexity and diversity of biogeochemical processes and cycles within the deep sea have begun to come to light. Various approaches, including field measurements, laboratory incubations, and thermodynamic modeling, have revealed a web of microbial metabolisms that serve to shape the chemistry of the ocean and provide the foundation of organismal symbioses. In fact, a vital synergy is now known to exist between biology and geochemistry that encompasses all domains of life (eukaryotes and prokaryotes, alike), influences the cycling of nearly all elements (including nutrients, metals, and radionuclides), and touches every possible ecological niche (spanning from the surface ocean to miles below the seafloor). As a community, we have an improved understanding of the nature of chemical/energy gradients in the ocean, and the corresponding constraints these gradients impose on life. Yet, we have only begun to scratch the surface of understanding the biogeochemistry of the deep sea.

While we are gaining a better of understanding of the biogeochemical fluxes and processes in some environments (e.g., shelves, seeps, vents), others are extremely limited (e.g., hadal, abyssal plain, sea ice). Further, we have only a minimal understanding of the influence of global stressors (e.g., ocean warming and acidification) on deep-sea biogeochemistry—a critical necessity given the importance of the deep sea in the health and functioning of the overall ocean ecosystem. In this report, we provide a set of goals and objectives for near future deep-sea biogeochemical research, and pose short- and long-term recommendations for meeting these objectives.

Overarching Goals and Objectives

The goal of biogeochemistry is to develop detailed elemental budgets that reflect an understanding of the biological, geological, chemical factors, mechanisms, reactions, and pathways that shape them. Biogeochemical research is inherently multidisciplinary and involves defining fluxes of materials at interfaces among oceanographic regimes. Therefore, biogeochemical research questions require integration of multiple subdisciplines within oceanography and with the broader Earth and environmental science communities. Advancing marine biogeochemical research requires collaboration among scientists and funding programs that have historically worked separately as subdisciplines and were based on parameters, such as water depth and proximity to geologic features (e.g., mid-ocean ridges and continental shelves). In specific consideration of the role of submergence science in facilitating biogeochemical studies, several overarching objectives emerge reflecting either those that remain poorly understood (despite previous research efforts) or those that reflect newly promising or societally urgent research directions.

1. To define mass fluxes and their influence of global ocean elemental budgets

Fundamentally, biogeochemical research in the deep sea and subsea floor asks questions about mass fluxes, with the aim of identifying the relative importance of specific processes, organisms, ecosystems, or regions. Quantification of mass fluxes in the ocean is intrinsically challenged by the nature of the milieu (e.g., physics of fluid advection, molecular diffusion, mixing, and more). In many systems, fluxes are often extrapolated using quasiconservative tracers, such as heat. In advectively driven systems, historical challenges arise with quantification of fluid flow rates for constraining mass flux. ***Future biogeochemical research goals should be to: (a) better quantify the fluxes of elements within and between oceanic regimes; (b) identify the origins/sources of these fluxes; (c) determine the feedback loop between organisms and elemental fluxes; and (d) define the importance of these fluxes on global ocean health, productivity, and functioning.***

2. To determine the role of coupled biogeochemical cycles and reactive intermediates

There has been an increasing appreciation over the past decade of the importance of coupled elemental cycles (e.g., carbon/iron, nitrogen/manganese, and more) in controlling elemental profiles and budgets in the ocean. In fact, the immense flexibility and plasticity of microbial metabolism allows for countless couplings between various major and minor chemical species. Further, reactive chemical species (RCS), of both chemical and biological origin, are emerging as important players in these biogeochemical cycles (Hansel *et al.,* 2015). Because of their rapid production and consumption, these RCS are short-lived and typically in low abundance. Yet, most of these reactive compounds exist long enough to interact with the surrounding geochemical and biological environment. In fact, there is an emerging recognition that these short-lived reactive species may even be essential to the overall efficiency of other major elemental cycles. These chemical species encompass numerous elements (e.g., O, N, S, Mn, Fe) and are also involved in myriad organismal activities, ranging from respiration to cell signaling. ***Future biogeochemical research goals should be to: (a) identify new couplings between elemental cycles; (b) identify and quantify reactive chemical species involved in biogeochemical cycling; and (c) discover new microbial metabolisms coupling (and controlling) elemental cycles.***

3. To integrate biogeochemical studies into larger scale ecosystem models

Deep submergence technologies and research have led to major advances in our understanding of mid-ocean ridge processes. However, of the integrated research sites, only the East Pacific Rise 9–10 N has data coverage sufficient to develop a first-order model for carbon cycling (German *et al.,* 2015). Thanks to past investment in deep submergence science, mid-ocean ridges are the best studied deep ocean ecosystems. Yet, much of the global mid-ocean ridge remains unexplored, and many aspects of hydrothermal systems are poorly described (*in-situ* metabolic rates, energetic budgets, chemosynthetic carbon fixation pathways). In addition, there are currently insufficient data to represent the variety of hydrothermal venting systems in biogeochemical models. For example, the contribution of chemoautotrophy to deep-ocean carbon budgets remains unconstrained. Thus, to obtain an improved understanding of the biogeochemistry of the deep sea and its connection to the global ocean, an improved capacity to scale-up biogeochemical reaction networks, mechanistic information, and local/region studies into larger scale ecosystem models is essential. ***Future biogeochemical research goals should be to: (1) increase the density of chemical and biological measurements in a diversity of deep-sea environments; (2) develop models to integrate biogeochemical data into broader scale ecosystem models; and (3) improve reaction networks and metabolic models by incorporating mechanistic data into thermodynamic and kinetic models.***

4. To develop novel *in-situ* instruments and sensors to enable key measurements in the deep sea

There has been an increasing awareness that many potentially important components to elemental budgets may comprise dynamic features missed by current deep submergence approaches. For instance, measuring reactive chemical species is intrinsically difficult because of their characteristically low abundance (typically pico to nanomolar) and short lifetimes (typically seconds to hours). Some compounds, which may exist in a dynamic metastable steady-state, immediately respond to even minor perturbations in their surrounding chemical environment. Thus, detecting these reactive unstable species is hindered by the inability to preserve them without significant modification or complete degradation. For particularly unstable or short-lived species, preservation is completely impossible and, as such, there are many environments where their presence and environmental relevance remains unexplored. Further, the biogeochemistry of the deep sea is immensely dynamic over both space and time. The present limitations on sample collection and field measurements greatly constrains our understanding of the biogeochemistry of the deep sea. The only remedy is the development of direct measurement capabilities of *in-situ* concentrations of these important chemical species. Further, recent and current investments in cabled observatories should advance biogeochemical research at specific locations in the near future by integrating these novel *in-situ* sensors, including quantification of fluxes and detailed process studies leading to integrated model development.

Thus, heavy reliance on collecting samples and returning them to the ship during field campaigns (or the shore-based laboratory) limits our ability to discover and quantify biogeochemical processes, particularly those with short-lived reactive intermediates and/or have dynamic spatial and temporal variability. ***Future research goals should be to: (1) advance deep submergence technologies allowing for in-situ detection, quantification, and experimentation to reveal dynamic aspects of marine biogeochemical processes missed by current approaches; and (2) develop new instruments/sensors to specifically target chemical species that cannot be measured using ex-situ approaches or currently available in-situ sensors.***

Recommendations

Within the next 15 years, the scientific community should strategically add data-rich, integrated-study sites to expand the number of well-studied ocean systems where important biogeochemical processes are occurring. Beyond mid-ocean ridges, a wide range of marine ecosystems have received little to no investigation (e.g., hadal, abyssal plain, sea ice, subsea floor, and tectonic interfaces, such as fracture zones). This overall lack of data for representative marine ecosystems limits our ability to quantify baseline conditions, develop models, and extrapolate findings from one location to the larger regional or global scale. In the absence of good models, we have only a limited predictive framework for understanding how perturbations, such as ocean acidification, will affect ecosystem function, including ecosystem services with relevance to human activity. Deep submergence technologies, existing and yet-to-be-developed, will be central to investigating these unexplored ocean provinces.

1. Short-term Recommendations (5 Years)

During the last two decades, scientists have realized that more high-quality data from diverse ocean monitoring systems is essential for us to have meaningful baseline data for revealing the nature of both long-term perturbations (global change) and short-term impacts (major geophysical, meteorological, or even anthropogenic events). To this end, the continued development and improvement of deployable, *in-situ* sensor technologies and analytical instrumentation remains a high priority for ocean biogeochemistry research. Sensors and instruments must be smaller, lighter, and cheaper for deployment on a range of deep submergence assets (with extended depth capabilities) and cabled observatories. Sensors and instruments must also include automated metadata acquisition and allow for simple integration of data from multiple sources.

In the short-term, we recommend that the community prioritize deployment of existing sensors, analytical instruments, and sampling equipment to begin to address biogeochemical data gaps regarding spatial and temporal dynamics of deep-sea and subseafloor systems. High-value activities would aim to extend current temporal and spatial coverage capabilities, including deployments at cabled observatories (i.e., Ocean Observatories Initiatives [OOI]), as well as on existing autonomous underwater vehicle [AUV], remotely operated vehicle [ROV], and human occupied vehicle [HOV] platforms.

We also recommend that the community begin using existing deep submergence assets for simultaneous, multiplatform expeditions (e.g., AUV operations occurring at a distance from ROV or HOV operations) to build operational competence and inform technology development needs. The primary advantage of these activities is to maximize the number and frequency of biogeochemically relevant observations per cruise. Multiple AUV units performing sensor sweeps and targeted sample collection could operate in parallel to water column, sea floor, and/or subsea floor experimentation. Telepresence capabilities would also be an essential aspect of these types of operations, especially on ocean-class vessels.

We recommend that a workshop (or similar process) be convened that is focused on the state of present technologies for *in-situ* sensors and instrumentation. The goal would be to systematically examine present technologies—strengths and limitations—and the degree to which they are compatible with current and planned deep submergence assets and science needs. An important goal would be to identify impediments to developing promising/essential sensors for full-ocean depths and extended deployment periods (e.g., months to years), such as sensor development issues (e.g., drift, standardization, calibration), pressure housings (e.g., materials, designs, configurations), and power supplies (e.g., batteries and/or alternative power sources). High-priority geochemical targets for biogeochemical research include methane, carbonate species (i.e., pH, hydrogen, and nutrients) (e.g., nitrate, ammonium, phosphate, silicate). New sensor and instrument capabilities for ocean biogeochemistry include detection of stable isotopic (e.g., ^{13}C, ^{15}N, ^{34}S) and short-lived reactive intermediate species (e.g., reactive oxygen species, sulfur and nitrogen intermediates, transition metals, and small organic molecules).

The Ocean Sciences Division at the NSF has long realized the need for researchers to design, build, and test sensors that are capable of long-term deployments under harsh conditions of temperature and pressure. The Ocean Technology and Interdisciplinary Coordination (OTIC) program has been one way to fund that need. However, during the last 5+ years, the program has suffered from inadequate funding, which has resulted in a loss of vision for sensor development. We recommend that this program receive a major overhaul in funding and personnel support that will advance sensors in all areas of biogeochemistry.

The NSF has funded special initiatives across several NSF programs during the years that have had major impact on deep-sea science. Continuing with that strategy, developing partnerships with NSF programs in other directorates, such as chemistry should lead to transformational sensors that provide unique data and information that would benefit society. In addition, the area of biogeochemistry, including terrestrial, freshwater, surface and deep ocean, could be significantly advanced if several NSF directorates engaged scientists to develop new robust sensors that could be used in a variety of environmental fields. Obtaining more high-quality data will also lead to better development and validation of models leading to better predictions of Earth and ocean processes that will have a positive impact on society.

We recommend that the three NSF programs primarily concerned with oceanographic research (Marine Geology and Geophysics, Biological Oceanography, and Chemical Oceanography) consider a new integrated biogeochemistry research program that will bring together the best possible researchers from these fields. As an analog program with similarly oriented research, the NSF EAR Geobiology and Low-Temperature Geochemistry program has become a highly successful program for terrestrial Earth Science, yet has remained programmatically isolated from research in marine biogeochemistry (perhaps because of, in part, limitations of program budget size). A newly oriented program in marine biogeochemistry should build on the previous successes of the Ridge 2000 program and the current GEOTRACES program, which has shown there is a significant release of elements from sea floor hydrothermal sources to the deep ocean and possibly to the surface ocean (Resing *et al.,* 2015). Many of these elements, but in particular iron, play important roles in fueling primary productivity in large regions of the ocean. A workshop funded by the NSF should be convened that will help design and guide the proposed integrated biogeochemistry research program.

2. Long-term Recommendations (10 to 15 Years)

During longer time horizons, it is anticipated that technological advances in biogeochemical sensors will provide abundant and reliable measurements of key parameters during extended scales of time (years) and space (km^2). Given such advances in data acquisition, there will be a strong need for data processing infrastructure and pipelines for integrating physical (e.g., fluid movement), geochemical (e.g., concentrations, isotopes), and biological (e.g., genetic, proteomic) data streams to begin leveraging such advances toward a broader and more comprehensive understanding of ocean biogeochemistry. These efforts may require international, multiagency, and/or multi-PI coordination. As this data density increases, new challenges will begin emerging in data archival and streamlined data access portals.

Coordinated efforts toward open-access and user-friendly engineering/technology platforms would help to broaden the user community and enhance overall science goals for submergence science. However, cultural impediments or hindrances may also remain involving PI-specific priorities for academic promotion, intellectual property, and/or patentable technologies. As biogeochemical sensor technologies mature during this longer time frame, there will be a greater need for the development of cross-calibration, standardization, and standard operating procedures.

We recommend new NSF-based efforts to bring together the community of submersible technology users and developers (possibly including interfacing with private industry representatives) in a workshop format to help unify efforts for inter-instrument comparisons, standardization, and calibration.

During the next decade, it is likely that the sea floor will remain largely unexplored and uncharacterized. We recommend continued emphasis on research and deep-sea submergence tool development for unexplored regions (i.e., hadal zone, passive margins). Specifically, advancing capabilities for detecting fluid flow—especially diffuse venting—in deep-sea environments across broader regions of the sea floor would help to prioritize allocation of submersible assets for the exploration of particularly uncharacterized environments. To this end, we would also like to see a "cultural widening" of programmatic directives that currently limit or discourage exploration science to include and accept research proposals with focused, yet more discovery-based, objectives. Continued development and deployment of advanced AUV-based mapping tools during coming decades will certainly help to bring unexplored regions "into focus," which may help to provide a greater impetus for allocating assets in more focused "discovery-based" research activities.

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ECOLOGY AND MOLECULAR BIOLOGY

By

David Emerson and Tim Shank

Overview

Ecological studies rely on the ability to carefully monitor and census natural populations, and correlate changes in diversity and ecosystem function either with changes in species abundances, interactions, and/or changes in the physicochemical environment. In addition, to test ecological concepts and hypotheses, the ability to do controlled manipulations is important—either of specific populations within an ecosystem or some ecosystem process. Attempting to do any of these things in the deep sea presents a series of special challenges that are important to address for the field to progress. In addition, deep-sea ecology spans a remarkable range of body size, from nanometer (e.g., viruses) to meters (e.g., large pelagic fish) and abundance; from microbes that can range from millions to hundreds of millions of individuals per cubic centimeter to macro-fauna in which abundance may be a few individuals scatted over many square kilometers. Nonetheless, understanding fundamental ecological interactions and the ecosystem functions and services of either micro- or macro-organisms in the deep sea is essential simply because, as a whole, the deep sea is the largest ecosystem on Earth. As such, it has important ramifications for the entirety of life on Earth. Some of the following key over-arching questions related to ecology are elucidated in the 2015 Changing Oceans Report:

1. How have ocean biogeochemical and physical processes contributed to today's climate and its variability, and how will this system change during the next century?
2. What is the role of biodiversity in the resilience of marine ecosystems, and how will it be affected by natural and anthropogenic changes?
3. How different will marine food webs be at mid-century and in the next 100 years?
4. What is the geophysical, chemical, and biological character of the subsea floor environment, and how does it affect global elemental cycles and understanding of the origin and evolution of life?

Over-arching questions

We have identified a number of areas that are important to working on these over-arching questions. A primary goal is to understand the larger thematic ecological questions around temporal and spatial variability of ecosystem that can be developed to drive hypothesis-driven research related to both microbial and macro-organisms, and ideally help tie them together. For example, we need a better understanding of the nutrient fluxes between microbes and metazoans (or higher animals), as well as specificity of interactions (e.g., symbiosis) between microbes and metazoans. From a microbe-centric perspective, the last 20 years have revealed the vastness of microbial diversity, yet begun to show that diversity is organized into specific assemblages—referred to as "microbiomes" that have unique properties. From this perspective, one can begin to ask what are the conditions that drive microbiome organization and resiliency?

Because ecosystems are inherently dynamic and responsive to change, it is important to conduct baseline studies using as many standardized methods as possible. Baseline data is important both for answering basic ecological questions and also for areas, such as restoration and conservation ecology, that are increasingly important as areas of the sea floor are likely to be exploited for mineral extraction and other human activities, including fisheries.

Collection of baseline data has a number of challenges. How dynamic is the system being observed? If deep-sea pelagic systems are dynamic, then coastal systems are very dynamic; and, in the Arctic, the hadal zones and mid-water column where our understanding is so poor, it is difficult to say. Another inherent challenge for macro-organisms is that sessile versus motile organisms require different levels of monitoring. Yet, another challenge comes in monitoring in areas of intensive human activity (e.g., fishing that makes use of deep submergence vehicles and other technologies challenging).

For microbial systems, long-term pelagic monitoring sites like the Hawaii Ocean Time-series (HOT) and Bermuda Atlantic Time-series Study (BATS) have been effective, but systematic deep-sea monitoring efforts are lacking; the mid-deep water column (e.g., below 500 meters [m] to the sea floor) is especially poorly sampled and understood. With regard to deep-sea vent systems, there are some intensively studied deep-sea vents (e.g., Juan de Fuca/Axial Seamount, 9° N at the East Pacific Rise, Loihi Seamount, Lau Basin); but legacy data has not been systematically analyzed. To what extent can new Ocean Observatories Initiatives (OOI) observatories (e.g., cabled array at Axial Seamount and Coastal observatories) be leveraged to these kinds of baseline efforts?

Beyond the development of new technologies and new monitoring schemes specific to the basic research initiatives funded through the National Science Foundation (NSF), what are the opportunities that exist for leveraging other sources of ecologically relevant information in the industrial realm? Can we participate in performing surveys related to deep-sea mining, oil and gas exploration or maintenance of underwater facilities? Also, how can we engage research institutes (e.g., the Monterey Bay Aquarium Research Institute [MBARI]) that have significant repositories of data related to mid-water surveys? Finally, is there nonclassified information collected by the U.S. Navy that would be useful such as surveys of both pelagic and benthic species?

