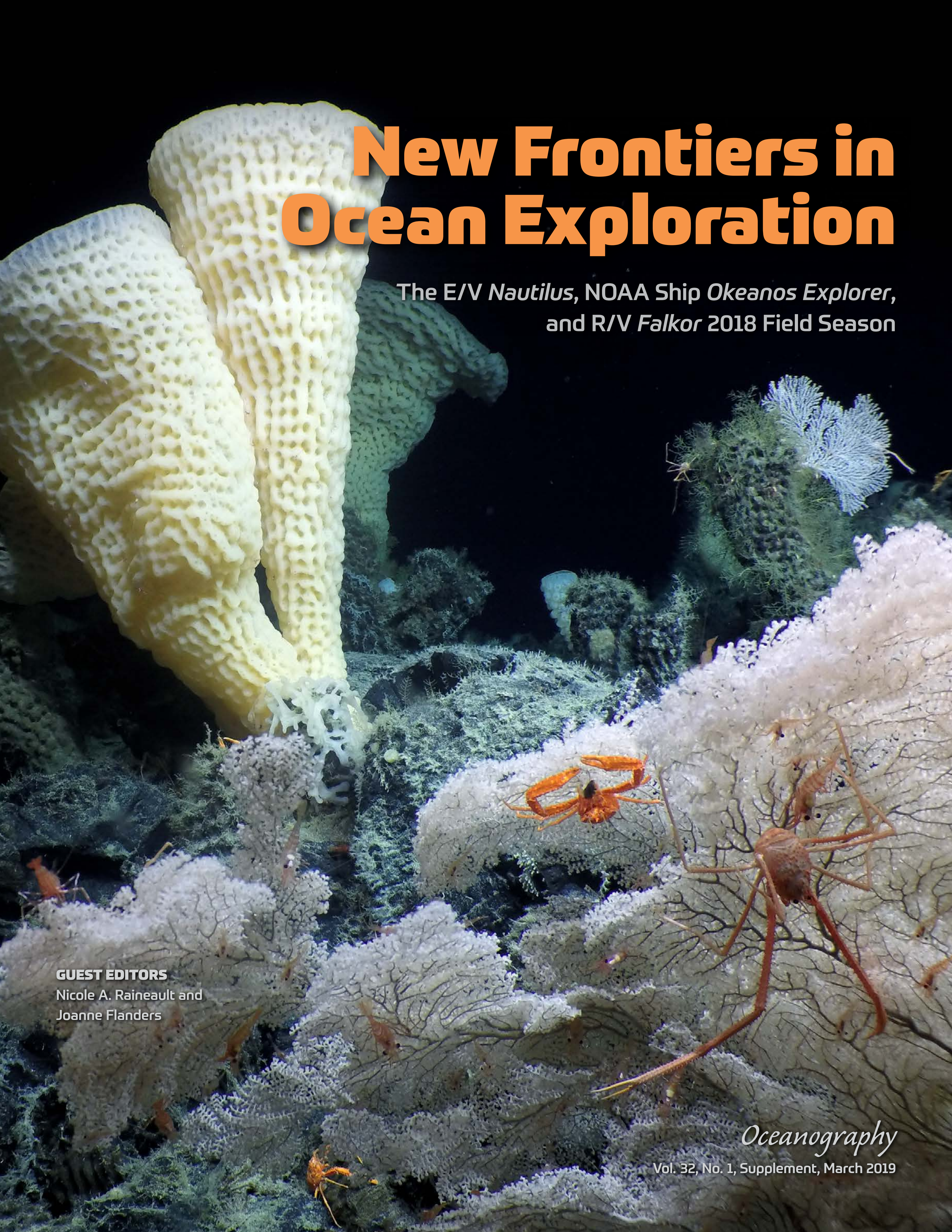

New Frontiers in Ocean Exploration

The E/V *Nautilus*, NOAA Ship *Okeanos Explorer*, and R/V *Falkor* 2018 Field Season

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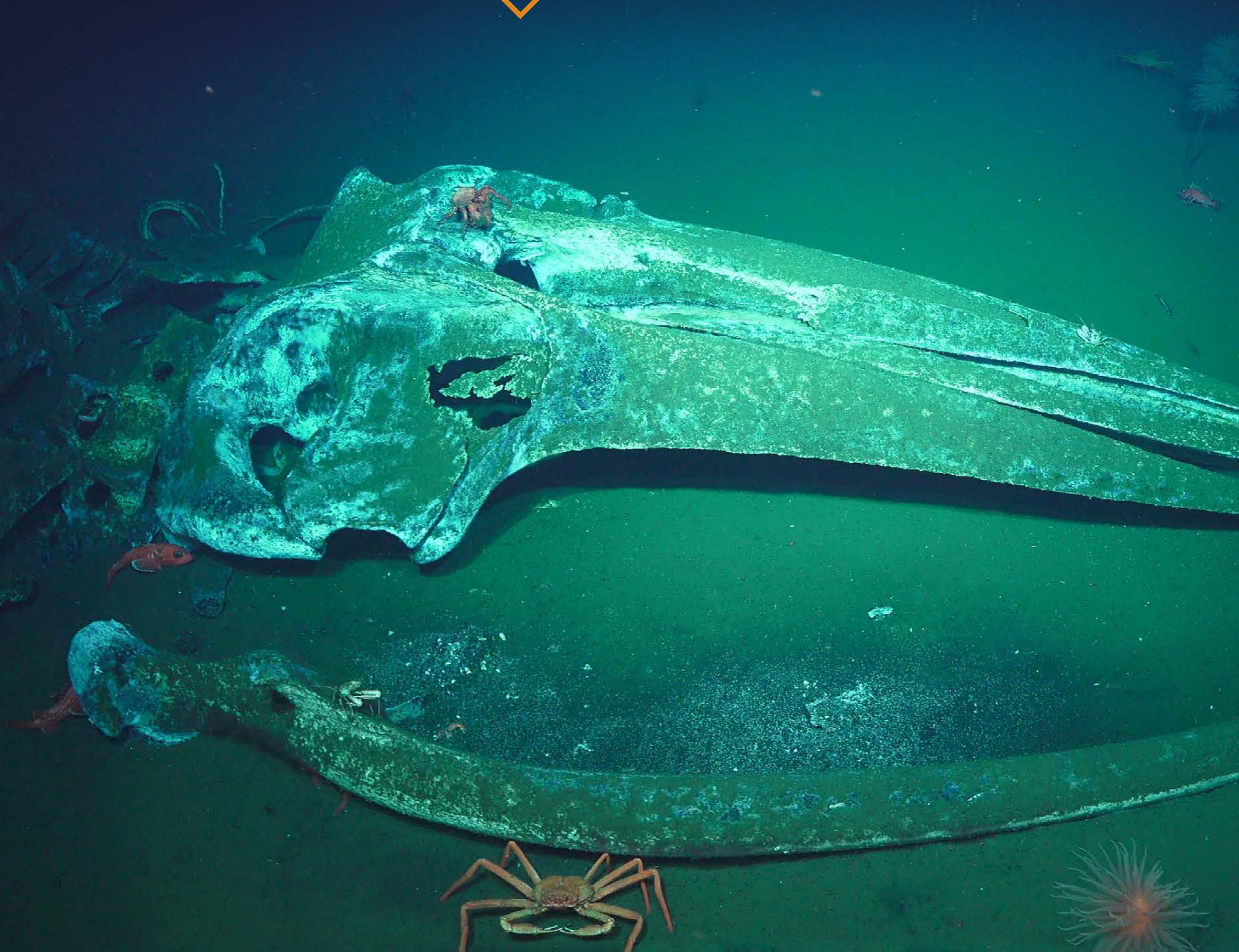
FRONT COVER
A bustling community of shrimp and squat lobsters in a towering city of glass sponges and soft corals (*Pinulasma nov.* sp. and *Parastenella* cf *ramosa*). This delicate deep-sea metropolis, affectionately nicknamed "Spongetopia," was discovered in July 2018 on the summit of Explorer Seamount in the Northeast Pacific. Explorer is Canada's largest underwater volcano and one of 40+ seamounts located in the proposed Offshore Pacific Marine Protected Area. *Image credit: D. Fornari (WHOI-MISO Facility), Northeast Pacific Seamount Expedition partners, and OET*

The R/V *Falkor* team dove on "Rosebud," a whale fall that was placed by researchers off San Diego, California, in La Jolla Canyon. Researchers noted changes in composition and life forms around the location in a beautiful, exciting dive investigating ecosystems unique to whale falls. *Image credit: SOI*



Contents

Introduction

By Nicole A. Raineault, William Mowitt, and Carlie Wiener

In this ninth installment of the ocean exploration supplement to *Oceanography*, we present highlights of the latest field seasons of three vessels that contribute to exploring the world ocean: the Ocean Exploration Trust's (OET) Exploration Vessel (E/V) *Nautilus*, NOAA Ship *Okeanos Explorer*, and Schmidt Ocean Institute's (SOI) Research Vessel (R/V) *Falkor*.

In 2018, the programs expanded efforts in the Pacific Ocean. *Falkor* explored the southern and eastern Pacific, *Nautilus* ventured further north to the Canadian seamounts and west to Hawai'i in the central Pacific, and *Okeanos Explorer* investigated the Gulf of Mexico and US Atlantic margin. The year 2018 also marked one decade of ocean exploration through NOAA's Office of Ocean Exploration and Research (OER) and E/V *Nautilus*. Read on to learn about this season's new discoveries, tests of novel technologies that will improve our ability to learn about the ocean, and the array of education and outreach activities that reach ocean explorers globally. We also include some retrospective pieces that provide insight on just how far our programs have come over the last 10 years.

The Ocean Exploration Trust celebrated its tenth E/V *Nautilus* field season by conducting missions that ventured further north and west than ever before. This supplement's first section briefly reviews our history (pages 14–19), sampling (pages 26–29), and education and outreach programs (pages 30–35) that demonstrate our commitment to innovating approaches and techniques that improve our exploration capabilities and engagement with students and the public. We then report on initial results and discoveries from the 2018 *Nautilus* field season, which explored the west coast of North America, from British Columbia to Southern California (pages 36–37). We surveyed previously unmapped seamounts and areas critical to understanding seabed mining impacts and explored the new underwater lava flows off of Hawai'i (pages 46–49). We also tested technologies that would improve our ability to sample rocks and enhance the information we collect on mapping cruises (pages 38–39). A continued partnership with NOAA's Office of National Marine Sanctuaries brought us to the expanded area of the largest US marine protected area, where we discovered several new species on remote seamounts (pages 50–51).

The second section of this supplement focuses on the advances and accomplishments of NOAA's Office of Ocean Exploration and Research and *Okeanos Explorer*. In 2018, the ship returned to the Atlantic basin, reaching a decadal milestone of exploration voyages. We review that decade and how this US ocean exploration program, with its dedicated flagship, is achieving the 2000 President's Panel for Ocean Exploration's vision for an innovative and bold program that conducts voyages of discovery (pages 58–69). We highlight the vision's connection to the Blue Economy (pages 70–71) and then NOAA Ship *Okeanos Explorer*'s evolution and core capabilities (pages 72–73) before turning to OER's renewed focus on the Atlantic Seafloor Partnership for Integrated Research and Exploration (ASPIRE) (pages 74–75). *Okeanos Explorer's* passage through the Panama Canal provided the opportunity for an expedition in the Gulf of Mexico, which included the first exploration of the sunken tugboat *New Hope*, and we describe our Gulf work (pages 78–81) before reporting on a series of ASPIRE

Port side of what is believed to be the tugboat *New Hope*, which was sunk during Tropical Storm Debbie in September 1965. *Image credit: NOAA OER* expeditions conducted along the Atlantic continental margin that filled in data gaps and contributed to Seabed 2030 and Galway Statement goals, which begins on page 82. We then describe findings from deep-sea habitat exploration around Puerto Rico and the US Virgin Islands (pages 90–91). OER's 2018 mapping achievements and advances are summarized next (pages 92–95), followed by an overview of OER contributions to the US Extended Continental Shelf Project. This project reached a historic American milestone in 2018, having collected all the data needed to determine the outer limits of the US Extended Continental Shelf (ECS). We describe *Okeanos Explorer's* own 2018 ECS contribution (pages 98–99) before turning to discussions of technology development and a new push to provide dedicated ship time aboard *Okeanos Explorer* for testing emerging technologies (pages 100–103). We next review a DEEP SEARCH expedition (pages 104–105) and then the wealth of data these expeditions provide, as well as how those data are collected and managed (pages 106–109). A series of articles on OER's engagement and outreach strategies, STEM-driven programs, and results from OER's first National Education Review follow (pages 110–117). We close the section with articles that highlight innovative work funded through OER grants that further leverage its mission. These projects include state-of-the art water column technology exploration, searches of submerged World War II battlefields, and exploration of the biodiversity and ecology of the vast and poorly studied Clarion-Clipperton Zone, among other innovative projects (pages 118–127).

In the final section, Schmidt Ocean Institute highlights some of their significant accomplishments in 2018, illuminating the important outcomes of expedition-based technology trials and software development, as well as new vent and species discoveries. From mysterious White Shark Cafés to methane bubbles emerging from the seafloor, new collaborations with autonomous vehicles and software helped to provide a better understanding of our dynamic ocean. This section charts 13 expedition outcomes that impacted ocean sciences this year. With its philanthropic efforts, SOI aims to demonstrate how scalable innovation can tackle important scientific and societal challenges (pages 128–137).

The year 2019 will bring some new partnerships that will grow our abilities to explore. *Nautilus* will investigate regions between the US west coast and Howland and Baker Islands in the Central Pacific and begin new partnerships with NOAA's Office of National Marine Sanctuaries in Thunder Bay and American Samoa. *Okeanos Explorer* will probe and explore the seafloor and water column in high-priority areas of the North Atlantic and expand its technology demonstration efforts, while continuing to advance its high-resolution mapping capabilities. *Falkor* will continue to focus on the Western Pacific, with projects that utilize advanced and coordinated robotic systems, artificial intelligence, and other frontier technologies to accelerate ocean research, conservation, and management. We invite you to follow our expeditions online. We look forward to sharing highlights of our discoveries with you next year.

A basket star is perched on a pinnacle blanketed by crinoids on Pilgrim Bank off Southern California. The photo was taken during E/V *Nautilus* cruise NA104. *Image credit: OET*

All Hands on Deck

The 2018 National Ocean Exploration Forum

By Katherine L.C. Bell, Adrienne Copeland, Jenni Szlosek Chow, Carlie Wiener, Alexis Hope, and David McKinnie

To fully explore and understand the ocean, we can no longer rely solely on a handful of large, expensive research vessels and a small, elite cohort of explorers. We truly need *All Hands on Deck* to do it!