Development of technologies relevant to ecological studies

Looking forward, what are the technologies needed to pursue questions of ecological relevance in the deep sea? Because deep-sea work is always going to be expensive and resource limited, it is important to make the most of sampling opportunities, which brings up a couple more philosophical points that are an important point to keep in mind during technology development. One of these points relates to sampling “intensively” versus sampling “intelligently.” Collecting a large amount of data not developed around a guiding hypothesis may not be the best use of time and resources, because it can result in large amounts of data not all that interesting. Another challenge is that while standardization of practices is commendable, it should not be done at the expense of innovation that can substantially improve the volume or kinds of data collected and at reduced costs.

Given these “provisos,” there is a general need for technologically driven approaches to automated and systematic sampling to increase the frequency of sampling, ability to simultaneously collect samples for biological analysis, and make geochemical analyses.

For monitoring and census-type studies, there are needs for vehicles that can operate remotely on the sea floor or in the depths to conduct longer-term studies, but still have mobility (i.e., are not fixed in a position). One priority is adaptive monitoring and/or sampling systems that can automatically identify targets of interest based on chemical or visual cues and take samples images, etc.

Some technologies required for this type sampling are cameras with sensors that enable tracking of organisms, and cameras with automated feature recognition that can be programmed to recognize certain organisms (e.g., deep-sea corals) and image those. These cameras could be coupled with hover-type autonomous underwater vehicles (AUVs). Other visual imaging technology ideas include: 1) cameras and associated technology that allow them to travel up and down tethered cables (spider-cams) to monitor mid-deep-ocean depths and; 2) use of lighting systems in the red/blue/infrared (i.e., nonwhite light) coupled with imaging systems to observe deep-sea creatures without the artifact of white light. Another significant advance would be stereo cameras that can acquire real-time data in a form that is easy to access, utilize, and analyze and has a capacity for visualizing moving as well as static.

To integrate organismal data with environmental data, there is a need for coupled integrated sampling systems that utilize multiple sensors to collect physical, biogeochemical, and molecular information/data in parallel. This integration may involve the integrated use of multiple platforms (e.g., AUV/remotely operated vehicle [ROV]) to efficiently work with dynamic ecological communities, which includes automated collections with robotics that could be deployed and monitored and manipulated remotely. There is also need for multiple sampling/survey vehicles that communicate with each other (e.g., drifter and sampler/feature-finder team of machines).

Sampling and monitoring of microorganisms requires specialized tools that are appropriate to the scale of their communities and activities. This requirement can include high-spatial resolution sampling (subcentimeter) of microbial mats and related microbial ecosystems types, and acquisition of chemical profiles for understanding microbial community composition and how it relates to biogeochemical processing. Specific tools include micromanipulators for high-resolution measurement or sampling of very dynamic environments like microbial mats or the sea—sea floor interface. Dynamic pumping systems that take precise volume samples with subcentimeter resolution in X-Y or Z coordinates would also be of value. Another important aspect of sampling microbes are preservation strategies and technologies that allow *in-situ* preservation of either organisms or nucleic acids, or proteins in a state that minimizes natural loss and decay. This preservation is especially important for activity studies related to the capture of messenger RNA (mRNA) from bacteria or archaea that has a rapid turnover rate.

Another important aspect for ecological studies is the capacity to do *in-situ* manipulation, which can be as simple as deploying baits and monitoring the consequences over time, or more complicated approaches, such as doing substrate uptake experiments for micro-organisms. Some of these technologies can be integrated with sampling technologies. For example, discrete pumping systems that can be used to add a substrate or a tracer for monitoring microbial function can also be used for collection of samples. Other applications (e.g., enclosed, or semienclosed incubation systems for determining *in-situ* process rates for chemosynthetic microbial communities) that could be autonomously monitored would need more specialized equipment. For macro-organisms, it would be useful to develop acoustic or other marker systems for tagging of organisms that could then be used to follow and trace organisms—either for life cycle or feeding studies.

A related topic is development of tools for *in-situ* molecular analysis, some of which are already in development (e.g., the deep-sea environmental sample processor used by MBARI to autonomously monitor specific microbial populations during tethered deployments. In general, most current molecular analysis tools are at best ready for ship-board deployment, rather than routine deep-sea deployment. Thus, a nearer-term goal is to take advantage of technologies that allow for rapid ship-board analysis that can then be used to guide subsequent sampling or experimental manipulations as part of a research cruise. As new technologies (e.g., real-time, nano-pore based sequencing) that have minimal power requirements develop, it may make *in-situ* analysis more likely. Such studies could be especially useful for transcriptome analysis to monitor gene expression in real-time. In the meantime, important objectives include sampling strategies that maximize preservation of samples and are capable of acquiring samples at the appropriate scales and are compatible with rapid on-deck processing.

Another specialized tool that would be useful is the capacity for ROV/human-operated vehicle (HOV) to operate a small drilling rig for shallow seafloor drilling and core acquisition that can be used for biological analysis.

Interfacing science and technology

One of the challenges of technology development for ecological studies is developing tools with as broad an applicability as possible, which can help keep costs down. Toward this end, it is useful to develop tools with as much modularity as possible (e.g., standardized pressure housings for cameras that could be produced in larger quantities, instead of being bespoke) could reduce costs substantially and also allow for more interchangability between vehicles. The same can be said for underwater pumping systems for sample collection or *in-situ* experimentation. It is reasonable to ask what the National Deep Submergence Facility's (NDSF's) role should be in this regard. For example, should there be a core tool bin within the NDSF or another facility that provides maintenance and repairs, etc., of mechanical tools commonly used by the community? Can those tools (beyond what is already there) be agreed on? Should there be a tool-leasing program? Ideally, a formal process should be established for tool sharing that reduces the risk associated by informal requests. Along with this process is the need for central information repositories that make scientists aware of the tools available and, in some cases, may provide instructions on how to use them.

A related issue is data processing, especially for mapping and imaging but potentially for other sampling/data collection types in the future. Under current funding models, image processing from NDSF assets, especially *Sentry* processing of images and map creation, is done by NDSF personnel on ship; and final processing of publication quality maps, etc., is up to scientists. However, NDSF personnel could contribute to these efforts for a relatively small effort/cost. Is there a need for a central facility that could provide image processing related to deep-sea research as a service for scientists?

Finally, it will be essential to develop regimens for training and building the workforce—both academically and technically—for high throughput data analysis (i.e., bioinformatics tools and computational science) related to more intensive data collection and manipulation that is certain to continue to grow into the future.

GEOLOGY

By

Nicholas (Nick) Hayman and Michael (Mike) Perfit

Overview

Tremendous advances have been made in our understanding of: 1) the construction and composition of the oceanic crust, 2) the styles, timing, and extents of volcanism at mid-ocean ridges and back-arc spreading centers, 3) magmatic and tectonic processes occurring in the lower crust, and 4) the relationships between magmatism, hydrothermalism, and biologic activity in many seafloor environments. Much of the progress that has been made is the direct result of long-term, focused studies in selected areas of the sea floor coupled with technological and analytical advances. The scientific advances that were made, and continue to be made, cross disciplinary boundaries reflecting the remarkable interdisciplinary nature of deep submergence science. Only in working collaboratively with separate groups have we been able to make so much progress. However, to continue to advance our knowledge of the Earth's greatest and arguably most important environment, we must continue the successful path that began with the initial DESCEND meeting in 1999.

During the DESCEND–2 meeting, the overlap in disciplinary fields and oceanic regions was apparent, and the Geology break-out group was cognizant of those topics the Benthic break-out group highlighted, but focused on specific science objectives, developments in technology, and outreach goals related to geological processes. A framework was developed that connected science goals to technology goals and social implications. Much discussion surrounded leveraging these efforts for broader education and outreach that could in turn reinvigorate the size and diversity of the science community, and generate more public support for the science objectives.

Since the first DESCEND meeting, geological deep submergence science questions have focused on the role of magmatism and tectonism in shaping the oceanic lithosphere and seafloor environment; how fluids pass through the mantle lithosphere, crust, and overlying sediment; and the nature of the sedimentary environments in the ocean basins. In each area of study, increased application of existing and evolving technology, and the efficient and new uses of deep submergence vehicles and observatory technologies have enhanced our scientific pursuits.

Overarching Goals

The Geology break-out group identified the following three "families" of science questions and goals:

1. *Magmatism and Tectonics*

Deep Submergence Science can address a range of open questions surrounding the seafloor expression and distribution of magmatic and tectonic processes. With a greater understanding of these processes and geophysical information, geoscientists can extrapolate into the subsurface, and establish the role of magmatic and hydrothermal fluxes in the Earth system.

Of key interest to deep submergence geoscientists are processes that link the mantle with the crust, and in turn, with the seafloor environment. During the last decade, there has been a new appreciation for the diversity of magma compositions that erupt on the sea floor, the range of intrusive activity in the subsurface, and the wide range of times scales of magmatic activity from seconds to millions of years. In the coming years, we hope to make great progress in answering the following:

- What is the spatial and temporal variation in volcanic activity on the sea floor?
- Through both the record provided by volcanism, as well as direct inspection of exhumed sections, what is the composition of the suboceanic and sub-arc mantle, and the extent of its heterogeneity?
- As we consider the "plumbing" system underlying the ocean lithosphere, what are the relationships between lavas, dikes, gabbros, melt-lenses, and a low-velocity zone and mantle?
- What are areas off-ridge axes where magmatism is important, such as seamounts that form along transforms and mid-ocean ridge axial flanks, and petite-spots that form near convergent margins?

Another large advance in our understanding of the oceanic lithosphere during the last decade has been the role of tectonic faulting. Mid-ocean ridges are the sites of many different kinds of faults, from abyssal hills that flank ridges to large detachment faults that expose deep crust and mantle to the sea floor, and to buried faults related to volcanic processes within the ridge axis. Transform faults are now recognized to be zones of complex deformation with slip processes that may shed light on earthquake hazards worldwide. Along convergent margins, faults play many roles, including dissecting the downgoing plate, generating destructive subduction-zone earthquakes, and accommodating extension in back-arc basins. Because faulting processes are intimately linked with magmatic ones in the oceanic lithosphere, we seek to answer the following:

- What are the time scales of faulting and volcanism, and how is faulting related to the initiation and loci of volcanism in fore-arc, arc, and back-arc regions; and along transform faults, abyssal hills, and oceanic core complexes?

In terms of our geologic understanding of the major deep-sea magmatic and tectonic regimes, we have made remarkable progress at the local scale in a few select localities, but this progress remains a scant sampling of the ocean floor and arc environments. These questions need to be addressed on a global scale. By considering exchanges both at mid-ocean ridges, across regions in the abyssal realm, to the deep trenches and back-arc basins associated with subduction zones, there is much work to be done in understanding the global submarine magmatic flux.

2. *Permeability*

Many of the questions surrounding the oceanic and arc lithosphere regard the fluxes across all scales. Indeed, all processes involving fluids (including melts) require permeability. We define *permeability* in the broadest way possible, from the measuring of permeability in Circulation Obviation Retrofit Kits (CORKs) or laboratory experiments to the distribution of fractures and faults at all scales, and to spatial patterns of hydrothermal alteration and mineral deposits.

To date, the range of permeability values for the oceanic crust and overlying sediment are based on a few *in-situ* measurements, geochemical estimates from global budgets, and work around the high-flux regions of hydrothermal vents. Yet, there is not a clear appreciation for how large the chemical and physical changes can be over time in any one place. Moreover, geoscientists continue to wrestle with the spatial distribution of hydrothermal alteration and to what extent this alteration extends into the mantle.

The key questions addressing this area are as follows:

- What is the permeability of the oceanic crust and overlying sediments?
- How do the chemical and physical changes of the oceanic crust over time affect the permeability?
- How does seafloor heat flow and crustal circulation change over time?
- What role to do faults play in the flow/distribution of hydrothermal fluids, alteration of the crust and upper mantle, and conduits for magmas?
- Do faults provide fluid pathways from the oceans into the mantle, along both mid-ocean ridges and along convergent margins?
- What is the altered composition of oceanic crust and to what extent does the chemical alteration affect the composition of submarine fore-arc, arc, and back-arc lithosphere?

3. *Sedimentary Environments*

Numerous processes are of acute interest in the sedimentary environments of the sea floor. The sediment-rich trenches, rift basins, continental shelf-slope-rise environments along passive margins, and fore-arc basins all are important parts of the Earth system, as we explore subsequently in our “links to society.” Driving questions that could harness deep submergence approaches in the coming years include the following:

- What are the sedimentary input/output parameters in subduction zones?
- What affect does the composition of sediments in subduction zones have on arc volcanism?
- What are the mechanisms of sediment transport, deposition, and deformation along margins?
- What controls hydrate stability?
- What controls slope stability?

Near-term and Long-term Recommendations

To tackle the previously listed science questions, the geoscience/deep submergence community must take new approaches to both its field strategies, technological innovation, and implementation; and how to connect the results and importance of our science to the public at large. The last point stems from a recognition that only through a dramatic shift in public engagement will the community secure the resources needed to advance the field across the board. There is no lack of exciting science to be promoted; but in general, we are ill-prepared or lack the resources (e.g., publicists) to “toot our own horn.” There were three basic approaches identified by the break-out group to address these deficiencies, as follows:

1. *Long-range (global) mapping and sensing*

Technology now allows systematic investigations of entire plate boundaries, yet with extraordinarily high resolution. Such approaches can lead to a wider and more permanent presence of science instrumentation in the oceans, thereby facilitating detection of active processes and a deeper understanding of seafloor structures and processes.

- Autonomous underwater vehicle- (AUV) mounted magnetometers are incredibly useful, but measurement of gravity and electromagnetic potential fields would also be useful.
- Autonomous measurements of crustal permeability and physical characteristics of the sea floor, as they pertain to fluid and heat flow.
- Using both sensing and mapping capabilities, long-range, basin-wide navigation will be required as technology moves from local, fine-scale studies to regional and global-scale investigations. Smart sensor arrays will need to be developed/improved; and potentially science applications will require remote landers and sampling capabilities. In all cases, autonomous operations will require minimal human input. Reasonable goals in the nearer term (5 years to 10 years) may well see initial characterization of broad regions through these approaches rather than a detailed site characterization but could be integrated into a selected area with fine-scale studies.
- Following the lead of discussions in the seismology community, deep submergence science should consider expendable sensor arrays resulting in low-cost distributed systems.

2. *Site-specific process-related studies in three dimensions:*

The advent of ocean observatories has meant that scientists and the general public can hope to witness and understand geologic processes operating at human time scales in three dimensions. Areas where deep submergence science can connect with observatories are through the facilitation of the following efforts:

- Observations need to be made at a wide range of time scales; and thus, any site-specific effort targeting active processes will need repeat visits and/or long-term monitoring to understand the rates and scales of the changes of interest.
- Seafloor geodesy is becoming a reality thereby enabling continuous and/or campaign-style observations. Deep submergence science can be coupled with geodetic approaches in a number of ways, including through field experiments, rapid response observations, and working away from any observatory nodes or field areas to understand the surrounding system.
- As marine science research becomes more autonomous, engineering efforts are sought to partner with geological science interests to work toward sampling and

docking AUVs, and deploying observatories in a range of locations. We suggest the University National Oceanographic Laboratory System (UNOLS) work with the NSF/U.S. Navy/National Oceanic and Atmospheric Administration (NOAA) to facilitate small meetings between scientists and engineers to brainstorm about the needs and possibilities for advanced research using new technologies.

3. *Sampling and imaging the sea floor and below, at sea and from shore-based laboratories:*

Many of the central activities of marine geoscientists revolve around campaigns to image and sample the sea floor in key localities. Yet, sampling and imaging capabilities of the geoscience community could be greatly advanced, as follows:

- Sampling capabilities could include shallow drilling and coring systems.
- *In-situ* geochemical analyses could be harnessed to determine regional trends and guide sampling priorities.
- Sampling by AUV should be developed.
- Pressure housing for hadal science needs to be developed.
- Multivehicle operations can be more fully utilized.
- More automation would bring more efficiency to the sample recovery process.

4. *The power of data and cross-organization connections*

The previously discussed three technological approaches need to balance with a strategy for collaboration with other science and technology organizations and agencies, and a plan for outreach and public engagement. All previously mentioned science and technology advances come with enormous implications for data management and how such data can connect scientists with each other, as well as national and international organizations/ agencies; and, in a digestible form, the general public. Future efforts should focus on the following:

- Developing seamless integrated data repositories
- Forums for scientists to work with technologists (see previous discussion)
- Exploration of machine learning for sampling and analysis, including artificial intelligence
- Avenues for data integration to be used as a messaging avenue and hypothesis generator
- Bringing a focus on software-based tools (e.g., topcoder)
- Novel approaches to deal with the interpretation of video data in particular, such as through gaming and visualization
- Increased availability of telepresence
- Use of technology advances to connect with other agencies (U.S. Navy, National Aeronautics and Space Administration [NASA], Energy Industry)

5. *Connecting to society*

Geoscience research, and marine research in particular, touches more and more on issues of direct relevance to society. A few topical areas include the following:

- Understanding the carbon cycle, including applications by way of Carbon-Capture-and-Storage ("Carbon and Geologic System in the 21st Century.... and beyond!")
- Linkages between volcanism and life
- Relationship between ridge activity and global climate change
- Geohazards generated within the marine realm (e.g., tsunamis, convergent margin earthquakes, landslides)
- Wealth within the oceans: energy and living/nonliving resources
- National security issues that involve the ocean's floor
- The unknown planet that we live on..."Mission to Planet Earth"
- Link to Earth's oceans and those oceans that may be present on other worlds under ice, along with possible past oceans (e.g., Mars)
- Aquifers in the ocean: crustal reservoirs of fluids
- Life connected from the hydrosphere into the mantle by way of magmatism and serpentinization
- Ocean archive being built along marginal shelves
- Plates connected and interacting on a global scale

The Geology break-out group also identified several areas where our science and technology efforts could connect with society in a more impactful way, as follows:

- Messaging through climate change issues and resources (both energy and food supply)
- Connecting scientists and engineers and technologists
- Champion exploring based work to excite the public
- Strengthening our education and public outreach
- Developing program-wide EPO office/community-wide services to professionalize outreach
- Not being afraid of political advocacy—support for lobbying organizations (i.e., Ocean Leadership)
- Leveraging the inspirational aspects of ocean sciences in Science, Technology, Engineering, and Math (STEM) efforts

In short: "This stuff is cool, realize that, use it."