On November 8–9, 2018, over 300 people gathered for the 2018 National Ocean Exploration Forum: *All Hands on Deck* at the MIT Media Lab in Cambridge, Massachusetts. The purpose of bringing together leaders and change-makers in ocean exploration, entertainment, recreation, and art was to imagine creative new ways to enable an open, inclusive global community of ocean explorers. Panel discussions, demonstrations, and hands-on workshops focused on the forum's themes of *Play, Imagine, Immerse, Create, Explore,* and *Connect*, inviting participants to consider different approaches to engage people and build a better understanding of, and appreciation for, the ocean. An ocean-based art exhibit was included that showcased the works of Schmidt Ocean Institute's Artist-at-Sea participants as well as the glass art of Whitney Cornforth, photography of Keith Ellenbogen, and "Micronauts," an immersive installation journeying into the world of ocean microbes.

The *Play* and *Imagine* themes focused on some of the most fundamental passions ignited in us when we were children playing games and listening to stories. Participants explored how to tap into play, games, recreation, and transmedia storytelling to spark curiosity in explorers of all ages in order to imagine a bright, optimistic future for the ocean. Two hands-on workshops focused on *Play* allowed participants to join in on the fun by designing and piloting a LEGO remotely operated vehicle in the Charles River or designing their own ocean exploration game. In the *Imagine* workshop, participants learned how to identify and craft an exciting ocean story to bring others along on a journey.

The *Create* and *Immerse* themes encouraged using modalities ranging from art and music to extended realities to create experiences that transported participants to other worlds. The groups explored new and exciting ways to create immersive experiences that conveyed the mystery, wonder, and inspiration of the sea. The *Create* and *Immerse* hands-on workshops allowed participants

Live interaction and panel discussion with NOAA Ship *Okeanos Explorer* and scientists during Boston Ocean Day at the New England Aquarium, Simons IMAX Theater. *Image credit: Sam Mitchell, University of Hawai'i*

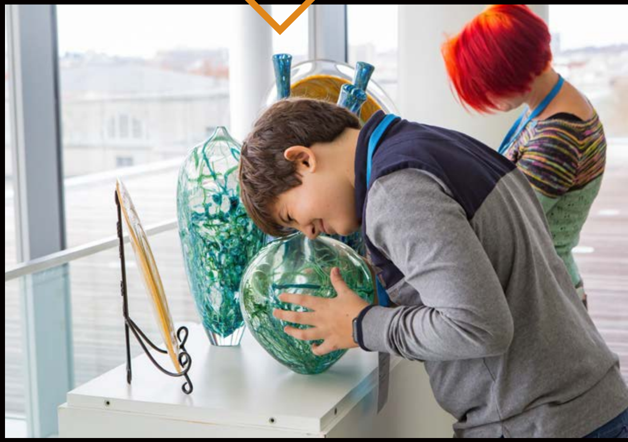
Participants attending the *Play* LEGO underwater robot workshop at the MIT Sailing Pavilion. *Image credit: Jon Tadiello*

to think of ocean exploration beyond the screen and the current aquarium experience—using technology and immersive environments, how can we create more exciting, impactful experiences?

The final themes of *Explore* and *Connect* focused on how to link a global community of ocean explorers with the ocean and with each other. Hands-on workshops illustrated how new tools and technologies can now allow everyone to explore their backyard ocean and how pop-up labs and crowd computing can entrain a new generation of ocean explorers. Through innovative technologies, like telepresence, anyone can join in and be a part of the exploration journey.

All Hands on Deck included Boston Ocean Day, held on November 10 in the Simons IMAX Theater at the New England Aquarium. Paired with the animated series *The Deep*, experts in the field of ocean exploration discussed topics ranging from underwater volcanoes to ocean acoustics to the twilight zone, capturing the imagination of all audiences. A concluding panel on ocean exploration gave the public an opportunity to dive deep into the world of ocean exploration with experts in the field and to ask questions live with scientists on NOAA Ship *Okeanos Explorer* as they investigated the deep waters off Puerto Rico.

Pau Anta and Kathleen Cantner explore ocean-inspired hand-blown glass by Whitney Cornforth from the MIT Glass Lab. *Image credit: Jon Tadiello*



While continuing the efforts of the 2017 National Ocean Exploration Forum to encourage a balance among participants, across disciplines, career stage, and gender, with a focus on an inclusive community, the 2018 Forum also took a different approach for attendance. It invited interested people across the globe to apply to attend and provided need-based small travel grants to Ocean Discovery Fellows. Of the 300 attendees, 42 Ocean Discovery Fellows came from 11 US states and 17 countries around the world; these Fellows were innovators with experience in science, technology, design, recreation, entertainment, storytelling, and community building. With participants that included scientists, artists, songwriters, engineers, and even surfers, attendance was the most diverse of any forum thus far.

Since 2013, the annual National Ocean Exploration Forums have brought together leaders in ocean exploration to discuss the goals of a national ocean exploration program—a NOAA-led, multi-agency federal collaboration with the private sector and academia. While the themes of more recent forums have varied, they have been based on recommendations from the forward-looking inaugural Forum held in 2013: *Ocean Exploration 2020*. Forums have emphasized the importance of using varied exploration platforms, developing new technologies, creating citizen science opportunities, increasing and fostering partnerships, improving low to no cost near-real-time data accessibility, and enhancing and expanding ways to communicate about ocean exploration.

The 2018 National Ocean Exploration Forum: *All Hands on Deck* yielded community recommendations to be captured in a formal report for release in 2019, revealing how the themes of *Play*, *Imagine*, *Immerse*, *Create*, *Explore*, and *Connect* can increase public engagement with and excitement about ocean exploration. Archived video, images, transcripts, and other information can be found at https://www.allhandsondeck.community/.

Expedition Support from the Inner Space Center

Collaboration is Key

By Colleen Peters, Dwight F. Coleman, and Catalina Martinez

To inspire the next generation of explorers, the Inner Space Center facilitates access to ocean exploration and research by pushing the boundaries of telepresence technology.

More than 30 years ago, Robert Ballard first proposed using satellites and high-bandwidth network connectivity to transmit data and imagery from the bottom of the ocean to shore in real time. The central hub for this technology, the Inner Space Center (ISC), was developed at the University of Rhode Island (URI) Graduate School of Oceanography (GSO) to connect ships at sea with a growing shore-based network. Partnerships with NOAA's Office of Ocean Exploration and Research and the Ocean Exploration Trust have enabled the Inner Space Center to operate as a robust, reliable, and versatile facility that can quickly adapt to support rapidly changing operational requirements. Today, based on nearly 15 years of collaborative efforts, OER, OET, URI, and other partners are able to apply "telepresence" technology to ocean exploration and educational endeavors routinely and globally today. This capability effectively erases geographic and physical boundaries and removes limitations on expertise at sea as well as on the available workforce.

URI student and ISC Intern, Benjamin Hooks, monitors a NOAA Ship *Okeanos Explorer* dive in Mission Control while a live interaction takes place with a high school in Rhode Island. *Image credit: Michael Salerno/URI*

Since 2009, the ISC has been steadily facilitating the telepresence-based operations aboard E/V *Nautilus* and NOAA Ship *Okeanos Explorer*. Live streaming video and audio from both of these ships are fully integrated into their operating models and are critical to their missions. Both programs rely on a cohort of shoreside scientists to assist in directing shipboard operations and sampling as well as in connecting to classrooms and other learning institutions for outreach during the expeditions. In addition to the two main ships, the ISC supports diverse expeditions aboard a variety of vessels, including those in the US academic research fleet and other ships of opportunity. The ISC's talented staff, including scientists, engineers, video producers, and students, collaborate closely with partners to develop innovative approaches to content delivery that use advances in satellite communications, networking, video broadcast, and streaming technologies.