PHYSICAL OCEANOGRAPHY

By

Daniela D'Iorio and Karen Bemis

Overview

To date, most physical oceanography studies using deep submergence facilities have been in the context of multidisciplinary studies, often related to mid-oceanic ridges. For example, deep submergence vehicles have been used to quantify physical properties of deep-sea hydrothermal plumes to understand transport and fluxes of heat from both high-temperature-focused flows and low-temperature-diffuse flow. Novel instrumentation development (acoustic, video, specialized flow, and temperature sensors, etc.) together with deep submergence facilities have allowed scientists to characterize hydrothermal plumes and diffuse flow on a variety of scales from the centimeter (cm)-to-meter (m) scales to the 10 m-to-1,000 m scales of local geology to the 1,000+m scales of the open ocean (D'Iorio *et al.,* 2012, Bemis *et al.,* 2012, Kelley *et al.*, 2014). On the smaller scales, these studies focused on quantifying the hydrothermal input into the ocean (Barreyre *et al.,* 2012, Mittelstaedt *et al.,* 2012, Hautala *et al.,* 2012) or how the physical environment influences biology (Bates *et al.,* 2013, Lee *et al.,* 2015). On the larger scales, the studies have focused on how the ridges (and related hydrothermal output) influenced ocean processes (Thomson *et al.,* 2005, 2009, Adams *et al.,* 2011, Resing *et al.,* 2015, Fitzsimmons *et al.,* 2017) or on collecting baseline data of the spatial and temporal variability for events of significance to be documented (Baker *et al.,* 2012, Baumgartner *et al.,* 2015). Water column data of currents and ocean density, together with high-resolution bathymetry, has also been helpful for the development of realistic and idealistic hydrodynamic models of deep-sea processes (Thomson *et al.,* 2009; Lavelle *et al.,* 2001, 2003, 2013).

Physical oceanographers are now beginning to recognize and exploit the potential uses for deep submergence vehicles characterizing deep-ocean and bottom-boundary layer processes. The ocean is a very active place over a range of spatial and temporal studies; as a result, ideal surveys would repeatedly cover wide areas at high-spatial resolutions in short time frames. Existing and emerging deep submergence technologies (e.g., deep gliders, autonomous underwater vehicles [AUVs]) have the potential to increase coverage, resolution, and sampling rates over conventional methods (e.g., Conductivity, Temperature, and Depth [CTD] tow-yos with simultaneous current profiles). The physical movement of water masses in three dimensions, together with its physical, chemical, and biological concentrations, are needed for interdisciplinary studies.

Overarching Goals

Three areas of unknowns stand out as particularly critical issues for physical oceanography and related interdisciplinary science, as follows:

1. Turbulence, and its effects on mixing and ocean dynamics, is an important issue at small-scales, regardless of location or process. Studies of such diverse

subjects as the effect of tidal currents on biota at hydrothermal vents or breaking internal waves over rough topography depend critically on understanding turbulent processes and how such diverse subjects affect temporal and spatial variability.

2. Fluxes into and out of the ocean are critical to understanding the global ocean balance. Fluxes are also important for inferring properties of their sources (e.g., the magmatic heat source at hydrothermal vents and the resulting flux of heat and chemicals carried by hydrothermal discharge).
3. The totality of the ocean is a big place and coverage, especially in the deep ocean, has been limited; but a number of programs have started to address this limitation (e.g., GEOTRACES).

Near-term recommendations

In the near term, we recommend focusing on several developments that are "ripe" for exploitation. Some of these recommendations focus on interdisciplinary support (i.e., important physical variables about or around hydrothermal systems and exploration tools for seeps, vents, etc.). Others focus on emerging technology that can potentially increase coverage (resolution) of measurements in the ocean.

1. **Support the development of a suite of effective, accurate, and available flowmeters suitable for operation in the deep ocean at fine, spatial scales to monitor vertical upwelling and horizontal advective flows.** The development of deep-ocean flowmeters suitable for measuring the three-dimensional (3D) flow field at high-spatial and temporal resolution within high-temperature hydrothermal flows or buoyantly driven hydrocarbon seeps is critical for the full understanding of these systems (both in determining source character and contributions to the ocean). A number of different instruments have been developed to address this limitation in our capability (Germanovich *et al.,* 2015, Mittelsteadt *et al.,* 2014, Xu *et al.,* 2014, McNutt *et al.,* 2012), but community agreement on accuracy and utility is lacking. *Two particular actions seem likely to improve the status quo: (a) a focused workshop to achieve community agreement and involvement, and (b) funding (reviewer) support for instrument development beyond initial prototypes (e.g., for field testing and ground truthing).*
2. **Encourage development of "gliders" and related communications and networking for distributed spatial coverage of the mid-to-deep oceans.** Many of the developments that have enabled under-ice glider use (e.g., local and drifting broadband sources to support underwater global positioning system [GPS] at 100-kilometers [km] to > 400-km ranges) suggest the potential for a glider or glider-like vehicle to explore broad areas of the mid-to-deep ocean in complement with the fine-resolution surveys by AUVs. Tracking the ocean-wide transport of hydrothermally sourced iron is one potential application area (Hatta *et al.,* 2015, Jeandals *et al.*, 2015). Combining gliders with networking and communications developments will enhance their effective coverage. Key efforts

involve the standardizing of communications like acoustic communications (encoding is currently proprietary) and the ability to effectively network a fleet of gliders or other sensor platforms.

3. **Develop event response, adaptive sampling strategies, and related tools**. For example, a resident AUV docked at Axial could both perform daily sampling surveys as well as investigate any usual signals received from observatory sensors, or gliders could check in with a base station for changing instructions (Baker *et al.,* 2012). Elsewhere, the frequency of sampling could change with the rate of signal change; and could lead to vent thermistors increasing their sampling rates with rapid increases in temperature or gliders sampling more frequently in areas of high gradient. This development is more about how to use facilities and technologies that exist than creating new facilities (although that may be important). Algorithmic, strategic, and programmatic issues are key to effective adaptive sampling.
4. **Encourage development of exploratory tools to locate vents, seeps, bubble plumes, and similar targets.** In the near term, increased use of acoustics on AUVs and recent developments in processing acoustic data suggest that now is the time to modify stationary acoustic imaging and detection techniques for use as exploratory tools. For example, the verified ability to image hydrothermal vent plumes (Bemis *et al.,* 2015) can potentially be applied to detect plumes while doing high-resolution mapping by capturing backscatter data throughout the water column. Similar techniques can detect seeps and bubble plumes (see Weber *et al.,* 2014). Furthermore, with the advent of cabled and noncabled underwater observatories, the necessary timing capabilities needed for effective acoustic tomography are becoming available.

Long-term recommendations

In the long term, there are many areas and directions that will support physical oceanography in the use of deep submergence facilities. The following short paragraphs note key areas of potential and critical innovation:

- Data integration, assimilation, and related modeling are key issues. As deep submergence capabilities begin to provide the underlying data to characterize the deep-ocean and bottom (~300-m above bottom) boundary layer, suitable deep-ocean models will be needed to assimilate the data and build understanding. At present, few such high-resolution models for the deep ocean are available.
- Another key issue is the development and efficient use of tools, such as smart releasable sensors or trackable released targets to build an understanding of a variety of dispersal processes. One particular example is tracking the Fe in plumes as it disperses into and across oceans (Hatta *et al.,* 2015).
- The facility to use sensors and vehicles as operational tools will become increasingly critical with the development of more such tools and increasing

desire to use such tools. A facility supporting the use of gliders, especially in the context of multiple glider programs, are a particular need.

- Finally, megameter underwater navigation capability (long baseline [LBL] is only up to 10 km) would support the use of sensors, trackable targets, and vehicles (e.g., gliders and AUVs) across the wide expanses of the deep ocean.

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APPENDICES

Appendix I: Remotely Operated Vehicles

By John Wiltshire and Peter Girguis

Introduction: A remotely operated vehicle (ROV) is a tethered underwater robotic vehicle generally controlled by an operator or operators from a surface vessel. ROVs are one of several deep submergence platforms, including submersibles, autonomous underwater vehicles, gliders, deep-sea observatories, and floating platforms used by scientists and engineers to further the progress of marine science and exploration. In some senses, they are an intermediate development between human occupied submersibles (HOVs), which came first, and fully capable autonomous underwater vehicles (AUVs) that are now the focus of the most significant new innovation. There are presently between 700 and 800 ROVs in operation worldwide for industrial and scientific use (not including smaller ROVs for hobby and recreational use). ROVs are classified into three main classes: Class I—those for observation only, Class II—those for observation with a payload option (most science ROVs), and Class III—work class ROVs. In 2014, there were 561 work class ROVs, largely in use in the offshore oil industry.

History: The history of ROVs goes back to the 1960s, and an effort to increase safety and reduce costs over the then-prominent HOVs and deep-manned, compressed–air, commercial-diving operations that were heavily used in the offshore oil industry at the time. While originally developed for the military, ROV technology was further refined in the early 1970s when private firms moved beyond highly specialized military applications in response to the needs of the oil industry to go ever farther offshore. ROVs were the significant factor that enabled the offshore industry to also move beyond diver depth range. ROVs continue to be used reliably in the offshore industry, and innovations in operational techniques and tool packages are expanding the scope of tasks these vehicles can perform. ROV manufacturing has been a highly competitive business. There are presently more than a dozen major companies worldwide building and supplying ROVs largely to offshore industry. Additionally, in excess of a hundred companies supply specialized components to research groups and individual ROV builders. An example of a well-known component supplier would be Schilling Robotics, who supply a high percentage of new ROV manipulators.

Design: The design of ROVs traditionally splits into two groups: 1) free swimming ROVs, which drag an attached neutrally buoyant cable and; 2) use of a tether management system (TMS) at the end of a load-bearing, usually heavily armored umbilical cable. The umbilical cable provides strength as well as carries electrical conductors and fiber optics. The ROV is attached to the TMS by a neutrally buoyant tether of 50 to several 100 meters in length. Power is sent down the tether to the ROV from the TMS. Video and data signals originating at the ROV are sent back through the tether to the TMS and then up the main umbilical cable to the operators onboard the surface vessel. The descending high-voltage power is distributed between the ROV and TMS. The TMS is usually either configured as a “top hat” or “garage.” A garage is a cage-like device in which the ROV is lowered to the appropriate depth and then swims out. The cage protects the ROV in the wave zone as well as in complex work situations—often with a lot of submerged piping, such as an oil rig. The ROV can be steered into position near a target of interest and unlatched to swim out for its investigation. The alternate configuration is a top hat in which the TMS sits atop the ROV and both descend as one package until the ROV disconnects in the target zone and then swims off. A variation of this system is a "two body" system where the two components are not locked together but launched separately. Typical tether lengths are no more than a few hundred meters to prevent the ROV from getting wrapped around the tether or snagging the tether on a bottom projection. In general, a top hat configuration is used for larger and deeper diving ROVs.

Power: Power for the ROV is electrical, generated on the support ship, and sent down the umbilical at high voltage. On the ROV, the high-voltage power typically is used to power a large electrical motor that in turn drives a hydraulic pump. On larger ROVs, the hydraulic dive is then used for thrusters, manipulators, and other power equipment. Larger work class ROVs might have power in the range of 200 horsepower (hp). Smaller exploration style ROV's powered in the 5-hp to 50-hp range (light- and medium-weight ROVs) often use electrical power to run a series of thrusters driven by brushless direct-current (DC) motors. Heavy work-class ROV systems carry much larger payloads and tools, weigh in excess of 3,000 kilograms (km), and are fitted with hydraulic thrusters. Four to six thrusters are typically arranged around the ROV in several orientations and protected by a shroud to increase thrust.

Notably, a few more recent ROVs carry batteries like an HOV or AUV, and have a hybrid mode in which they can disconnect the tether and swim freely like an AUV. In these hybrid systems, the absence of needing electrical power to be delivered through the tether results in a drastically small and lighter tether that simply harbors the fiber optics used to control the vehicle from the surface vessel.

Lights and Cameras: ROVs typically carry an extensive range of underwater lights and cameras. The lights are set to optimize the effectiveness of high-definition (HD) cameras. Currently, the favored lights are light-emitting diode (LED)-based, which have low-power requirements and produce strong luminosity (often collectively more than 250,000 lumens from a dozen or more lights). Video cameras are moving toward HD as well as 4K (or ultra-long holdtime Dewer [ULHD]); yet, digital still cameras continue to provide the highest quality image to guide the ROV and allow effective sampling by the manipulators as well as to document finds. Cameras may be mounted at several positions on the ROV and on the tether management system component. Often organisms are identified visually by remote scientists who are tapping into the ROV camera feed through a telepresence option. For this reason, crystal clear video is of the highest importance, because it will be used to control mission outcomes.

Manipulators: Most ROVs—with the exception of the simplest Class I observation ROVs—carry one or two manipulators. Advanced manipulators are fully joystick controlled and have a feedback mechanism to give a skilled operator a sense of the strength of the grip. With six degrees of freedom, these manipulators can be as dexterous as a human hand. In all cases, they can pull and turn handles, and deploy equipment and experiments.

Advantages: ROVs offer several advantages over other marine exploration systems. ROVs can allow a larger number of people to be part of the scientific and exploration activities, without anyone being in a position of higher risk caused by construction dangers or equipment failure inherent in using an HOV underwater. ROVs offer essentially unlimited bottom-time subject only to operator fatigue and vehicle maintenance. Heavy equipment can be run on the bottom not subject to the vagaries and limitations of battery power. With a strong umbilical, the lift potential back to the surface is considerable.

Limitations: The key disadvantage of an ROV is being tethered to a very costly research vessel typically prohibited from other operations when the ROV is in the water (though the surface vessels can deploy autonomous craft and can take surface samples, etc.). The cables supporting the ROV operation can become snagged on the bottom (i.e., coral head or rough overhang) or entangle on themselves, which limits the ROV in entering challenging and unknown bottom terrain. Moreover, the ROV provides a virtual experience, watching the exploration on TV, rather than the tactile sense of actually being there as in an HOV. ROVs are an extremely valuable tool but are basically a vertically operating system that requires constant surface support with high and unavoidable attendant costs.

Examples of Science-focused ROVs

Woods Hole Oceanographic Institution (WHOI) Remotely Operated Vehicle (ROV) *Jason II*. *Jason*, the best-known U.S. ROV, was designed by the WHOI's Deep Submergence Laboratory and became operational in 1988 for scientific investigation of the deep ocean and seafloor. It has completed more than 750 dives. Typical dives are 1 to 2 days, but it has worked up to 5 days. It is a two-body ROV system; with *Medea* serving as a tether management system that decouples *Jason* from surface motion and also has its own cameras and mapping capability. Both *Medea* and *Jason* are designed to operate at a maximum depth of 6,500 meters (m). They can be operated from a variety of vessels. *Medea* is connected to the surface ship by a 0.68-inch armored cable with 3 fibers and 3 electrical conductors. *Jason* is connected to *Medea* by a neutrally buoyant tether 50 m in length. *Jason* is designed for detailed survey and sampling tasks that require a high degree of maneuverability. It weighs 4,082 kilograms

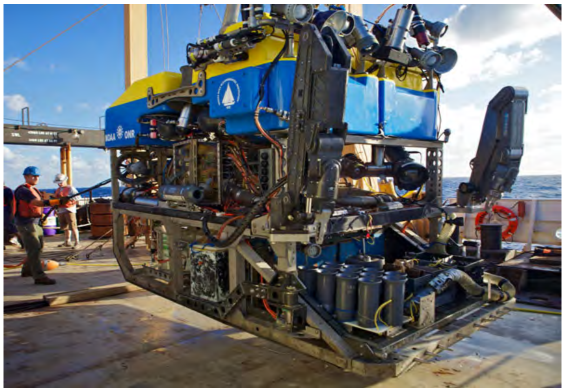


Figure 4: The Remotely operated vehicle JASON2 prepares for launch. © Woods Hole Oceanographic Institution

(kg). This system has been designed to be a reliable ROV “workhorse” for the scientific community.

Monterey Bay Aquarium Research Institute ROV *Ventana* and ROV *Doc Ricketts:* The Monterey Bay Aquarium Research Institute (MBARI), an early ROV adopter, has two ROVs—*Ventana* and *Doc Ricketts*. These ROVs are equipped with two manipulator arms for grabbing, moving, or placing items in the sea. High-definition video and still cameras on the vehicles record images of sea life, geology, and experiments. As with all exploration vehicles, the two ROVs carry a variety of sampling equipment and sensors for collecting information about the ocean and seafloor. They have several interchangeable tool sleds—metal frames bolted underneath the main body of the ROV—outfitted for various scientific missions. By putting most of the discipline-specific tools on the tool sled, it is easy to switch the tools out between tasks, such as a biology dive to a geology dive. This step minimizes the turnaround time between dives. For instance, scientists studying the gelatinous animals in the midwater may use a suction sampler, which is a kind of “slurp gun” that sucks animals into a plastic canister to bring them back to shore; while scientists studying the ocean floor might use push cores—foot-long clear plastic tubes— pushed into the seafloor to pull out samples of the sediment for further study. MBARI offers a very wide array of ROV-proven science tools.

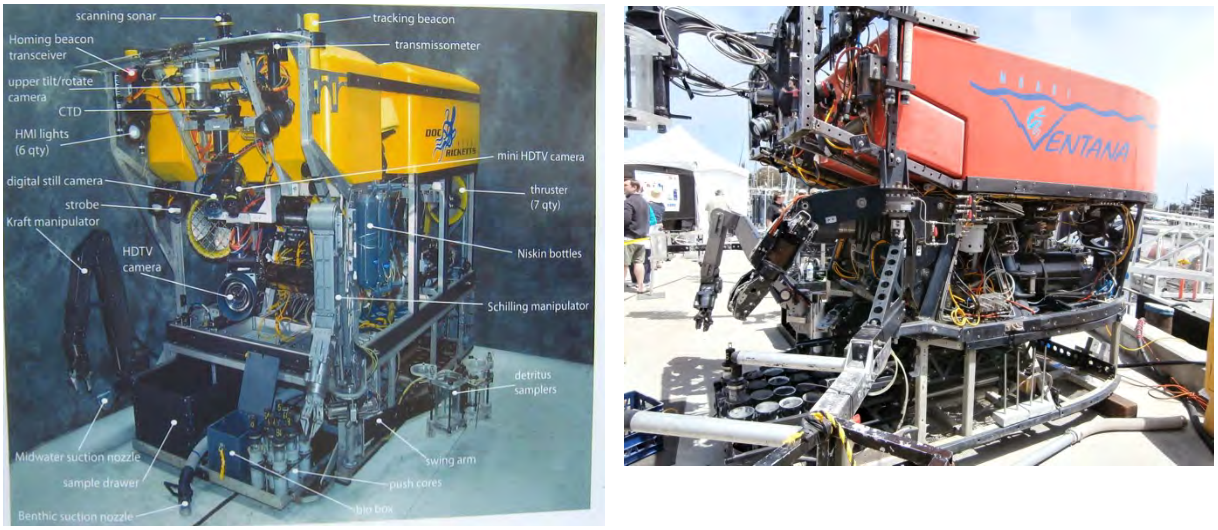


Figure 5: Left The ROV *Doc Ricketts* is a commercial ROV owned and specially modified by the Monterey Bay Aquarium Research Institute (MBARI) for use in midwater and benthic research; (right) the ROV *Ventana* is another MBARI ROV that works in the Monterey Canyon. © MBARI.

Ocean Exploration Trust ROV *Argus* and ROV *Hercules:* The Ocean Exploration Trust (OET) is a nonprofit organization founded in 2008 by Dr. Robert Ballard. Its overall goal is to engage in pure ocean exploration, as well as engaging educators and students of all ages in ocean exploration, thereby offering them hands-on experience in ocean exploration, research, and communications. The OET owns and operates two

ROVS: the *Argus* and *Hercules*. Typically, deployed as a two-body system, the ROVS *Argus* and *Hercules* make a potent combination for deep-sea exploration. The ROV *Argus* is equipped with high-powered floodlights and a high-definition (HD) camera with a robust optical zoom that enables it to take “bird’s eye” views of the science operations being conducted by the ROV *Hercules*. Also, the ROV *Hercules* is equipped with an equally nice complement of lights and cameras, as well as scientific sampling equipment. In the interest of advancing the vehicles’ capabilities in ocean exploration, the OET is continuing to acquire and incorporate a wider range of tools and sensors to move ocean exploration beyond the acquisition of maps and images. These ROVs are dedicated to service on board the Exploration Vessel *Nautilus*, which is equipped with a satellite system that frequently broadcasts standard- and HD video from their seafloor exploration to students, educators, policy makers, and scientists around the world.

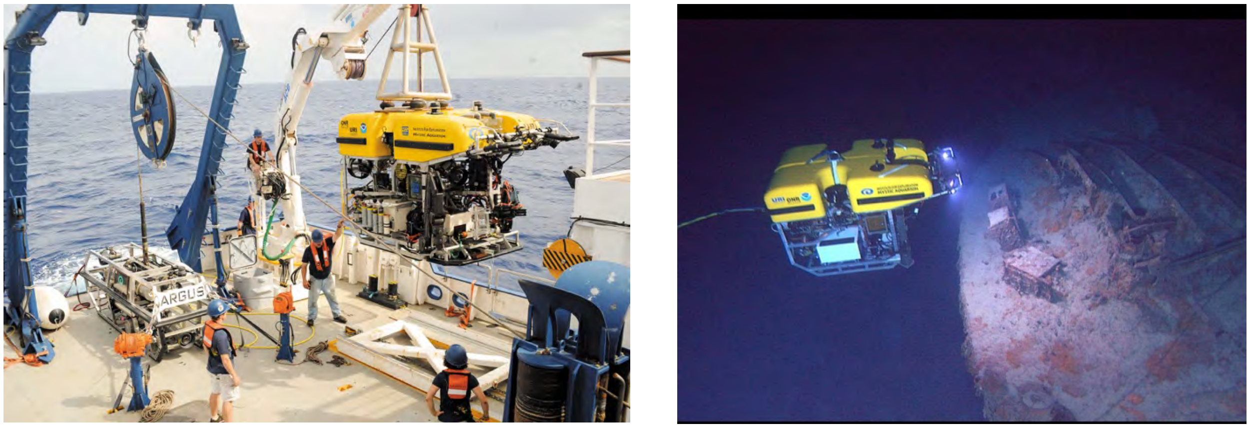


Figure 6: (left) The ROVs *Hercules* and *Argus* on the deck of the Exploration Vessel *Nautilus* as they prepare to dive; (right) the ROV *Hercules* is well suited for both archaeological and scientific missions of exploration, and also streams HD video to thousands of people worldwide, free of charge. © Ocean Exploration Trust.

National Oceanic and Atmospheric Administration Ocean Exploration Program’s ROVs *“Seirios”* and *“Deep Discoverer* 2” (D2): While the Exploration/Vessel (E/V) *“Nautilus”* has pioneered the use of telepresence for exploration, outreach, and charter science expedition, the National Oceanic and Atmospheric Administration’s (NOAA) ship the *“Okeanos Explorer*” is the only U.S. research ship solely dedicated to scientific ocean exploration. The ability to involve large numbers of scientists, through telepresence-enabled centers, is a major innovation in the ROV world. A telepresence-enabled platform, *“Okeanos Explorer*” uses satellite technology to transmit data and video in real-time from the ship and ROVs working at depth to a shore-based hub in which the video is transmitted in HD out on Internet 2 to a variety of receiving stations onshore that include a number of Exploration Command Centers located around the country. The University of Rhode Island's Inner Space Center receives the HD Internet 2 video feed and makes a lower-resolution version available by way of standard internet. Access to the video and a suite of internet-based collaboration and communication tools enables scientists located on shore to join the operation in real-time.

To facilitate telepresence-enabled research, the *Okeanos Explorer* hosts two ROVS: the *Seirios* and the *D2*. These ROVs have similar capacities and roles as the ROV *Argus* and *Hercules*, though the ROV *D2* is a substantially larger vehicle. Like the *Argus* and *Hercules*, both vehicles are well-equipped with high-intensity lights and cutting-edge camera systems.

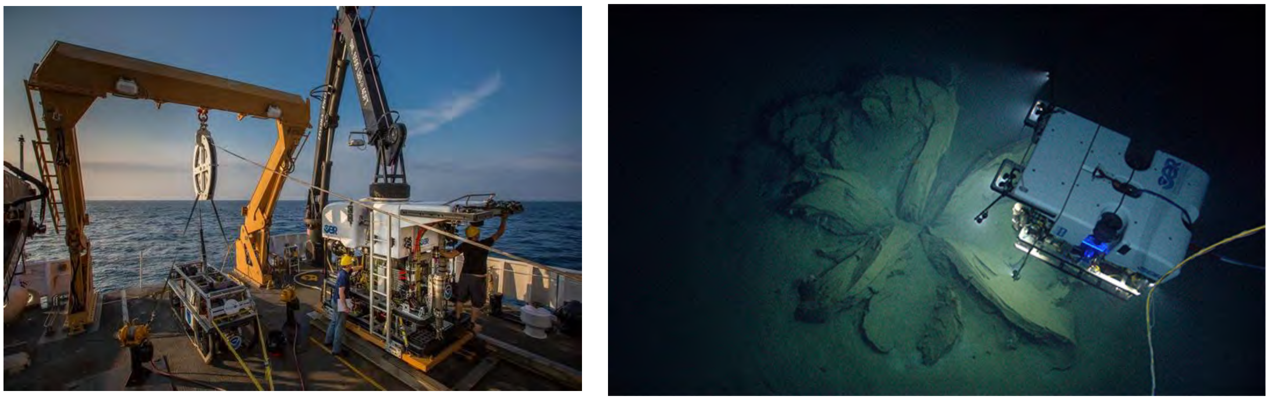


Figure 7: (left) The ROVs *Deep Discoverer 2* (D2) and *Seirios* on the deck of the Exploration Vessel *Okeanos Explorer* as they prepare to dive; (right) the ROV *D2* is designed to capture HD video and high-resolution stillframe imagery for scientific exploration with little or no material sampling. The D2 also streams HD video live, free of charge. © National Oceanic and Atmospheric Administration.

WHOI Hybrid ROV *Nereus:* Advances in battery technology raised the prospect that a vehicle with ROV-like capabilities could be built with an onboard power pack, eliminating the need for a heavy armored cable and the substantial infrastructure needed to deploy and recover this cable. The hybrid ROV (HROV) *Nereus* was a vehicle capable of operating in one of two complementary modes: 1) freely swimming as an autonomous underwater vehicle (AUV) to survey large areas of the depths, map the seafloor, and give scientists a broad overview; and 2) an ROV tethered to the ship using a microthin, fiber-optic cable and controlled by the pilots onboard. Through this tether, *Nereus* transmitted high-quality, real-time video images and received commands from skilled pilots on the ship to collect samples or conduct experiments with a manipulator arm. While the *Nereus'* abilities to function as both an AUV and ROV had many advantages, the system did have

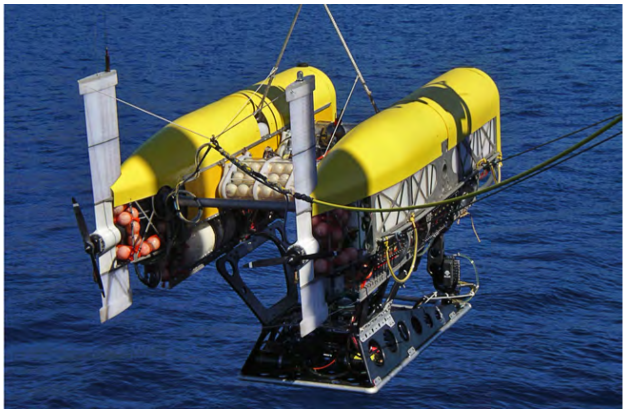


Figure 8: The hybrid ROV *Nereus* was a revolutionary vehicle design that was capable of full ocean depth dives by combining the best attributes of an AUV and an ROV. © WHOI

its limitations in sample capacity and manipulator capabilities. Nevertheless, the onboard battery packs, the lighter tether—along with many other advances, such as lighter high-pressure housings—enabled engineers to design the HROV *Nereus* to be capable of working at full ocean depths (ca 11 kilometers [km]). The HROV *Nereus* did eventually work near its ultimate limit, but much of its time was spent in shallower environs, because its smaller infrastructure "footprint" allowed it to be deployed off relatively smaller vessels than was needed for the ROV *Jason* and comparable systems. Because of technical issues, the HROV *Nereus* was lost in May 2014 during an expedition to the Kermadec Trench.

Schmidt Ocean Institute *ROV "SUBastian"*: The Schmidt Ocean Institute vehicle development path is expected to include the design and construction of three ROVs—tentatively delivering one vehicle per year starting in 2016, and ultimately resulting in the creation of a unique robotic fleet. Each subsequent HROV design will incorporate "lessons learned" from the development and testing of preceding vehicles and will take advantage of the latest technologies, thereby creating more capable, efficient, and reliable vehicles. The first vehicle will be rated for 4,500 m, followed by a 6,000-m AUV, 7,000-m HROV, and possibly, an 11-km HROV. The hybrid nature of the vehicles means that at an appropriate time or depth the tether can be disconnected allowing the ROV vehicle to effectively become an AUV. Each new vehicle will be equipped with a suite of sensors and equipment to provide it with the capability to collect a broad array of data and samples.

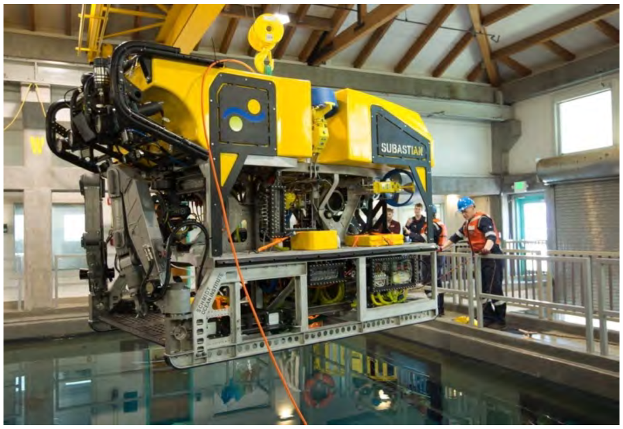


Figure 9: The ROV *SUBastian* is owned and operated by the Schmidt Ocean Institute, and is one of the newest research ROVs in the U.S., employing many of the latest imaging, propulsion, and sampling technologies. © Schmidt Ocean Institute

WHOI *Nereid* under-ice HROV*:* The HROV *Nereid* is an "under-ice" vehicle built to travel laterally—up to 40 km (i.e., 25 miles) without the encumbrance of a traditional ROV tether. Like the HROV *Nereus*, the *Nereid* receives control signals and transmits data back to the operators through a disposable fiber-optic tether. Accordingly, the *Nereid* also carries its power onboard as battery packs. The *Nereid* is capable of hosting a suite of acoustic, chemical, and biological sensors for investigating under-ice habitats. The *Nereid* is rated to 2,000 m and has been successfully used in several trips to the polar regions.

Figure 10: The hybrid ROV *Nereid* is specially designed for use under ice, enabling investigators to conduct experiments in regions inaccessible to traditional ROVs and HOVs. © WHOI.

Other platforms: A wide range of institutions is now operating ROVs. Deep Ocean Exploration and Research (DOER) has produced a recent series of relatively low-cost, deepwater ROVs, including one rated to 6,000 m for the University of Hawaii and now stationed in the central Pacific in Honolulu, Hawaii. With this proliferation of new available ROVs, distant shipping of the formerly few available vehicles, such as *Jason,* may not now be necessary with good available options close to many exploration sites.

The future of ROVs: The future of ROVs is moving toward more capable, easier-to-control vehicles with a greater suite of available tools; deeper depths; and more autonomy. There will be a shift in development interest from straight ROVs to AUVs or, more likely, HROVs. Telepresence has proved itself a successful innovation and is certain to expand with more exploration command centers and greater participation in ongoing expeditions. Cost control will be a major factor in the commercial sector with a movement toward smaller ROVs being used off smaller, cheaper vessels whenever possible. While large ROVs have found a niche in the offshore oil and gas industries, and the communication industry for underwater manipulation, cable burial, and inspection tasks, they will be under severe pressure to reduce costs as these industries suffer economic stress. ROVs will continue as an extremely valuable component of the suite of tools thereby giving us full access to the ocean.

Appendix II: Human Occupied Vehicles (HOVs)

By Bruce Strickrott

Introduction: A human occupied vehicle (HOV) is a human-occupied, untethered submersible vehicle that provides a first-person, real-time platform for observation and interaction with underwater environments. HOVs allow the occupants to experience an unparalleled view of the marine habitat and offer an excellent means to directly perform research, experimentation and exploration. Many current scientific HOV platforms are capable of diving very deep ocean depths and are frequently referred to as DSVs (Deep Submergence Vehicles). Typically, HOVs carry one Pilot and two observers on a dive of approximately 8 to 12 hours in duration. HOV operations include a surface support vessel that provides at-sea facilities for submersible maintenance and upkeep and accommodations for the submersible crew and scientific participants. Typically, the support ship is an oceanographic research platform with many advanced scientific capabilities. Support ships provide additional research possibilities during periods when the DSV is on deck for daily maintenance and upkeep, often enabling 24-hour research operations. HOVs are particularly valuable when utilized collaboratively with other submersible vehicles, in particular Autonomous Underwater Vehicles (AUVs) and Remotely Operated Vehicles (ROVs).

History: The history of HOVs began in the 1600’s with primitive examples of human-occupied submersibles (Cornelius Drebbel). Since that time there have been many advances in HOV technology, primarily with the advent of military submarines in the late 1800’s and the 1900’s. The use of HOVs for research and exploration began in earnest in the 1960s. The Bathyscaphe “*Trieste*”, built and designed by European engineers, was one of the first deep diving human-occupied submersibles. *Trieste* is famous for completing the first dive to 11,000 meters, the Challenger Deep, in 1960. However, although *Trieste* could dive to the deepest known point in the ocean, it had a number of shortcoming. It was a very large vehicle, difficult to operate, and had limited maneuverability. Development of more capable HOVs for science use began in the 1960s and has continued through to the present day. The majority of the current deep-sea research HOVs are owned and operated by various nations, often affiliated with their respective navies. Additionally, a number of independently owned and operated human-occupied vehicles are currently operating and provide some measure of access for scientific research and exploration.

Design: Historically, HOV design developments paved the way for the development of other deep water vehicle technologies (ROVs and AUVs). Modern day HOVs often incorporate advanced technologies developed for ROVs and AUVs. Cross platform compatibility often improves the capabilities of the three classes of vehicles. The designs of deeper diving HOVs for scientific use have a number of similar characteristics. Typically, a moderately sized personnel sphere is mounted to an external frame, often manufactured of titanium or other metals. Together, they provide the primary mounting points for the vehicle’s principal systems and components.

The personnel sphere defines the human occupied space and typically may contain one or more acrylic viewports for use by the pilot and observers. Viewports provide the occupants multiple positions for direct observation of the external environment. Historically, HOV personnel spheres have been manufactured of metallic alloys (titanium or steel). A number of shallower diving HOVs utilize full acrylic personnel spheres or are of hybrid hull designs that incorporate larger hemispherical viewports mounted in unique hull shapes of metal alloy or composite materials. Specially shaped syntactic foam blocks provide principal fixed buoyancy for the vehicle. Air and water ballasting systems allow the pilot to adjust the HOV's buoyancy to effect descent, ascent and mid-water or bottom operations. HOVs typically operate at or near neutral buoyancy during bottom operations. Variable ballasting systems provide a means to add or remove mass to the vehicle to effect various mission profiles, compensate for the addition of scientific samples, adjust for desired positive or negative buoyancy. Multiple thrusters, mounted at various points on the frame, provide motive force for maneuvering. Advanced digital control systems allow the pilot to perform precise movement in three axes.

Modern HOVs include advanced state of the art computational equipment. Advanced USBL and DVL equipment combined with high tech navigational display systems provide very accurate, real time vehicle positional data. High bandwidth fiber optic computer data networks enable the use of complex sensors and samplers that have greatly improved scientific interactions with the sampling sites.

Power: HOVs rely on large high energy batteries as a primary source for power. Various battery chemistries and technologies are employed with most HOVs using lead acid (PbAc) or lithium ion polymer (LiPo). Batteries may be maintained at 1 atm in pressure tolerant housings, or designed in PBOF (pressure balanced oil filled) assemblies. Primary battery power (120 VDC or 240 VDC) is distributed for use in higher power components (lights, thrusters, pumps etc). 24 VDC and 12 VDC (nominal) are distributed for use in powering other vehicle systems and components (sensors, cameras, data systems, video equipment, etc.).

Lights and Cameras: Modern HOVs incorporate high intensity LED lighting, multiple HD and 4K video cameras, and high resolution digital still cameras, to enhance the occupants' ability to observe and record the external environment. The use of professional grade video display systems and digital storage equipment (in-hull and onboard the support vessel), have significantly improved HOVs' ability to collect and process digital imaging data. New camera technologies (low light, ultra-wide angle, 4K) have expanded the quality and type of imaging data available to the occupants. Specialized packaging (Pan and Tilt Zoom) with significantly reduced camera sizes, have enabled improved placement and usage of imaging equipment. HOVs now experience the high definition video and still imaging technologies used on ROVs.

High quality hand-held cameras, used to capture images through the submersible's viewports, provide additional imaging capabilities for the observers.

Manipulators: HOVs utilize hydraulic manipulators for sampling and interaction with the environment. Commercially available manipulators (Schilling, Kraft) are readily available and widely utilized on HOVs. Most HOVs carry two manipulators, each with 7-function capabilities.