The ISC was live streaming video well before many of the popular Internet technologies available today. As smartphones, multitouch screens, advanced high-speed publicly accessible networks, and widespread streaming on the commodity Internet become commonplace, the ISC works hard to innovate faster in order to keep pace in this rapidly evolving environment.

In the early days of telepresence-enabled ocean exploration, from about 2004 to 2008, the prototype ISC and its partners developed expensive technical solutions for video/audio/data transmissions from ships, primarily modified from the professional broadcast industry. Off-the-shelf, or "prosumer" grade, electronics did not exist, and high-quality video streaming on the Internet was nascent at best. These expeditions relied on Internet2, available primarily at universities and other research-based institutions, high-end encoders/decoders, and broadcast-quality intercom systems to interact with ships from shore at specially designed Exploration Command Centers.

From about 2010 to 2015, the ISC modified the technologies and developed innovative and less expensive ways to conduct telepresence-based exploration by using equipment meant for Internet broadcasting instead of traditional over-the-air television-style broadcasting. Prior to the proliferation of typical "cloud" services, the ISC and its partners had to rely on expensive hosted solutions to pay-per-view for each stream and end user, whether the users were members of the general public, exploration scientists based on shore, or trained telepresence participants.

Today, with free hosting solutions provided through YouTube and sophisticated Internet-based streaming technologies, the ISC is conducting business with more people at overall lower costs. Compression technologies and schemes for optimizing satellite bandwidth use have come a long way; we can send more data through narrower pipes at lower costs and maintain high quality of service. This unique way of conducting ship-based work both at sea and from shore, coupled with accessing data in real time is broadening the field well beyond the ocean sciences and expanding the collective vision of what is possible for the future.

The flexible and collaborative nature of these partnerships enables the ISC to continuously advance research and development efforts despite these challenges. During 2018, a significant change to the satellite network supporting NOAA Ship *Okeanos Explorer* was tested and implemented. The ISC team worked closely with the Global Foundation for Ocean Exploration technical team to completely redesign, rebuild, and operate the networking infrastructure that facilitates telepresence connectivity and interactivity. Building on the ISC's experience with supporting satellite and terrestrial network connectivity for E/V *Nautilus* and other research vessels, the joint team partnered with Verizon's Satellite Solutions Group to implement a private circuit to the ship, hung off URI infrastructure. This new architecture proved to be robust and error free, with Verizon 24/7 management and quality-of-service policies in place. As a result, the team was able to reduce overall network latency, minimize packet loss, and improve the stability of live video streams, voice intercom traffic, and data transfers. As part of the network, the team installed and supported five VOIP phone lines and provided high bandwidth wireless and wired Internet connectivity, which led to improved operational workflows for telepresence video/audio/data, as well as quality of life onboard the vessel.

Innovative ideas can be quickly converted into tangible results that directly benefit the scientific community. Research and development is continuous in order to provide improvements to the ships' networks and the ISC's capabilities. The ISC is currently working with its partners to develop strategies for near-real-time data transfer, dive video accessibility, and increased science communication through media. Through this persistence, the ISC has successfully supported hundreds of research expeditions, worked with dozens of federal agencies, academic institutions, and outreach partners, and reached thousands of audiences worldwide.

A NASA SUBSEA shore-based team was stationed at the ISC Mission Control for the 2018 E/V *Nautilus* expedition that explored Lōʻihi Seamount. NASA scientists observed the shipboard science team to learn how scientists and engineers communicate objectives via telepresence. The NASA team will return in May 2019 for the next phase of the project. *Image credit: OET*

ISC Highlights from 2018 By Colleen Peters and Dwight F. Coleman

Although the ISC schedule largely revolves around the sailing schedules of NOAA Ship *Okeanos Explorer* and E/V *Nautilus*, the ISC supports projects on board and on shore year-round. The following are some 2018 highlights.

VOLVO OCEAN RACE STOPOVER— ONE OCEAN EXPLORATION ZONE

In addition to helping coordinate the URI GSO involvement in the Volvo Ocean Race Stopover event in Newport, Rhode Island, from May 12 to 20, 2018, the ISC provided an interactive exhibit as part of the One Ocean Exploration Zone (OOEZ). More than 3,400 students from 52 schools around New England paraticipated in guided field trips to the OOEZ and Race Village. The ISC exhibit featured fish-building and bioluminescence activities, deep-sea rocks and specimens, as well as a selection of underwater videos displayed on an iPad kiosk. The ISC and its main partners, NOAA's Office of Ocean Exploration and Research and the Ocean Exploration Trust, provided educational materials and videos. Over 101,000 people visited the Race Village during this event.

URI-ISC interns Erin Chile and Gloria Keough help set up the ISC exhibit at the Volvo Ocean Race One Ocean Exploration Zone at the Race Village in Newport, Rhode Island. *Image credit: ISC/Colleen Peters*

Live interaction between NOAA Ship *Okeanos Explorer* and a classroom in New Jersey, hosted at and produced by the ISC. *Credit: ISC*

ENHANCING LIVE INTERACTION CAPABILITIES

The Skype a Scientist program (https://www.skypeascientist.com/) matches classrooms with scientists around the world. As part of this program, the ISC facilitated several live interactions between classrooms and Catalina Martinez, Regional Program Manager for OER. NewTek Talk Show, which integrates Skype into the ISC Production system, provides the ISC with the new capability to feed multiple sources of video and audio to the audience. As Catalina discussed various topics of ocean exploration with students, the ISC inserted relevant video clips from the *Okeanos Explorer* program to enhance the conversation. This capability provides the audience with a free and easy way to connect to the ISC and the vast library of exploration content provided by our partners.

WORLD OCEANS DAY TRI-SHIP CONNECTION

On June 8, 2018, the ISC coordinated and hosted a live interaction between NOAA Ship *Okeanos Explorer*, E/V *Nautilus*, and R/V *Falkor* as part of the globally celebrated World Oceans Day. The event reached over 6,000 viewers across four YouTube and four Facebook live streams, a more than tenfold increase from the previous year's event. Viewers heard from scientists, engineers, and crew as they discussed the important (and exciting!) work they conduct to explore and understand our changing ocean. The ISC leveraged the ability to stream to multiple platforms, which significantly broadened the reach of this annual event. An archive of this interaction can be viewed on the ISC's YouTube Channel at https://youtu.be/NeOINR-Ag9s.

Colleen Peters hosts the 2018 World Oceans Day Tri-Ship Connection at the University of Rhode Island Inner Space Center. *Credit: ISC*

The ISC designed and built Mobile Telepresence Units outfitted with video, audio, and production components to support live broadcasts from polar regions using the newest Inmarsat satellite constellation and services, known as Global Xpress. *Image credit: ISC/Kyle Sidlik*

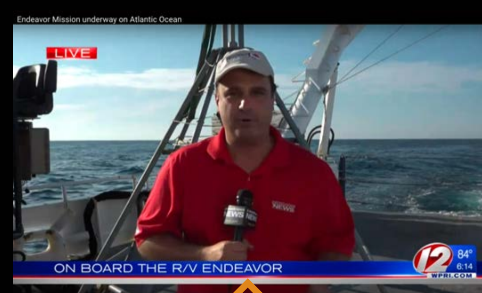
SATELLITE TESTING FOR TELEPRESENCE ON POLAR REGION RESEARCH VESSELS

The ISC team is supporting two significant National Science Foundation funded projects to conduct live broadcasts to museums and aquariums from two polar research vessels, one that operates in the Arctic and the other in the Antarctic. Both projects involve using creative techniques to broadcast live from these remote regions using the newest Inmarsat satellite constellation and services, known as Global Xpress. This Ka-band satellite technology allows ships to broadcast live video at lower bit rates and lower cost than traditional C-band or Ku-band satellite technologies. During the Northwest Passage Project, the scientific team will conduct chemical and physical oceanographic research in the Canadian Arctic Archipelago. During the project Antarctic Broadcasts: Broader Impacts Through Telepresence (ABBITT), the scientific team will conduct research at Palmer Station and aboard R/V *Laurence M. Gould*. The informal science education component to these projects involves (in part) live broadcasts to public audiences at partner venues such as the Smithsonian Institution's National Museum of Natural History. To support these efforts and to technically prepare for the projects, the ISC tested throughput and stream quality through a number of Global Xpress systems, including one aboard R/V *Neil Armstrong*, with excellent results, considering the cost savings and ease of use. This testing proves that telepresence-enabled research expeditions could be accomplished using smaller satellite antennas with lower cost components and air time.

MOBILE TELEPRESENCE SUPPORT ON URI'S R/V *ENDEAVOR*

In April 2018, undergraduates from URI's Honors Program departed on a six-day oceanographic expedition aboard R/V *Endeavor*. As a partner in a Rhode Island Endeavor Program funded project, the ISC coordinated telepresence activities to support live programming from the ship. Four broadcast opportunities were provided to school groups, where classes connected with the ship, learned about research activities, and were able to ask questions of cruise participants in real time. Over 1,000 students participated and submitted approximately 75 questions. In addition to numerous social media posts highlighting expedition activities, three Facebook Live events, with video and real-time Q&A, were also conducted with almost 2,000 views.

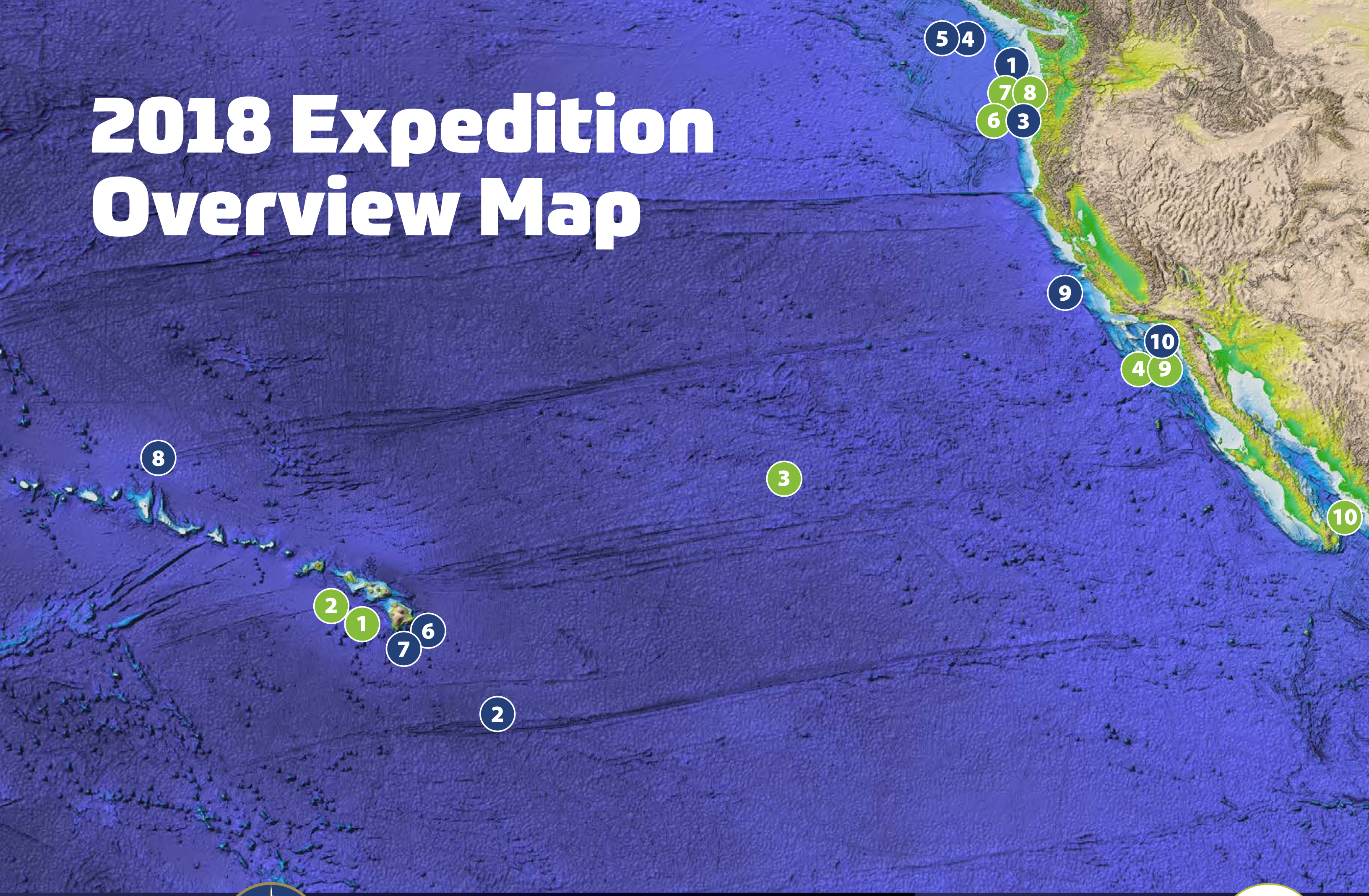
From July 31 to August 2, 2018, the ISC supported telepresence activities aboard R/V *Endeavor* as part of the 2018 Rhode Island Teacher at Sea (RITAS) program. RITAS provides an opportunity for Rhode Island teachers to actively participate in ocean science research and then bring their experiences back to their classrooms. What made this year's expedition unique was the participation of RI Channel 12, WPRI, meteorologist T.J. Del Santo, who also sailed with the teachers and scientists. During the expedition, T.J. shared his experiences through his online weather blog and delivered live reports from the ship during WPRI 12 Eyewitness News broadcasts. ISC telepresence support was key in making these live broadcasts possible.