Science Capabilities: Modern HOVs provide the scientific observer with the opportunity to perform direct observation, experimentation and sample collection during a dive. Science baskets provide significant science payloads of 400 pound or more. State of the art fiber optic data interfaces and high bandwidth computer networks allow the implementation of complex sensors and samplers for in-situ collection (mass spectrometers, raman spectrometers, laser scanners, multi-beam sonars, electro-chemical fluid samplers, etc.). Experienced HOV pilots provide many years of direct sampling and navigational experience to aid the scientific observers.

Advantages: HOVs provide many advantages for scientific research and exploration over other vehicle technologies. Foremost is the ability to provide the occupants with a first-person, direct observation, real time experience that greatly enhances the spatial understanding of deep sea environments. Human observation and presence often uncovers significant details and unique nuances of a particular habitat that may be very difficult to detect with other observational methods. Direct observation by the occupants, enables an opportunity to truly experience the complex terrain and varying ocean bottom topography.

HOVs are highly maneuverable and can act independently of the support vessel. Their unrestricted motion can easily maneuver in and around complex and challenging bottom structures. HOVs are capable of rapid, on-site decision making and response to local events. They are well suited to work in tandem with other vehicle technologies. Missions that include joint HOV/AUV operations, can greatly enhance the quality and quantity of data collected during a cruise. High resolution imaging and maps, generated by the AUV, are excellent when used in-hull during the human-occupied diving operations (navigational underlay, AUV identified sampling locations and site specific senor data).

Limitations: HOV missions are limited in duration due to human factors, available battery power, and life support capabilities. High energy battery technologies are reducing the impact of available power on dive duration. Advancing battery technologies are enabling much longer dive times. Most HOVs operate during daylight hours and recover in the evening, for routine upkeep and maintenance.

Although HOVs provide a first-person opportunity, the number of individuals that can participate during a dive, is limited by the size of the vehicle and personnel sphere. Typically, two scientific observers are present in-hull. However, recent developments in optical and acoustic data transmission technologies are enabling opportunities for observers onboard the support ship to directly participate in the human-occupied diving operations. Acoustic modems are capable of transmitting vehicle data and images to the surface at a reasonable rate. Optical modems have enabled high bandwidth video and data transmissions from the HOV allowing real-time participation by shipboard observers.

Future of HOVs: Human-occupied presence in the deep ocean, particularly for scientific investigation, will continue to play a critical role in human understanding of Earth's systems. Advanced HOVs will enable specialized sampling and experimentation capabilities that greatly enhance the value of direct human presence. Deeper diving submersibles will enable human exploration and investigation of remote hadal environments without the limitations of a cabled unmanned system.

The value of the experience of an actual visit to the seafloor, cannot be understated. Direct observation, unimpeded by the limitations of video imaging systems, enable the observer to employ the innate human ability to uniquely assess a situation. Direct presence allows the human mind to create intuitive connections between observed events and the spatial characteristics of a particular environment.

Throughout history humans have continuously utilized our ability to employ advanced technologies to enhance our capabilities. The human presence in the deep ocean, like human spaceflight, is a natural and necessary aspect of our continued growth as a curious and evolving species. HOVs will play a continued role in enabling theses experiences.

Examples of Science-focused HOVs: At present there are a number of deep diving HOVs operating around the world including *Alvin* (USA), *Pisces* IV & V (USA), *Triton* Sub and *Deep Rover* (USA), *Nautile* (France), *Shinkai* 6500 (Japan), *Jiaolong* (China) And *Mir 1 & 2* (Russia).

HOV *Alvin (USA):* The US Navy and the Woods Hole Oceanographic Institution (WHOI) developed the first modern scientific research submersible, DSV *Alvin* in 1964. *Alvin* operations have continued since original commissioning with periodic upgrades and overhaul periods every 5 years. WHOI operates *Alvin* as a part of the United States' National Deep Submergence Facility (NDSF), which also includes the ROV *Jason*, and AUV *Sentry*. *Alvin* carries three passengers (pilot, 2-observers) and provides them with five viewports, three 7-inch (178 mm) forward viewports and two 5-inch (127 mm) side viewports. Standard equipment includes one 7-function Schilling manipulator and one ISE manipulator, high intensity LED lighting, five HD video cameras, HD digital still cameras, 4-pan/tilt units, configurable science basket, digital scanning sonar, multi-beam sonar, CTD, magnetometer, fiber-optic hull penetrators, digital command and control system, digital science data system, variable ballast, trim system, and an acoustic data/image transmission system. In 2013, *Alvin* completed its most extensive upgrade including a new larger titanium hull and a suite of new components that provide future capability of diving to 6500 meters. The new systems and equipment greatly improve the vehicle's operational and scientific research capabilities.

Alvin was built by the Woods Hole Oceanographic Institution and is operated from its support vessel the RV *Atlantis*. As of January 2017, Alvin has completed 4872 dives with continued operations through 2019. *Alvin* is currently rated to 4500 meters and will complete final systems conversions to 6500 meters in 2020.

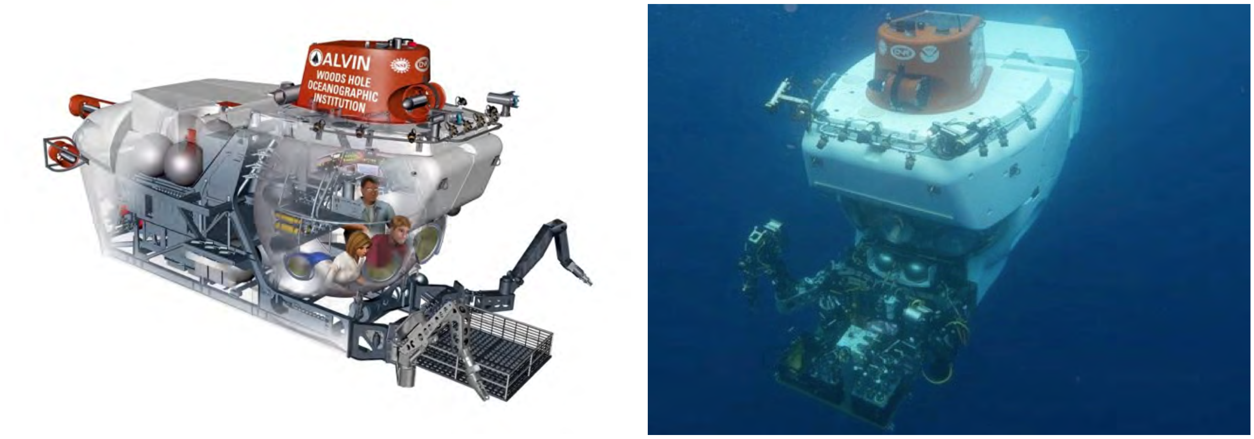


Figure 11: The HOV *Alvin* is the world's most accomplished submersible. The recent upgrade allows users to record HD video, run a suite of instruments, and –in the coming months- dive to 6500 meters. © WHOI

***Pisces IV* & *V* (USA):** The Hawaii Underwater Research Laboratory (HURL) has operated two three-person HOVs, *Pisces IV* and *V* for scientific diving and exploration since 1986. Both submersibles have a maximum operating depth of 2000 meters and offer observers direct observation through three 6-inch (152 mm) viewports.

Standard equipment includes HD video cameras, variable ballast system, dual Schilling Titan 7 manipulators, CTD, digital scanning sonar, HMI lighting, and a suite of science sampling devices. The *Pisces* submersibles are capable of simultaneous operations from HURL's Launch, Recovery and Transport (LRT) platform. *Pisces* submersibles were manufactured by Hyco International Hydrodynamics in Vancouver, British Columbia (CANADA). *Pisces VI* is currently being refurbished by a private team in Salinas, Kansas for eventual return to service.

***Triton* and *Deep Rover* (USA):** *Triton* and *Deep Rover* are two HOVs operated by the private, non-profit Dalio Ocean Initiative. Both are rated for diving to 1000 meters. *Triton* can carry three passengers (pilot, 2-observers) while *Deep Rover* can carry two persons (pilot, observer). Both have acrylic sphere construction providing wide fields of view. Standard equipment for both submersibles includes HD video cameras, still camera, system, manipulators, HMI lighting, sample basket. Both submersibles are operated off of the support ship *Alucia*.

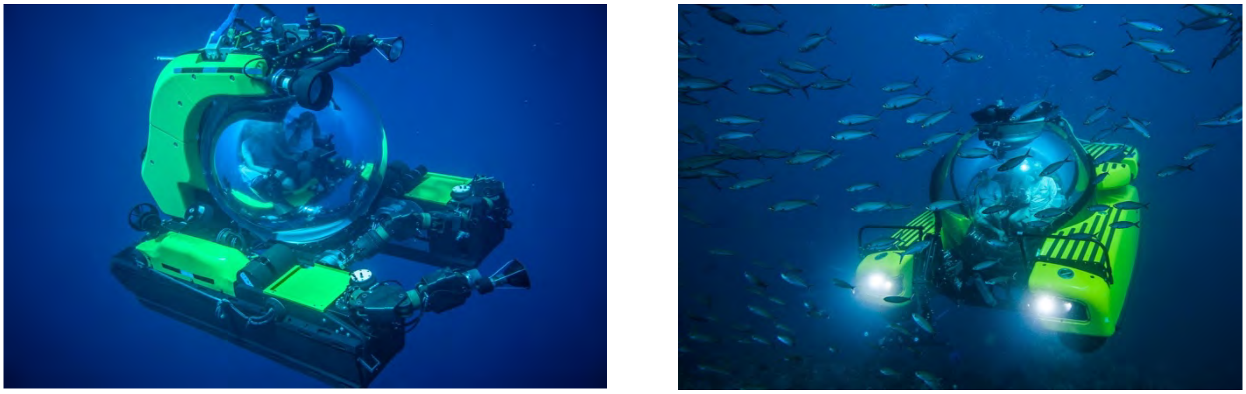


Figure 12: The HOVs *Triton* and *Deep Rover* are adapted from commercial vehicles, and are now capable of conducting a full suite of scientific measurements and samples.

***Mir 1 & 2* (RUSSIA):** *Mir 1* and *2* are deep diving HOVs capable of diving to 6000 meters. The two submersibles are owned by the PP Shirshov Institute for Oceanology although currently the two submersibles are leased for commercial use. *Mir 1* and *2* carry three persons each (pilot, 2-observers) and provide them with one 7 inch (200 mm) and two 4 inch (120 mm) viewports. Standard equipment includes video cameras, still camera, variable ballast and trim system, dual 7-function manipulators, CTD, observation sonar, HMI lighting. *Mir 1* & *2* are capable of joint operations. They were originally operated off of the support ship the *Akademik Keldish*. Both *Mirs* were manufactured by Rauma-Repola in Finland.

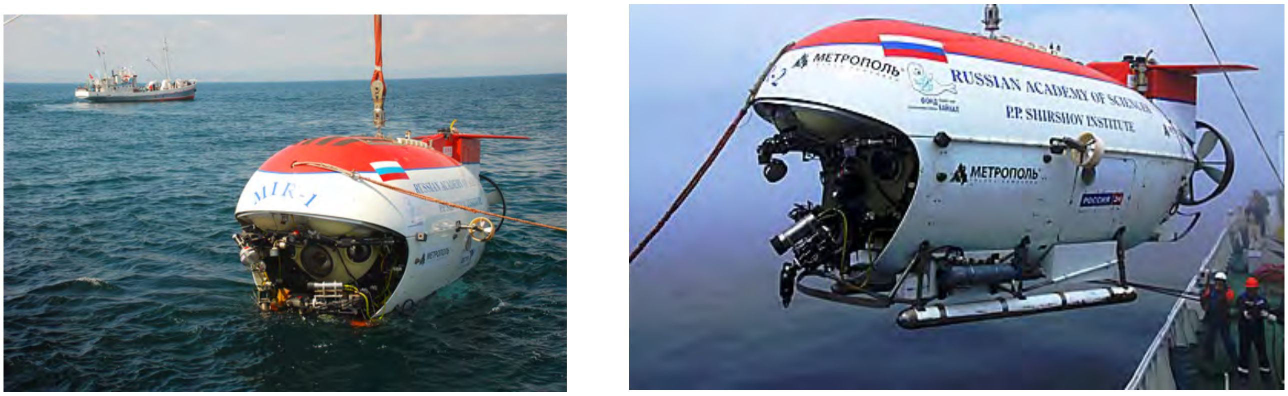


Figure 13: The HOVs *Mir-1* and *Mir-2* are deployed from the same surface vessel, allowing investigators the opportunity to have two vehicles on site. The *Mirs* have been used extensively in research, exploration, and film-making. © Russian Academy of Sciences.

***Nautile* (FRANCE):** The French Research Institute for Exploration of the Sea (IFREMER) operates the manned submersible *Nautile*, originally commissioned in 1984. *Nautile* carries three persons (pilot navigator and observer) and can reach depths of 6000 meters. Standard submersible equipment includes three 4.72 inch (120 mm) viewports, HD video cameras, variable ballast and trim system, dual manipulators, CTD, panoramic sonar, HMI lighting, retractable science basket. *Nautile* is operated from one of two support ships, the *Pourquoi Pas* or the *L'Atlante*.

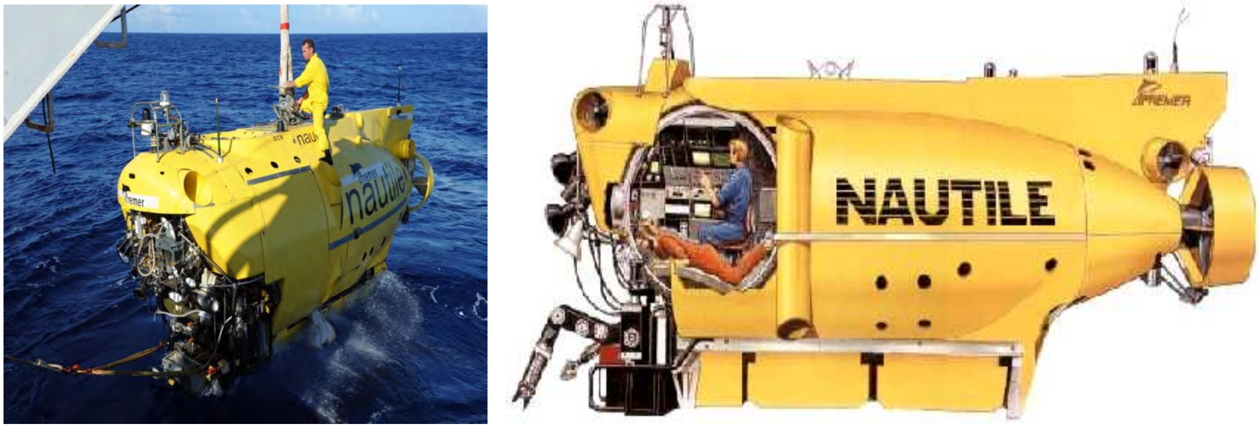


Figure 14: The HOV *Nautile* has done extensive work in the mid Atlantic, and has played a marked role in the discovery of new ecosystems. © IFREMER.

***Shinkai* 6500 (JAPAN):** The Japanese Agency for Marine-Earth Science and Technology (JAMSTEC) operates the human occupied submersible 6500. *Shinkai* was commissioned in 1991, and is capable of diving to 6500 meters and was the deepest diving science HOV until 2011. *Shinkai* carries three persons (pilot, co-pilot, observer) and provides them with three 5.51 inch (140 mm) viewports for direct observation. Standard equipment includes HD video cameras, still camera, variable ballast and trim system, dual 7-function manipulators, CTD, observation sonar, HMI lighting, 2 science baskets. *Shinkai* was manufactured by Mitsubishi Heavy Industries and is operated from its support vessel *Yokosuka*. Since original manufacture, *Shinkai* has been

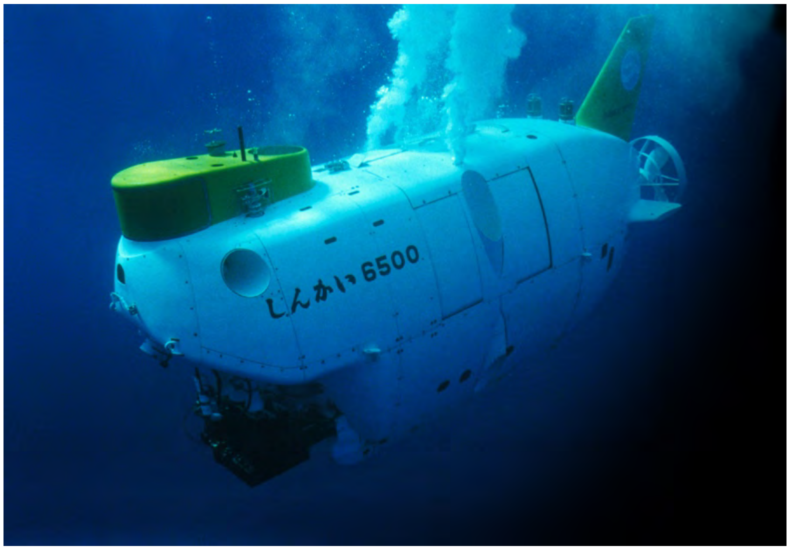


Figure 15: The HOV *Shinkai 6500* is one of the deeper diving HOVs, and continues to explore the deep ocean © JAMSTEC.

upgraded to replace the single, larger rear propeller assembly with additional separate fore/aft and lateral thrusters.

Jiaolong **(CHINA):** The *Jiaolong* is the deepest diving HOV in service, capable of diving to 7000 meters. *Jiaolong* is operated by the Chinese Oceanic Institution and has seen service since initial dives in 2011 and 2012. *Jiaolong* carries three persons (pilot, 2-observers) and provides them with one center 6-inch (152 mm) and two 4 inch (102 mm) port and starboard viewports. Standard equipment includes HD video cameras, still camera, variable ballast and trim system, dual 7-function manipulators, imaging sonar, HMI lighting, sample basket. The *Jiaolong* operates off the support ship *Xiangyanghong*.