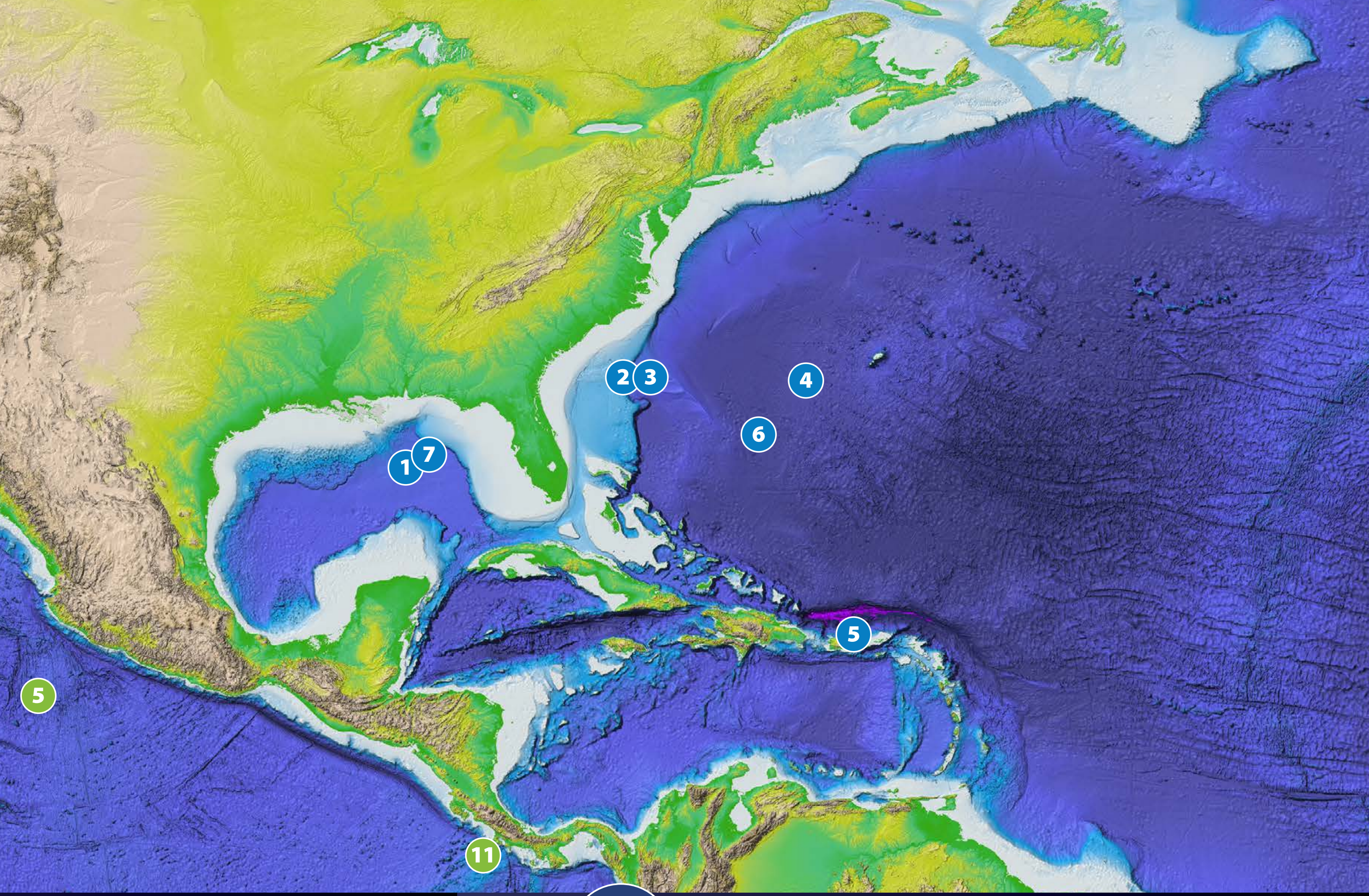
Meteorologist T.J. Del Santo of RI Channel 12, WPRI, sailed aboard R/V *Endeavor* to deliver live reports from the ship during WPRI 12 Eyewitness News newscasts during the Rhode Island Teacher at Sea cruise. *Image credit: WPRI*

ROV *Hercules* explores unnamed seamount 9 in Papahānaumokuākea Marine National Monument on E/V *Nautilus* cruise NA101. *Image credit: OET*

2018 Expedition Overview Map



E/V *NAUTILUS* EXPEDITIONS



R/V *FALKOR* EXPEDITIONS

NOAA SHIP *OKEANOS EXPLORER* EXPEDITIONS

* ASPIRE

A sunstar climbs over a rock covered in coral on Dellwood Seamount off the coast of Canada during E/V *Nautilus* cruise NA097.

PART 1

Ocean Exploration Trust – E/V *Nautilus*

Ocean Exploration Trust and E/V *Nautilus*

THE FIRST TEN YEARS (2009–2018)

By Robert D. Ballard

The Ocean Exploration Trust came into existence in late 2008 with the acquisition of *Alexander Von Humboldt*, built in East Germany in 1967. Its original name was *Georgius Agricola* in honor of the "father of mineralogy," but in 1970 the East German government took over the ship and renamed it. Following German reunification, the ship was put up for auction and purchased by New York businessman Vincent Viola, who donated it to OET to support its ongoing program with NOAA's Office of Ocean Exploration and Research. The ship was named *Nautilus* in honor of Jules Verne's mythic submarine, and it is an exploration vessel, "E/V," rather than a research vessel, "R/V," because its primary mission is to conduct scientific expeditions where there is little to no information, rather than traditional hypothesis-driven research.

In August 2009, E/V *Nautilus* carried out is first expedition in shallow water to locate and document many of the warships that were sunk during the historic Battle of Gallipoli, including the British warships HMS *Irresistible*, HMS *Ocean*, and HMS *Triumph*, the French battleship *Bouvet*, and the German cruiser *Breslau* given to the Ottoman Navy and renamed *Midilli*. This work was presented in the National Geographic documentary *Gallipoli's Deep Secrets*. Early expeditions were conducted without the help of a dynamic positioning system, so the ship would anchor to hold position during ROV dives.

For the next five years, from 2009 to early 2013, the Ocean Exploration Trust spent over $17 million in private funds to upgrade *Nautilus*, increasing the technical complexity of its annual field program as enhancements were made (pages 26–29). Another important facet of OET's program was the development and testing of a wide range of new sensors systems, which are highlighted in previous issues of *New Frontiers in Ocean Exploration* (Bell and Fuller, 2011; Bell and Brennan, 2013; Bell et al., 2012, 2014, 2015, 2016, 2017; Raineault et al., 2018).

Research in the early years focused on the emerging field of archaeological oceanography. More specifically, efforts went toward proving the existence of ancient deepwater trade routes in the Mediterranean Sea, as well as exploring the deepwater regions of the Black Sea to search for highly preserved ancient shipwrecks in its anoxic bottom waters, first proposed to exist by Willard Bascom (1976). The program, funded by OER and the National Geographic Society, successfully documented numerous ancient deepwater trade routes in the Mediterranean,

ROV *Hercules* documents the wreck of the Greek M/V *Dodekanisos* in the Aegean Sea in 2011. The ship sank in a storm in 1958.

Amphoras photographed in the Mediterranean Sea during a 2012 expedition that was mapping Knidos shipwrecks at high resolution.

Aegean, and Black Seas. The discovery of over 40 ancient shipwrecks and countless other discarded artifacts provided clear evidence of these trade routes (e.g., Ballard et al., 2000, 2002; Ballard, 2009; Brennan and Ballard, 2014). Most important of these discoveries was the highly preserved early 3rd century BCE Hellenistic merchant ship Ereğli E, which showed evidence of both pegged mortise-and-tenon and laced construction—and it also contained human remains (Davis, et al., 2017). Equally important was the discovery of numerous artifacts and ancient shipwrecks on Eratosthenes Seamount dating back to the Bronze Age (Ballard et al., 2017) that documented a complex series of deepwater trade routes that had changed over time.

Several cruises were also conducted in collaboration with Serhiy Voronov, Head of the Department of Underwater Archaeology of Ukraine. The focus of his work was on the maritime history of the Crimean continental shelf, which led to the discovery and documentation of several World War II warships, including *Dzherzynsky*, *Lenin*, *Prut*, *Doob*; four submarines; one barge; and two patrol boats. This effort also discovered the dreadnaught warship *Ekaterine II* from the Crimean War and two Byzantine shipwrecks off Chersonesos on the Crimean peninsula, as well as a highly preserved 1970s-vintage Soviet helicopter located in the deep anoxic waters off Sevastopol.

Deepwater archaeological oceanography was not the only focus of OET's efforts in the 2009 to early 2013 timeframe. Several expeditions concentrated on exploring the geological and biological aspects of the Mediterranean, Aegean, and Black Seas. A particular focus was the collision of the African and Eurasian Plates. Expeditions targeted the Kolumbo Volcanic Rift Zone off the island of Santorini, the Anaximander mud volcanoes, the Nisyros submarine volcanic field, and the compressional regime of Eratosthenes Seamount (e.g., Bell et al., 2012; Nomikou, et al., 2012; Carey et al., 2013). Exploration of Eratosthenes led to the unexpected discovery of low-temperature hydrothermal vents hosting tubeworm and mollusk chemosynthetic ecosystems. Other expeditions examined Gorringe Bank in the Eastern Mediterranean off Portugal, the Western Mediterranean Sea off Spain, submarine volcanoes of the Aeolian Arc and Straits of Sicily, and deepwater corals and cold seeps along the continental margin of Israel (e.g., Rubin-Blum et al., 2011; Hilario and Cunha, 2013; Vieira et al., 2014). Working in territorial waters of Ukraine, Turkey, Greece, Cyprus, Italy, Israel, Spain, and Portugal fostered collaborations between nations, as scientists from each host nation sailed with us on expeditions.

In the winter of 2012–2013, *Nautilus* was outfitted with a hull-mounted Kongsberg EM 302 multibeam sonar and Knudsen sub-bottom profiler. OET tested the systems off the coast of France before mapping across the North Atlantic and beginning three years of work in the Gulf of Mexico and Caribbean Sea.

CARIBBEAN SEA

OET's work in the Caribbean Sea focused on exploring the Lesser Antilles subduction zone, including the impact of volcanic eruptions on the seafloor around the island of Montserrat, the active Kick'em Jenny submarine volcano off the island of Grenada, and cold seeps off Barbados (e.g., Watt et al., 2015; Gobin et al., 2017; Mittelstaedt and Smart, 2017; Michel et al., 2018). Of particular interest was

An octopus spied on some recent lava flows along the Galápagos Spreading Center in 2015.

the discovery of active cold seeps at the distal margin of the Kick'em Jenny. Interior volcanic collapse triggered an avalanche, and the overlying pressure of the debris on the organic-rich sediments beneath led to methane release (Carey et al., 2014). The methane seeps support rich chemosynthetic ecosystems colonized by sessile organisms, including large mussels with commensal scale worms, clams, gastropods, crinoids, anemones, shrimp, and polychaetes, as well as octopods, holothurians, crabs, ophioroid sea stars, and benthic fishes. Given the extensive global distribution of turbidity currents and other mass wasting processes taking place on the continental margins of the world, this region of the ocean that has gone largely unexplored may merit additional exploration.

Another focus of this three-year effort was the Caribbean Plate's northern translational boundary. OET investigated possible natural hazards associated with earthquakes and tsunamis generated by sudden plate motions, as well as benthic biology in the Greater Antilles north of Puerto Rico (e.g., Andrews et al., 2014). In addition, we explored hydrothermal vents of the Mid-Cayman Rise, conducted significant mapping surveys of the deeper portions of the Mesoamerican barrier reef off of Belize, and examined the geology and biology of the Windward Passage and the Jamaica Channel in the vicinity of the 2012 Port-au-Prince earthquake (e.g., Marr, 2015; Anderson et al., 2016).

Two cruises explored the carbonate platforms of the Great Bahamas Bank and offshore Florida. Extensive mapping of northern Bimini, the west slope of the Great Bahamas Bank, and south of the Dry Tortugas was followed by a series of ROV dives that included inspection of an apparent sinkhole located at the surprising depth of 824 m.

GULF OF MEXICO

Moving into the Gulf of Mexico, OET's program shifted away from ancient archaeology to modern maritime history. Surveys sought to characterize three early nineteenth century shipwrecks off Galveston, Texas, one thought to be a privateer vessel (Monterrey A) and the other two associated "prize" ships. The wreck was extensively mapped and imaged at high resolution before and after the recovery of artifacts from Monterrey A (Vaughn, 2015).

Another expedition documented a series of World War II ships sunk by Germany during "Operation Drumbeat" in the early stages of the war. The vessels included the oil tankers *Gulfpenn* and *Guldoil*, the bauxite-laden freighter *Alcoa Puritan*, and the passenger ship *Robert E. Lee* sunk by Nazi submarine (U-boat) *U-166*, which was itself investigated during this expedition. Evidence gathered during this expedition resulted in the US Navy reversing its previous finding that patrol boat PC-566 could not have sunk *U-166* because the crew had no anti-submarine training. The original ruling resulted in the captain, who reported the incident, being relieved of his command. The captain was posthumously honored by the Navy. This story was told in the NOVA documentary *Nazi Attack on America* (2015).

A three-year program with researchers funded by the Gulf of Mexico Research Initiative (GoMRI) sought to understand the effects of both natural oil and gas seepage, as well as the enduring impacts of the 2010 Deepwater Horizon disaster, on deepwater coral communities. This Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) group showed that the spill affected deep-sea corals through 2017 (Ruiz-Ramos et al, 2017; Girard and Fisher, 2018; Girard et al., 2018). Another group, the Gulf Integrated Spill Response Consortium (GISR), also sponsored by GoMRI sought to understand and predict the fundamental behavior of petroleum fluids in the ocean environment. These cruises focused on collecting field measurements needed to validate numerical models of oil and gas distribution in the water column above two natural hydrocarbon seeps in the Gulf at depths near 1,000 m. Equally important to these researchers was gaining a better understanding of the fate and transport of gas bubbles generated by the numerous natural seeps within the Gulf of Mexico (Wang et al., 2016).

Studies of large brine lakes within the Gulf of Mexico focused on the unique ecosystems living around these seafloor pools, which are four times more saline than seawater. Barite commonly rims the pools, while the fluids within the pools have high concentrations of iron as well as sulfide and methane that drive associated chemosynthetic ecosystems containing massive concentrations of mussels.