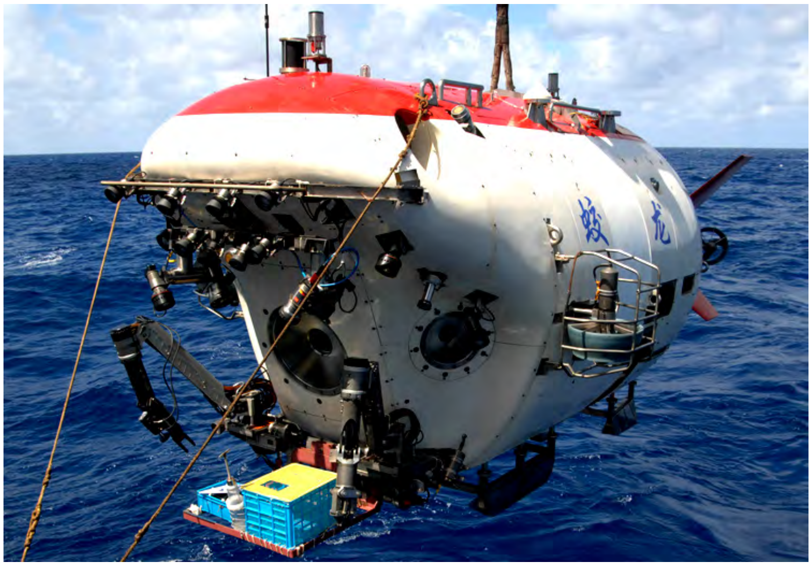


Figure 16: The HOV *Jiaolong* is the deepest diving HOV in service, and is equipped with a modern suite of tools for deep ocean exploration © Chinese Oceanic Institution.

Appendix III: Autonomous Underwater Vehicles

By Carl Kaiser

The Autonomous Underwater Vehicle *"Sentry":* The autonomous underwater vehicle (AUV) *Sentry is* designed for operations down to 6,000 meters (m) (19,685 feet) in depth, with a design that emphasizes extreme maneuverability, close-bottom following, large and innovative payloads, and rapid transit to and from the seafloor. The *Sentry* can be mobilized readily for use as a stand-alone vehicle on a wide range of research vessels but can also be used very effectively in tandem with *"Alvin,"* an ROV, such as the National Deep Submergence Facility's (NDSF) *Jason* or a wide variety of other cabled or free swimming assets to improve the efficiency of deep submergence investigations. Key *Sentry* performance metrics are included in **Table 1.**

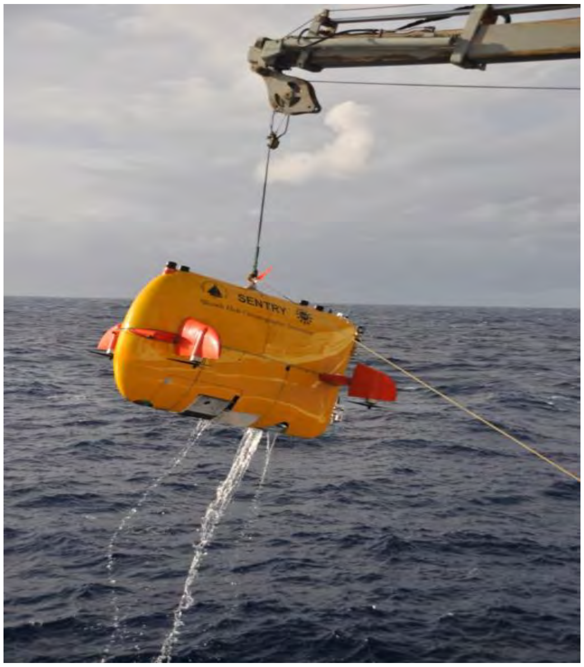


Figure 17: The AUV *Sentry* is one of hundreds of AUVs in service. Notably, the AUV *Sentry* is one of a few AUVs that is tailored precisely for seafloor mapping, including the ability to hover. © WHOI.

Sentry carries an extensive scientific sensor suite (

Depth capability	6,000 meters
Length	2.9 meters (9.7 feet)
Width	2.2 meters (7.2 feet)
Height	2 meters (6.5 feet)
Weight	1,451 kilograms (3,200 pounds) without extra science gear
Operating range	70–100 kilometers, (38–54 miles) depending on speed, terrain, and payload
Operating speed	0–1.0 meters/second (0–2 knots)
Propulsion	4 brushless direct-current (DC) electric thrusters on pivoting wings
Energy	Lithium ion batteries; 18 kilowatt hours
Bus power	48–52 volts DC
Endurance	28–60 hours depending on mission type
Recharge time	10 hours, 16-hour full turnaround from surface to release
Descent/Ascent speed	40 meters/minute for both descent and ascent, 2,400 meters/hour
Navigation	Ultra Short Baseline (USBL) navigation with real-time Acoustic Communications, Doppler Velocity Log (DVL), and Inertial Navigation System (INS)

Table 2) and produces bathymetric, sidescan, chemical, and magnetic maps of the seafloor; and is capable of taking high-quality digital color photographs in a variety of deep-sea terrains, including along mid-ocean ridges, and at ocean margins and in complex settings, such as hydrothermal vent and cold-seep ecosystems.

The *Sentry*'s navigation system uses a Doppler velocity log and inertial navigation system, aided by acoustic navigation systems (i.e., USBL). The USBL system also provides acoustic communications, which can be used to obtain the vehicle state and sensor status as well as to retask the vehicle.

The *Sentry's* operations are approximately a 70/30 split of the routine to the innovative. Approximately 70% of the use is for standard survey types. The remainder includes integration of custom sensors or samplers, or in some cases, the development of new sensors, samplers, mission types, etc. Some degree of development, customization, or integration happens for nearly every cruise; and larger changes or additions may require more planning and either a separate proposal or a community consensus of the need for the capability. Selected previous custom sensor integrations are shown in

Table 3.

Table 1. **Key *Sentry* performance metrics**

Depth capability	6,000 meters
Length	2.9 meters (9.7 feet)
Width	2.2 meters (7.2 feet)
Height	2 meters (6.5 feet)
Weight	1,451 kilograms (3,200 pounds) without extra science gear
Operating range	70–100 kilometers, (38–54 miles) depending on speed, terrain, and payload
Operating speed	0–1.0 meters/second (0–2 knots)
Propulsion	4 brushless direct-current (DC) electric thrusters on pivoting wings
Energy	Lithium ion batteries; 18 kilowatt hours
Bus power	48–52 volts DC
Endurance	28–60 hours depending on mission type
Recharge time	10 hours, 16-hour full turnaround from surface to release
Descent/Ascent speed	40 meters/minute for both descent and ascent, 2,400 meters/hour
Navigation	Ultra Short Baseline (USBL) navigation with real-time Acoustic Communications, Doppler Velocity Log (DVL), and Inertial

	Navigation System (INS)

Table 2. Standard *Sentry* sensors

Sensor	**Model**
Sonardyne Ranger 2 w/Avtrack2	Ranger 2
Woods Hole Oceanographic Institute (WHOI) Long Baseline (LBL)	Custom
Inertial Navigation System (INS)	IXSEA PHINS 1 INS
Doppler Velocity Log (DVL)	RDI 300 kHz
Pressure Depth Sensor	Paroscientific 8B7000
CTD Sensor	SBE FastCAT 49
Dissolved Oxygen	Aanderaa Optode w/fast foil
Turbidity	Seapoint Optical Back Scatter (OBS)
Side Scan Sonar	Edgetech 2200-M 120/410kHz
Sub Bottom Profiler	Edgetech 2200-M 4-24kHz
Magnetometers	3x APS1520 3 axis
Camera	Prosilica GC-1380C Digital Still Camera
Multibeam	Reson 7125 MBES 400 kHz w/7216 receiver

Table 3. Selected Custom Sensors Previously Used on *Sentry.* These require either collaborative agreements with the owners or incur additional cost or both.

Sensor	Owner
Tethys Mass Spectrometer	Dr. Richard Camilli – WHOI
Chelsea Aquatraka	Dr. Richard Camilli – WHOI
3-D Image Reconstruction System	Dr. Oscar Pizzaro – Australian Center for Field Robotics
Eh Probe	Dr. Ko-ichi Nokamura
Miniature Autonomous Plume Recorder (MAPR)	Sharon Walker – National Oceanic and Atmospheric Administration (NOAA) Pacific Marine Environmental Laboratory (PMEL)
Oxygen Reduction Potential (ORP) Sensor	Sharon Walker – NOAA PMEL
SUPR microbial and larval filter sampler	Dr. Chip Beier – WHOI

Appendix IV: Gliders and Other Low-Power Vehicles

By Oscar Schofield, Josh Kohut, Grace Saba, and Scott Glenn

The Need. There is a critical need to collect regional data (hundreds to thousands of kilometers [km]) to enable interpretation of data collected at local scales (<1 km to 10 km) during oceanographic experiments. Historically, this mapping need has been fulfilled using research vessels and satellites. The advantage of the ship-based sampling is that it allows for a wide range of measurements to be made throughout the water column; however, the disadvantage is that it represents an extremely expensive (i.e., money and people) approach. Additionally, as sea-going experiments typically only have access to one vessel, extensive mapping efforts come at the expense of the ship time that can be committed to address the science questions that are the focus of the expedition. In contrast, satellites can provide sustained regional to global coverage for a wide range of ocean properties (e.g., heat, salinity, circulation) for sustained periods of time. Despite these strengths, satellites can only sample the ocean's surface and thus are not well suited for characterizing subsurface and seafloor processes. Therefore, there is a need for integrating new systems into oceanographic experiments capable of cost-effectively maintaining a sustained subsurface presence that can collect a wide diversity of data over thousands of kilometers. This motivation led to the development of a whole new class of autonomous vehicles known as "buoyancy gliders" (Davis *et al.,* 2003; Ericksen *et al.,* 2001; Sherman *et al.,* 2001; Webb *et al.,* 2001). Several different classes of gliders currently exist, and all available types have proven their utility to support science. For this review, we focus on the glider system with which we are most familiar, Slocum gliders (Webb *et al.,* 2001; Schofield *et al.,* 2007); however, we emphasize that success rates are high for all glider systems.

Glider platforms. Buoyancy gliders are increasingly filling the "mesoscale sampling needs" for ocean science. Gliders maneuver through the ocean at a forward speed of 20 centimeters per second (cm/s) to 30 cm/s in a sawtooth-shaped gliding trajectory, deriving its forward propulsion by means of a buoyancy change and steering by means of a tail fin rudder. Pitch is regulated by shifting batteries back and forth within the glider. An altimeter and depth sensor enable preprogrammed sampling of the full-water column. Depth ranges of the systems range from >5 meter (m) to typically 1,500 m. It should be noted that currently efforts are being conducted to develop a deep (5,000 m, for Seaglider platforms) glider capability. The primary vehicle navigation system uses an onboard global positioning system (GPS) receiver coupled with an attitude sensor, depth sensor, and altimeter to provide dead-reckoned navigation, with back-up positioning and communications provided by an Argos transmitter. Two-way communication with the vehicle is maintained by a radio frequency (RF) modem or the global satellite phone service iridium, which allows for shore-based operators to pilot the systems remotely adjusting the mission as needed based on recently collected subsurface ocean data. The glider systems are generally modular thereby allowing a range of science instruments to be integrated into their science payloads. Currently, a wide range of physical, chemical, and biological sensors have been integrated into gliders. Instrument size and power needs are generally the limiting factor for which sensors are appropriate for gliders. Because gliders move slowly, if a sensor draws too much power, it will dramatically shorten the mission duration, and the mission will have small spatial footprint.

Glider operations generally consist of four components. The first is glider preparation that has three major scopes of work that include onshore ballasting of the glider to be operational in the water mass where it will be deployed. The gliders have a density range in which they can effectively operate, and the weight of the glider must be optimized for the mission. Additionally, glider preparation includes integrating the desired sensor package and general check-out procedures. The second phase is deployment of the system. For our team, this procedure is usually a tag team with a shore side technician talking to people on ships/boats/zodiacs. The shore-side technician generally has control of the glider remotely, and field-side people operate under the guidance on the experienced shore-side technician, which means less experienced part-time personnel can anchor the “wet work. We prefer to launch from as small a vessel as possible (but note, we have launched directly from global class University-National Oceanographic Laboratory Systems [UNOLS] vessels and large U.S. Navy ships), with communication mediated through a hand-held Iridium phone. After a deckboard check out followed by a series of *in-situ* dive tests, the glider is then directed to begin its science mission. The third phase is focused on piloting the glider from the shore—monitoring glider health, choosing flight waypoints, tuning flight performance, and adjusting sensor sampling frequency. The fourth component is recovery; and again, the shore-side technician directs field personnel into place and assists remotely in the recovery. By keeping the experienced technician shoreside, the operations are scalable with a single technician being able to manage many different missions on different ships simultaneously. The final analysis phase begins after the full data set is downloaded from the glider. During the data mission, we transmit decimated data back to shore (30% to 50%) to keep the glider moving (at the surface during data transmission, the glider is effectively a surface drifter) thereby still providings ample data for flight planning and representing hundreds and thousands of profiles allowing for science even if the glider is lost at sea.

Operational Statistics. Gliders transitioned from experimental platforms to becoming critical science tools in the early 2000s. While initially the number of groups flying gliders was small, the number of laboratories now flying gliders has grown dramatically during the last decade. The statistics of the success of these systems for individual groups have been documented (Brito *et al.,* 2014; Rudnick *et al.,* 2016) and show a range of success. While some (Brito *et al.,* 2014) suggest a mission success rate of ~50%, others (Rudnick *et al.,* 2016) show much higher success rates. Given this information, we subsequently highlight our personal experience in operating gliders.

Our team began to operate gliders in 2003 for science missions without the support of large engineering teams. Since that time, we have run 406 missions that have mapped ocean properties of more than 170,000 km during 9,000 days in many regions around the world (Figure 18). During that time, as numerous new glider groups have formed, we have been frequently asked to assist them in glider preparation, piloting a glider during the mission, and providing a glider data mirroring role. By combining these various missions, our group has seen the number of missions conducted each year increase from 5 in 2003 to ~30 missions each year during the last 5 years. These annual missions represent a significant number of days at sea (Figure 2B). The team consists of two glider technicians augmented by faculty/graduate students/advanced undergraduate students thus providing cost-effective scalable salary options for the operating laboratory. Applying the criteria specified by Rudnick *et al.* (2016) and only counting the missions in which our team was involved in all aspects of the mission, we find a success rate of 84% (Table 1). This success rate mirrors those reported by Rudnick *et al.* (2016). During the hundreds of missions, our team has had nine glider losses since 2013. The majority of those losses were associated with external factors (i.e., storms, sharks, ships) and not associated with the actual glider. Additionally, four of the losses were during the early years of the gliders representing the transition from an engineering tool to a science tool. These statistics demonstrate that gliders are a robust technology for supporting

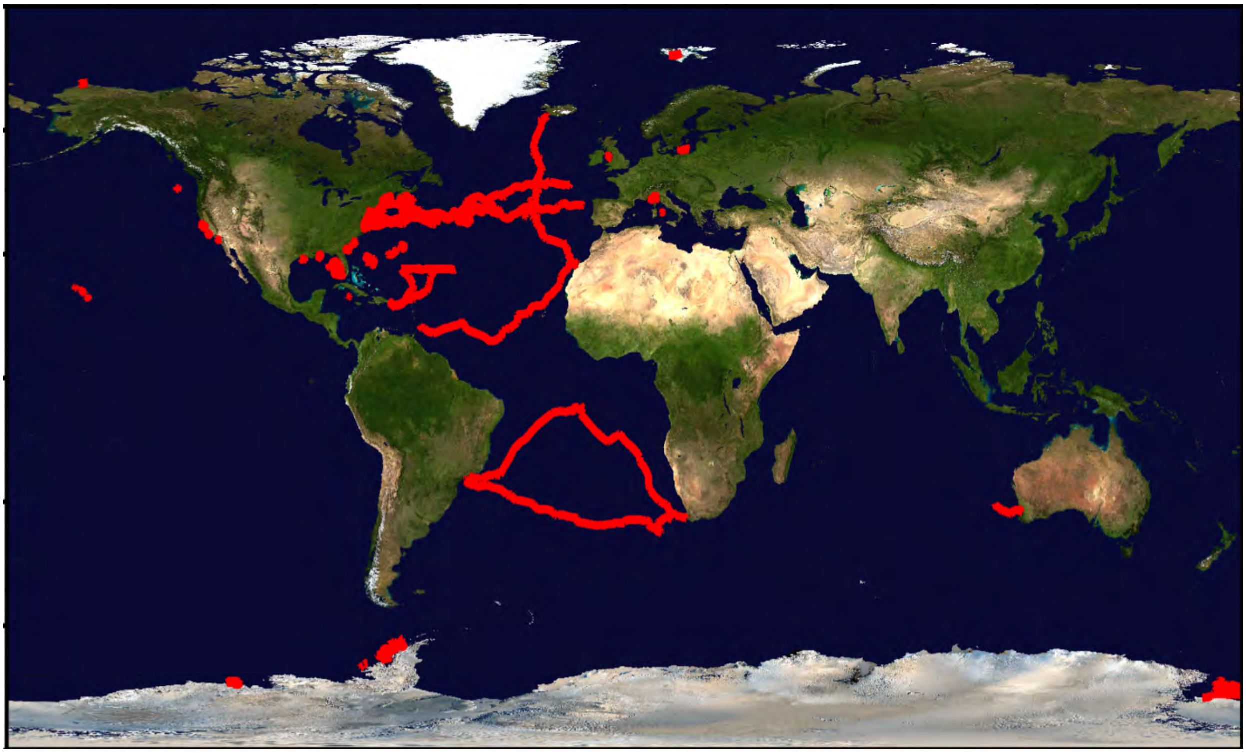
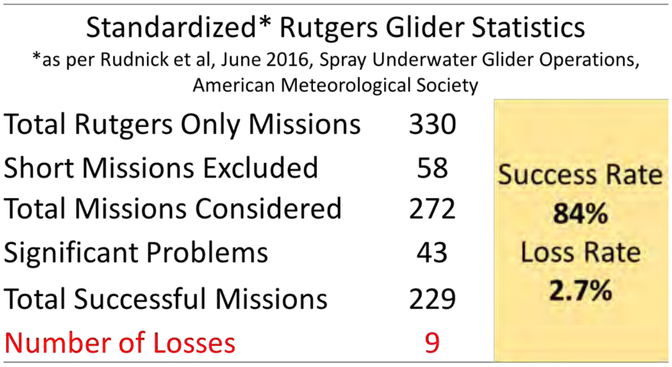


Figure 18: The red marks indicate glider missions conducted by the Rutgers glider team.

Table 1. Glider statistics by the Rutgers glider team.



Standardized* Rutgers Glider Statistics

*as per Rudnick et al, June 2016, Spray Underwater Glider Operations, American Meteorological Society

Total Rutgers Only Missions	330	
Short Missions Excluded	58	Success Rate
Total Missions Considered	272	**84%**
Significant Problems	43	Loss Rate
Total Successful Missions	229	**2.7%**
Number of Losses	9	

ocean science.

Data flow for the gliders is rapidly maturing. Gliders, especially during coastal missions, can collect thousands of profiles (>5,000/month) depending on the mission profile; therefore, one of the next community needs will be developing community tools for enabling efficient and increasingly standardized data processing and visualization scripts. There is currently a transition from where data only resides in an individual database to where it will now also flow to a centralized glider data assembly being built/maintained by the National Oceanic and Atmospheric Administration (NOAA). Beyond collating the many glider missions, it also allows glider data to flow directly to the Global Telecommunication System supporting global weather and ocean models.

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Appendix V: Ocean Observatories

By Stephanie Sharuga

Introduction

As improvements in technologies have facilitated exploration and resource development deeper in the ocean, there has been a responding need to increase the scope and scale of studies on marine environments. Exploration of these environments (and in particular, the deep sea) has been met with many challenges, including the vast extent and depths of the oceans, lack of light and ability of remote sensing to penetrate far below the sea surface, and limitations to physical human presence in the deep sea. Complicating this is the fact that ocean systems are highly dynamic, and there is consequently a need for long-term data to better understand biological, chemical, geological, and physical processes. More traditional expeditionary science involving research conducted by using ships, while still important, is typically periodic and therefore limited in temporal scale. Long-term, continuous temporal data is crucial, however, for developing a comprehensive understanding of natural and anthropogenic-induced changes to the ocean. This data is becoming increasingly important for responsible, sustainable management of marine environments and their resources.

Serious conceptual visions of large-scale, regional cabled ocean observatories for ocean research began several decades ago. The idea behind these observatories was to create a more permanent human presence in the ocean that could facilitate long-term research across continuous temporal scales, in a variety of marine environments and, in some cases, span from sea surface to seafloor. These envisioned observatories would consist of suites of technologically advanced instruments as part of moorings and/or connected by way of high-powered, high-bandwidth networks installed permanently on the seafloor, thereby enabling collection of continuous observations and, in the case of the latter, providing a real-time connection between the ocean and scientists, educators, and the general public.

Advantages and Limitations

Ocean observatories provide unprecedented opportunities to study marine environments *in–situ*. The long-term temporal scope and capability to encompass broad spatial extents are perhaps the greatest advantages of ocean observatories because they facilitate research aimed at developing a more thorough understanding of a wide variety of often inter-related ocean processes. Real-time data streaming and open access (in most cases) to this data allow for a diverse global audience to participate in and contribute to the research. Further, this access also facilitates many potential education and outreach opportunities that may otherwise be unavailable, including providing additional (and often unique) technical and educational training in marine sciences. It greatly contributes to raising awareness on ocean sciences and related conservation and resource sustainability issues, which thus contributes to a better informed general public, increased buy-in, and more effective environmental management and policy decision-making. Ocean observatories also create local employment opportunities, potentially boosting local economies as a result.

Despite these benefits, there are still limitations to ocean observatories. While the technologies associated with these observatories are often considered to be among the most state-of-the-art and technologically advanced, they still suffer many of the same limitations and issues faced during ship-based research. This is particularly an issue in the deep sea and more extreme marine environments where the technologies and sensors need to be engineered and tested to be able to withstand the continual stresses to which they will be exposed on a regular basis. This, along with the complex logistics of ocean observatory systems, often makes these systems expensive and complicated to build, install, and maintain. There are also capacity-based limitations related to developing these systems and maintaining optimal functionality (e.g., data streaming limitations and outages, etc.). Further, developing even broader, global-scale ocean-observing systems not only faces these challenges but also the additional complications associated with building and coordinating infrastructure and resources across international boundaries.

Examples of Ocean Observatories

Ocean Networks Canada: Ocean Networks Canada (ONC), detailed information available at http://www.oceannetworks.ca/), founded in 2007 as a major initiative of the University of Victoria, operates world-leading ocean observatories for the advancement of ocean and Earth sciences. These observatories collect long-term biological, chemical, geological, and physical ocean data in support of research into complex ocean and Earth processes using progressive approaches not previously possible. The observatories of ONC feature unique scientific and technical capabilities that allow researchers the ability to remotely operate instruments and receive data anywhere around the world in near real-time. Long-term observations facilitated by ONC have wide-ranging applications in both science and policy fields, including fields related to ocean and climate change, earthquakes and tsunamis, marine pollution, resource development, security, and ocean management.

Currently, ONC consists of 2 regional and 4 community observatories, with 7 additional shore stations. More than 850 meters (m) of seafloor backbone cables support these observatories, which feature more than 50 instrumented sites with platforms; 7 mobile instrument platforms; and 400 instruments containing more than 5,000 sensors that are online 24 hours a day, 7 days a week, and 365 days a year. Huge volumes of data are collected, archived, and distributed each day, at no cost of usage to scientists. The two primary components currently comprising ONC are the almost 50-kilometer (km) Victoria Experimental Network Under the Sea (VENUS) and 800-km North East Pacific Time-series Underwater Networked Experiments (NEPTUNE) cabled observatories, which are primarily operated by the University of Victoria.

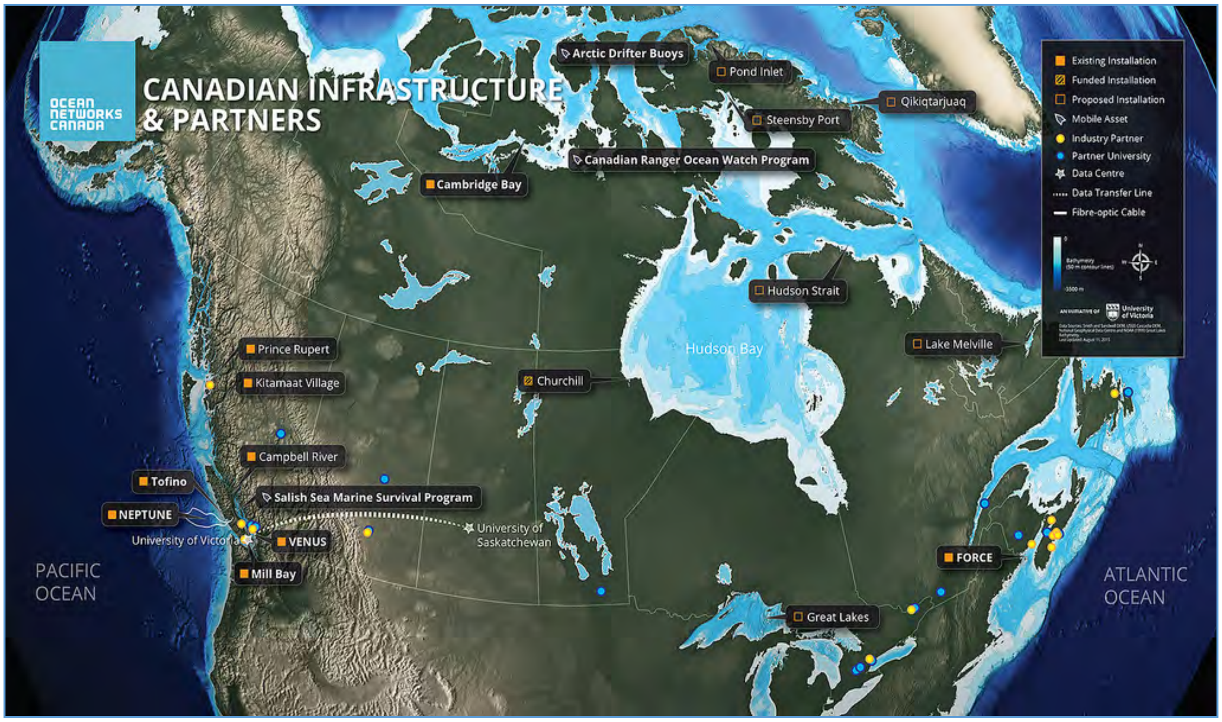

Figure 19: Map of Ocean Networks Canada Canadian infrastructure and partners. © Ocean Networks Canada.

VENUS is a coastal observatory in the Salish Sea that includes sites in the Fraser River Delta, Strait of Georgia, and Saanich Inlet of Vancouver Island, British Columbia (BC). Expansions of VENUS have included to its seafloor network, coastal radar, and surface systems, with instrumentation to also be installed on BC Ferries vessels. VENUS includes the following:

- The Fraser River Delta site has 3 instrument platforms located in a soft, sediment-covered, and unstable slope area at a depth of 108 m. The main research at this site is related to sediment stability and submarine slope failure. This research is facilitated by a Seismic Liquefaction In-Situ Penetrometer (SLIP) instrument that uses piezometers, accelerometers, and inclinometers. Another suite of instruments known as the Delta Dynamics Laboratory (DDL) provides additional environmental information on water properties, turbidity, and currents, along with hydrophones for listening for undersea landslides and earthquakes. More information can be found at: http://www.oceannetworks.ca/introduction-fraser-delta.
- The Strait of Georgia site is located in the southern area of the Strait of Georgia, between southern Vancouver Island and the Fraser River Delta. This site has 6 instrument platforms with 3 at the Central node (300-m depth) and 3 at the East node (170-m depth). Key instruments at this site include hydrophones, multifrequency echosounders, and Coastal Ocean Dynamics Application Radar (CODAR). The research conducted at this site is diverse and encompasses studies on estuarine circulation, tides, marine mammals, salmon, and sediment

transport. More information can be found at: http://www.oceannetworks.ca/introduction-strait-georgia.

- The Saanich Inlet site is located in an inlet just north of Victoria, BC at the southeastern coast of Vancouver Island. There are 4 platforms at a depth of 100 m representing variable seafloor compositions. The diverse suite of instruments at this site include a hydrophone, echosounders, cameras, sediment traps, profiling instruments (e.g., conductivity temperature depth [CTD] and oxygen sensors), and more. The principal research at this site focuses on low-oxygen ecology, inlet renewal and chemical cycles, and forensics. More information can be found at: http://www.oceannetworks.ca/introduction-saanich-inlet.

NEPTUNE is the largest of the ONC cabled observatories and is located off the southwest side of Vancouver Island. It currently features six main sites: Barkley Canyon, Cascadia Basin, Clayoquot Slope, Endeavour, Folger Passage, and Middle Valley. Research at these sites varies greatly on the characteristics of each site and encompasses a wide variety, including terrestrial-marine interactions; physical sciences and coastal physical oceanography; ocean biogeochemistry; seafloor fluids and gases; sediment dynamics and seafloor stability; earthquakes; gas hydrates; benthic and water column processes; marine fauna and biodiversity; marine mammals; plankton, upwelling, and productivity; and unique deep-sea biological, chemical, and geological processes. NEPTUNE includes the following:

- Barkley Canyon is located at the leading edge of the Cascadia subduction zone; and extends from a depth of 400 m near the continental shelf edge down the continental slope to the canyon axis at a 985-m depth. The seafloor at this site features the presence of methane gas hydrates and hydrate mounds in some regions. This site has the highest number of instrument platforms with eight located in different locations in the canyon and at varying depths, along with several moorings. These platforms and moorings are equipped with a wide variety of sensors, including cameras, profiling instruments (e.g., CTDs and Acoustic Doppler Current Profilers [ADCPs]), oxygen sensors, and seismometers. Highlights of this site are two mobile platforms: the Vertical Profiler Partnership for Observation of the Global Oceans (POGO), which allows for water column measurements; and the deep-sea crawler *Wally,* which is remotely controlled by scientists by way of the internet. More information can be found at: http://www.oceannetworks.ca/introduction-barkley-canyon.
- The Cascadia Basin site is located in the center of Cascadia Basin, which is an abyssal plain region that extends from the base of the continental margin to the mid-ocean ridge. There is one instrument platform located at a depth of 2,660 m, which features a Circulation Obviation Retrofit Kit (CORK), piezometer, and seismometers. More information can be found at: http://www.oceannetworks.ca/introduction-cascadia-basin.
- Clayoquot Slope is located on the mid-continental slope off south-central Vancouver Island and is characterized by soft muddy sediments 3-km to 5-km thick with some gas hydrate deposits. There is one instrument platform at a

depth of 1,258 m, along with a series of scientific drill holes filled with instruments extending down several hundred meters into the sediment. The platform includes sensors that measure tidal pressure, temperature, currents, seismic activity, and more. In addition, the world's first ocean observatory-connected Controlled Source Electromagnetic (CSEM) experiment is at this site, along with a SeaFloor Compliance (SFC) apparatus with the world's first ocean floor live-streaming gravimeter. More information can be found at: http://www.oceannetworks.ca/introduction-clayoquot-slope.

- The Endeavour site is located in the deep Endeavour segment of the Juan de Fuca Ridge, at the spreading boundary between the Juan de Fuca and Pacific tectonic plates. The hydrothermal vent fields at this site are surrounded by four instrumented moorings, with mooring arrays positioned to the northwest, northeast, southwest, and southeast. Instruments deployed at this site provide constant real-time data on heat-flux dynamics, current flow, seismic activity, dissolved minerals, and micro- and macro-organism behavior and population characteristics. More information can be found at: http://www.oceannetworks.ca/introduction-endeavour.
- Folger Passage is ONC's shallowest site and located off the southwest coast of Vancouver Island in the mouth of Barkley Sound. There are two instrument platforms at this site—Folger Pinnacle located at a 23-m depth and Folger Deep located at a 100-m depth. A variety of instruments are located at this site, including profiling instruments, such as ADCPs and CTDs, oxygen sensors, a camera, echosounder, and hydrophone. Research at this site is diverse with a general focus on ecosystem-based studies. More info can be found at: http://www.oceannetworks.ca/introduction-folger-passage.
- Middle Valley is the newest addition to ONC and located in the Middle Valley on the Juan de Fuca Ridge. Proposed research for this site includes studies on hydrothermal systems, ocean crustal hydrogeology, tectonics and seismicity, marine mammals and ocean noise, benthic ecology, and water column plumes. More info can be found at: http://www.oceannetworks.ca/introduction-middle-valley.

In addition to the two main observatories, ONC also features smaller community observatories. A newer and featured addition to ONC is the Cambridge Bay Community Observatory—otherwise known as the Arctic Observatory—installed in 2012 in Cambridge Bay, Nunavut. This community observatory is a small, cabled seafloor observatory scaled-down version of VENUS and NEPTUNE. It is the first of its kind in Canada's Arctic region and provides year-round, continuous monitoring of the northern environment to increase understanding and protection of Arctic marine ecosystems. The observatory has an underwater instrument platform on the seafloor at approximately 6-meters depth and is linked by cable to a wharf connection. The platform has an underwater high-definition (HD) video camera and microphone, an instrument to measure ice thickness, and a suite of sensors that measure seawater properties. More information on this community observatory can be found at: http://www.oceannetworks.ca/cambridge-bay-community-observatory-backgrounder.

Ocean Observatories Initiative

The Ocean Observatories Initiative (OOI) detailed information at http://oceanobservatories.org/ and http://www.interactiveoceans.washington.edu/) is an integrated ocean research infrastructure consisting of science-driven platforms and sensor systems designed for measuring biological, chemical, geological, and physical characteristics and processes spanning from sea surface to seafloor. OOI is funded by the U.S. National Science Foundation (NSF) and managed and coordinated by the Consortium for Ocean Leadership, with many implementing organizations responsible for construction and development of various aspects of the program. The program features a diverse range of scientific applications and possible research topics spanning across many disciplines, including ocean-atmosphere exchange; climate variability, ocean circulation, and ecosystems; turbulent mixing and biophysical interactions; coastal ocean dynamics and ecosystems; fluid-rock interactions and the sub-seafloor biosphere; and plate-scale geodynamics.

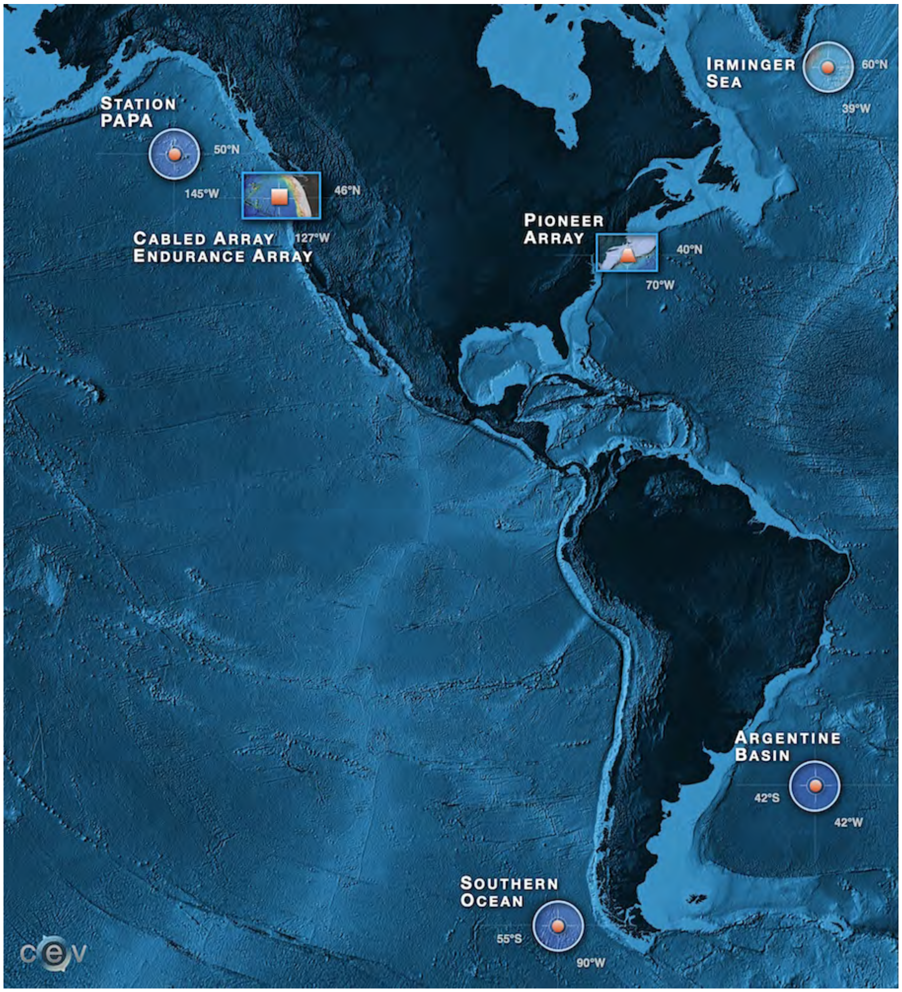

Figure 20: Map of the OOI research arrays. Photo Credit: OOI Cabled Array program and the Center for Environmental Visualization, University of Washington.

The OOI research arrays consist of the following:

- The Coastal Pioneer Array is located off the New England coast and consists of a frontal-scale moored array with three electromechanical surface moorings and seven profiler moorings representing a range of depths. The moored array is supplemented by nine mobile platforms consisting of six Coastal Gliders and three autonomous underwater vehicles (AUVs) aimed at providing multiscale observations across the broader area. These platforms supply information on physical oceanographic patterns. More information can be found at: http://oceanobservatories.org/array/coastal-pioneer/.

- Coastal Endurance (i.e., the Endurance Array) utilizes both fixed and mobile assets to observe cross-shelf and along-shelf variability in the region off the Oregon and Washington coasts known for coastal upwelling. The array has two cross-shelf moored array lines: the Oregon Line (or Newport Line) and Washington Line (or Grays Harbor Line). The lines each have three fixed sites—with one each on the inner shelf (~25 m to 30 m), shelf (~80 m to 90 m), and slope (~500 m to 600 m)—to represent the range of unique biological, geological, and physical processes across the area. All sites contain fixed sensors at the top and bottom of the water column, and an adjacent water column profiler. There are also mooring lines for multiscale observations, along with Coastal Gliders that move between the fixed sites. More information can be found at: http://oceanobservatories.org/array/coastal-endurance/.
- The global arrays, including the Global Argentine Basin, Global Irminger Sea, Global Southern Ocean, and Global Station Papa, comprise the global component of OOI that aims to represent critical but under-sampled high-latitude locations. These sites each include a network of moorings that support sensors for measuring air-sea fluxes of heat, moisture, and momentum—along with biological, chemical, and physical water column properties. There is a combination of fixed (mooring) platforms, as well as mobile (gliders) platforms that sample within and around the fixed platforms. The array at Global Station Papa is one of the oldest oceanic time series where surveying has been conducted since 1949, and is occupied in coordination with the National Oceanic and Atmospheric Administration (NOAA), which has a surfacing mooring at the site. More information on these sites can be found at: http://oceanobservatories.org/array/global-argentine-basin/, http://oceanobservatories.org/array/global-irminger-sea/, http://oceanobservatories.org/array/global-southern-ocean/, and http://oceanobservatories.org/array/global-station-papa/.
- The Cabled Array is the first U.S. ocean observatory to span a tectonic plate, providing a constant real-time data stream from across the Juan de Fuca plate. The array is a high-power, high-bandwidth network utilizing modified telecommunications cable, which features two-way communication between shore and the scientific sensor arrays throughout the water column and on the seafloor. It consists of two sub-arrays: 1) Cabled Continental Margin Array (http://oceanobservatories.org/array/cabled-continental-margin/) and 2) Cable Axial Seamount Array (http://oceanobservatories.org/array/cabled-axial-seamount/). There are three instrumented cabled mooring sites (Axial Base, Slope Base, and Oregon Offshore) with additional complimentary sensors (e.g., moorings and profilers) on the Cabled Array and Endurance Array for interdisciplinary water-column processes observations. This part of the array provides insights into air-sea interactions, shelf-slope interactions with the deep sea, and coupled atmospheric/oceanic phenomena in the region. Two additional sites—Southern Hydrate Ridge and Axial Summit—have cabled seafloor

instruments that provide insights into actively venting methane hydrate systems and volcanically active areas featuring hydrothermal venting. A diverse set of instruments are at these two sites, including biological, chemical, and geophysical sensors; an HD camera, and a digital still camera. More general information on the Cabled Array can be found at: http://oceanobservatories.org/array/cabled-array/.

Other Examples of Observatories and Observing Systems

Monterey Accelerated Research System: The original purpose of the Monterey Accelerated Research System (MARS) cabled observatory was to provide a testing ground for scientists to test equipment and instruments that may subsequently be deployed as part of OOI, etc. It consists of 52 km of undersea cable carrying data and power to a science node located at a depth of 891 m in Monterey Bay. The main hub has eight nodes to which science experiments can be attached directly; and thus facilitate a wide range of experiments and research collecting biological, chemical, geological, and physical data on the marine environment at the site. Examples of current instruments include a hydrophone for passive acoustic monitoring and the Monterey Ocean-Bottom Broadband Seismometer for detecting earthquakes. More information can be found at: http://www.mbari.org/at-sea/cabled-observatory/ .

ALOHA Cabled Observatory: The ALOHA Cabled Observatory (ACO) was deployed in 2011 at Station ALOHA, approximately 100-km north of Oahu, Hawai'i, and boasts the deepest (4,728-m) electrical outlets and internet connection in the world. Station ALOHA is the site of the long-term Hawai'i Ocean Time-series (HOT) open measurement program, which has been visited many times each year during the past several decades. ACO consists of five modules connected together on the seafloor, including the junction box, observatory module, camera tripod, a bottom node, and a mooring. Sensors on the modules provide live video and measurements of currents, pressure, salinity, sound, and temperature. More information can be found at: http://aco-ssds.soest.hawaii.edu/.

European Sea Observatory NETwork (ESONET) and European Multidisciplinary Seafloor and water column Observatory: The European Sea Observatory NETwork (ESONET) initiative was purposed to assess available European capacity in ocean observatory infrastructures. This eventually led toward development of European Multidisciplinary Seafloor and water column Observatory (EMSO) in 2007, which aims to prepare the future institutional framework of the ESONET initiative. EMSO is a large-scale, distributed, marine research infrastructure of fixed-point ocean observing systems designed for monitoring environmental processes and their interactions. Observatory nodes are deployed at key sites around Europe, including from the Arctic to the Atlantic, throughout the Mediterranean, and to the Black Sea. There are currently 11 deep-sea nodes and 4 shallow-water test nodes, which are: Azores Islands, Balearic Sea, Black Sea, Canary Islands, Galway Bay, Hellenic Arc, Iberian Margin, Koljoe Fjord, Ligurian Sea, Marmara Sea, Molene Island, Norwegian Margin, Porcupine

Abyssal Plain, Svalbard Islands, and Western Ionian. EMSO currently focuses on open ocean areas beyond the continental shelf (with additional collaborations with shallow-water initiatives, including for test nodes) to address research questions related to climate change, marine ecosystems, and natural hazards. EMSO nodes host a variety of sensors with capabilities to measure parameters, such as acidity, water temperature, direction and intensity of currents, seabed movements, etc. Some are connected to land stations by way of cable while others work autonomously by way of satellite. The EMSO observatories are diverse and include both cabled infrastructures and standalone observatories that are supported by remotely operated vehicles (ROVs) and AUVs. Data is open access to scientists and public bodies. More information on ESONET, EMSO, and the individual nodes comprising the EMSO observatories can be found at: http://www.esonet-noe.org/ and http://www.emso-eu.org/site/.

Integrated Marine Observing System: The Integrated Marine Observing System (IMOS) consists of a National Mooring Network designed for long-term monitoring of biological and physical oceanographic parameters in Australian coastal ocean waters. It consists of several components, such as a network of National Reference Stations (NRS) that include vessel-based sampling, regional arrays of shelf moorings, acidification moorings, and passive acoustic observatories. There are currently seven NRS stations in operation around the continent that build on three long-term monitoring locations where monthly water sampling has taken place since the 1940s. The seven sites are fully instrumented with *in-situ* moored ocean sensors and generally include enhanced sampling for nutrients, microbes, phytoplankton, small zooplankton, and other environmental variables. A wide range of configurations of deployed shelf moorings characterize and monitor regional processes. Acidification moorings are colocated at some NRS sites to allow for collection of the full set of parameters for effectively characterizing water acidification, and this data contributes to related national and international research priorities. Acoustic listening stations provide baseline data on ambient oceanic noise, detection of underwater events, detection of fish and mammal vocalizations linked to ocean productivity, and monitoring of whale species. The NRS and shelf array moorings have a variety of instruments, such as acoustic Doppler current profiles, CTDs with turbidity and dissolved oxygen sensors, fluorometers, and WetLabs Water Quality Meters. Boat-based sampling also occurs monthly at the NRS, and includes CTD and Secchi disk sampling, hydrochemistry and plankton sampling, and general water sampling. More information can be found at: http://imos.org.au/.

Argo: Argo consists of a broad-scale global array of more than 3,000 profiling floats used for measuring temperature, salinity, and velocity of the upper ocean. These floats are distributed across the global oceans and have an average of 3-degree spacing. The floats cycle to 2,000 m depth every 10 days and have 4- to 5-year life spans for individual instruments. The near real-time data collected by the Argo floats are publicly available through Global Data Assembly Centers in Brest, France and Monterey, California. Argo is designed to build on and compliment other upper-ocean observing networks by extending temporal and spatial coverage, depth range and accuracy, and enhancing them with additional salinity and velocity measurements. More information can be found at: http://www.argo.ucsd.edu/.

OceanSITES: The OceanSITES network is a global system of long-term deep-sea reference stations that measures dozens of oceanographic and other variables, as well as monitoring the full depth of the ocean from the air-sea interface down to 5,000 m. The network currently includes approximately 30 surface and 30 subsurface arrays, with satellite telemetry enabling near real-time data access to scientists and the public. OceanSITES complements other existing networks (e.g., Argo) by expanding temporal and depth-range measurements on biogeochemistry, physical oceanography, water transport, meteorology, and other parameters relevant to research on the carbon cycle, ocean ecosystems, geophysics, and ocean acidification. More information can be found at: http://www.oceansites.org/index.html.

Dense Oceanfloor Network System for Earthquakes and Tsunamis: The Dense Oceanfloor Network System for Earthquakes and Tsunamis (DONET) is a submarine-cabled, real-time seafloor observatory network (completed in 2011) established off the coast of Japan predominantly for earthquake and tsunami monitoring. It features a large-scale, real-time seafloor research and surveillance infrastructure for long-term earthquake, geodetic, and tsunami observation and analysis. The network consists of approximately 300 km of backbone cable system with 5 science nodes and 20 observatories. DONET2 (the second phase of DONET, started in 2010) aims to monitor a wider region expanding to the west side of the original network. It is of a larger scale than the original and will have 450 km of backbone cable system with 2 landing stations, 7 science nodes, and 29 observatories. More information on DONET can be found at: https://www.jamstec.go.jp/donet/e/index.html.

Marine Cable Hosted Observatory: A Taiwanese project similar to DONET, the Marine Cable Hosted Observatory (MACHO), has also been under development off the east coast of Taiwan. The main purpose of MACHO is to establish offshore seismic stations, provide early earthquake and tsunami warnings, and monitor submarine volcanic activity.

East China Sea Coastal Seafloor Observatory System: The East China Sea Coastal Seafloor Observatory System (ECSSOS) includes China’s first experimental seafloor observatory system, Xiaoqushan Seafloor Observatory, and a coastal seafloor observatory system. The system consists of multiple junction boxes and instruments that perform full-time and continuous monitoring. More information can be found in the article: https://link.springer.com/content/pdf/10.1007%2Fs11434-011-4620-y.pdf.

The Future of Ocean Observatories

The need for increasing and improving on interdisciplinary long-term, broad-scale temporal and spatial monitoring of oceans will continue to grow in the future, particularly as human influences on marine environments continue to increase. This monitoring provides an impetus for the continued growth and expansion of current ocean observatories and observation systems, as well as promoting the development of new ones. This will be particularly important in relation to linking ocean observations and research on a global scale, which is important because oceans and human impacts to marine environments know no international boundaries. In addition to the ocean observatories in use or under development across the globe, there is a growing complementary set of organizations and coordinating frameworks aiming to develop and facilitate coastal and ocean observations on this global scale. These include the following:

- Integrated Ocean Observing System (IOOS, https://ioos.noaa.gov/)
- Global Ocean Observing System (GOOS, http://www.goosocean.org/), including IOOS GOOS, European GOOS (EuroGOOS), North-East Asian Regional GOOS (NEAR-GOOS), Coastal GOOS
- European Ocean Observing System (EOOS, http://www.eoos-ocean.eu/)
- Atlantic Ocean Observing System (AtlantOS, https://www.atlantos-h2020.eu/)
- eReefs (http://ereefs.org.au/ereefs)
- Marine Geological and Biological Habitat Mapping (GEOHAB, http://geohab.org/)
- Partnership for Observation of the Global Oceans (POGO, http://www.ocean-partners.org/)
- Group on Earth Observations' (GEO) Global Earth Observation System of Systems Ocean Data Networking System (GEOSS-AP, http://www.jamstec.go.jp/geossap/)
- Committee on Earth Observation Satellites (CEOS, http://ceos.org/)
- Global Climate Observing System (GCOShttp://www.wmo.int/pages/prog/gcos/index.php)

This appendix is designed to provide basic information (and associated links for additional resources) on the more well-known and developed ocean observatories around the world. It is not meant to be an exhaustive list, but instead, to provide a broad overview of the diversity of ocean observatory systems out there and their respective capabilities. As technologies and technical capabilities continue to increase in ocean research, so will the abilities and applications of ocean observatories and observations systems. Because of the grand scope of these systems, both in space and time, what will be most important to their future development is continued international coordination and collaborations, which will help ensure that: 1) marine research adequately represents the global nature of our oceans; 2) diverse groups (and thus capacities) of scientists, engineers, the general public, and other stakeholders are included; and 3) costs are consequently minimized.

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APPENDIX VI: Summary of recommended investments and tradeoffs.

Needed Investments	**Scientific & Operational Efficiency Goals**	**Potential Impacts**
New relationships/programmatic mechanisms among federal agencies and foundations to bring different scientific communities together; expansion of international collaborative agreements among government agencies.	Enhanced cross-disciplinary efforts, increased operational efficiencies through use of more diverse assets, broader community engagement, more opportunities for shared funding and infrastructure access.	Interagency or international program diversity, fiscal requirements, scheduling, etc., may inadvertently complicate opportunities for collaboration.
Full-ocean depth hybrid robotics systems (e.g. vehicles, landers, instruments) coupled to advanced communications technologies for vehicle navigation and command/control.	Whole basin maps, higher resolution temporal/spatial sampling, provides presence in remote regions, possibility to reduce logistical and operational costs through fewer personnel at sea, etc.	Requires significant capital investment but with potentially very high pay-off. Fewer personnel at sea may have negative impacts on serendipitous discoveries; should be mitigated via improved telepresence capabilities.
In situ sensor development with full ocean depth capabilities, long deployment potential and advanced communication capacity for data offloading through novel modes (e.g., optical comms)	Massive improvement in relating physical, chemical, and biological processes, sustained presence especially in conjunction with robotics, powerful synergy with ocean observing infrastructure.	Advanced sensors developed without regard to ease-of-use or automation may see limited scientific use. The effort must be well coordinated across disciplines in the earth-ocean sciences and engineering.
Improvements in large dataset(s) management and interactive data exploration & analysis tools	Unprecedented capacity to tackle system-level questions; harness new talent and technology for an array of applications; Enhance interactions with planetary science, climate modeling, genomics, etc.	Increased support for big data efforts may adversely impact funding/development of core observational/field activities; new developments could quickly be rendered obsolete; may prove to be of limited value in developing predictive capacity (Earth sciences are prone to model-observation mismatches, broadly speaking)
Additional support for exploring and studying previously, poorly-understood habitats (e.g.,	Areas for new advances/discoveries; economic potential (EEZ, mineral	When resources are limited, may adversely impact ongoing activities; each region (esp.

shallow shelf, midwater, sub-ice ocean, abyssal plains, and hadal zones of trenches)	abundance); assess unquantified Earth-ocean system reservoirs (e.g., nutrient cycle, volatile exchange); hazards assessment (earthquakes, tsunamis, gas hydrates).	polar) pose challenges for exploration/study; difficult to assess best approach; hard to quantify cost/benefit of exploration when compared to studies in known regions.
Foster better coordination and programmatic linkages among federal agencies, philanthropic foundations, and business interests to leverage collective resources for greater impact and efficiency.	Movement in new directions that do not emerge naturally from peer review or existing management tiers; enhanced efficiencies can lead to a net increase in scientific productivity; improved diversity of stakeholders, from scientists and engineers to policy makers.	Wasted effort on insurmountable interagency challenges; potential for catastrophic logistical errors resulting from overly complex management; conflicting agency or philanthropic missions can cause logistical and/or public relation problems.
Support scientists and engineers in communicating the societal relevance of Earth-ocean phenomena, and provide the most current, relevant data to all stakeholders, including the broader public and decision makers.	Essential to build greater trust and dialogue among scientists and lay persons; enhanced access of scientific data to policy makers, industry partners, etc; enhanced role of scientists in commercial maritime activities, e.g. ecosystem assessments, policy decisions.	Limited efficacy if scientists are not provided with communication/media training opportunities; higher potential for miscommunication if scientists are not well trained in communication; risk of further politicization of science.
Develop programs to promote inclusivity and increase diversity in the ocean sciences; engage and train next generation of scientists, engineers and educators that will study Earth-ocean systems in the future.	A more diverse, inclusive culture; greater interest in ocean sciences among the broader population; greater attention to ocean sciences, resulting in increased support for research, engineering and related activities.	Limited efficacy if there is insufficient investment or assessment. However, there are very few risks or costs associated with these activities. Investment tends to be modest, and payoff tends to be neutral or positive.

CLOSING REMARKS

by

Peter Girguis

The role of the ocean in maintaining the stability of our environment cannot be overstated. The ocean keeps the planet habitable for all organisms (especially humans) through its capacity to store and distribute heat and regulate atmospheric gases. Oceanic microorganisms produce over half the oxygen in the atmosphere, and fish and other megafauna provide a sizeable proportion of humankind's nutrition.

After 140 years of oceanographic science, it is also apparent that our understanding of the ocean is in its infancy. In the last fifty years alone, humankind's exploration of the ocean has led to discoveries that have reshaped our understanding of the origin and the evolution of our planet and all life. Scientists also visited the mid-ocean ridge system, the longest and largest mountain range on Earth at ~65,000-kilometer (km) in length, which is the product of earth-shaping plate tectonics and influences marine geochemistry, as well as organismal ecology and evolution. The hydrothermal vents associated with this ridge system and other seafloor features emit dissolved metals into the overlying water, which are now believed to play a role in providing trace element micronutrient for upper-ocean marine communities. A recent effort to document all marine life have found that up to 20 million animal species may live in the deep sea alone: an order of magnitude increase the known marine biodiversity. The ocean is also home to a staggering diversity of microbes that play a critical role in our planet's habitability, e.g., regulating the input of the potent greenhouse gas methane to the atmosphere.

Concurrently, we are also aware of humankind's impact on the ocean and how the resulting changes in our ocean system damages and destroys habitats. Extreme weather events severely impact human populations who live near the ocean, and depend upon the ocean for their nutrition and livelihood. Increasing ocean temperatures and acidity threaten both shallow and deep marine communities alike. The rising demand for food, energy, and minerals are all leading to the exploitation of resources from marine environments for which we have little baseline data.

Yet the deep-sea research community is at a turning point as it seeks to propel research into the 21st century through advances in science, technology and culture. The recommendations presented herein reflect their desire that the US scientific community will remain at the forefront of research, engineering, and education. This community also recognizes the challenges that humankind (and the biosphere writ large) are facing and will face in the coming years. Through their research, ocean scientists hope to provide the broader community, including policymakers, with the fullest understanding of our ocean-earth system so that they –and we all- can protect this life-giving resource through effective management practices including the promotion of sustainable ocean enterprises.