PACIFIC OCEAN BASIN

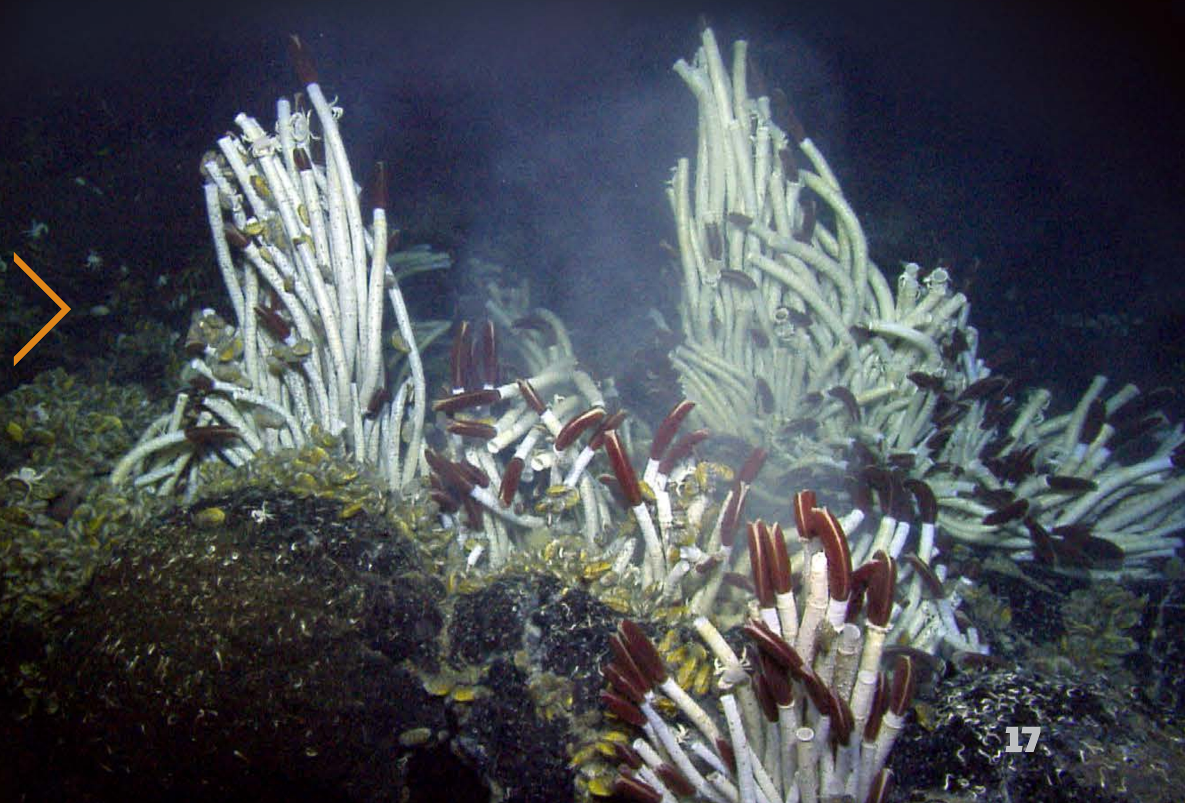
In May 2015, *Nautilus* entered the Pacific Ocean for the first time via the Panama Canal. The ship's initial stop was the Galápagos Islands where it conducted two major surveys. The first was a return trip to the site of the 1977 discovery of hydrothermal vents along the axis of the Galápagos Spreading Center (GSC). The initial objective of this cruise was to see how this region had changed over the last 40 years. Several important discoveries were made, including the presence of massive sulfide deposits around once-active high-temperature "black smokers." These deposits extended for 8 km along the axis of the GSC rift valley. The so-called Iguanas Vent Field—containing the tallest and largest number of active vents observed anywhere along the GSC—was also explored.

Despite numerous expeditions to the GSC since 1977, little is known about the ocean floor surrounding the Galápagos Islands themselves. For that reason, OET put forth a major effort to map areas surrounding the Wolf-Darwin Seamount Chain and the submarine flanks of the larger islands, in particular, Fernandina, where the active hotspot is presently located. ROV dives collected rock samples for geochemical analysis and obtained the first in situ observations of hydrothermal iron-bearing tubular nontronite deposits, as well as the apparent incubation of shark eggs near hydrothermal vents (Lubetkin et al., 2017; Salinas de Leon et al., 2018). Many new species have been identified and are in the process of being described (e.g. Cairns et al., 2018).

Nautilus mapped its way north from the Galápagos Islands, collecting nearly 44,700 km^2 of bathymetric data. These detailed maps revealed seafloor features not seen in maps derived from satellite altimetry. Abyssal hills with cauldron-like depressions and seeps were detected off the coast of California, and would become the focus of future ROV operations on Redondo Knoll. One of the major long-range objectives of OET's Basic Exploration program is to map the entire Exclusive Economic Zone (EEZ) off the US West Coast as well as EEZs located in the Central and Western Pacific.

NEW FOCUS ON THE US EEZ

After spending its initial six years conducting workshop-driven Basic Exploration programs in various international areas of interest and within the high seas, OET shifted focus to exploring primarily within the US EEZ in the Pacific in collaboration with OER.



Riftia pachyptila tubeworms and *Bathymodiolus thermophilus* mussels thrive amidst the active Tempus Fugit hydrothermal vent on the Galápagos Spreading Center in 2015.

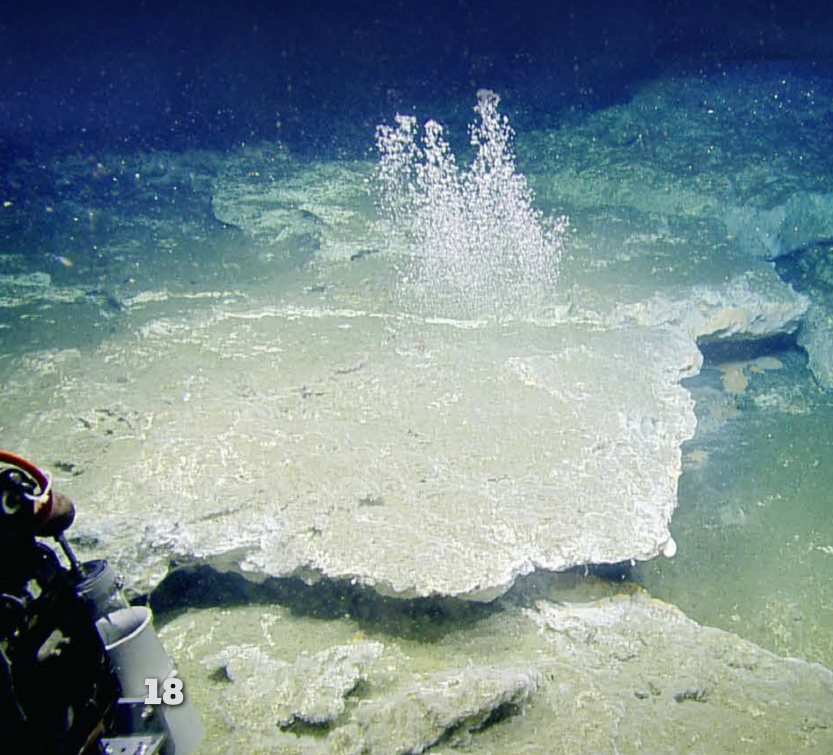
Nautilus expeditions within the US EEZ have investigated a variety of targets of interest to researchers. One such target, SS *Coast Trader*, sunk by the Japanese during World War II while carrying nearly 8,800 barrels of heavy fuel oil, was a potential hazard to the marine ecosystem immediately outside the Olympic Coast National Marine Sanctuary (NMS; Delgado et al., 2017). During our latest field season, explorations included the recent submarine eruptions off the Big Island of Hawaiʻi, the April 2018 underwater earthquake off Los Angeles, California, and the March 2018 meteorite impact off the Oregon coast. These surveys were rapid responses to recent events that OET incorporated into already planned expeditions. This type of timely response is critical for observing, mapping, or sampling events that are time-sensitive or may provide time-critical insight needed for decision-making.

One example of a partnership that helps inform management decisions within the US EEZ is OET's long-standing work with NOAA's Office of National Marine Sanctuaries. In 2015, OER began funding an annual effort to use *Nautilus* to map and explore the deeper portions of national marine sanctuaries—most of which are completely unknown. In support of this project, OET has conducted expeditions in all of the sanctuaries along the US West Coast (Channel Islands, Monterey Bay, Greater Farallones, Cordell Bank, and Olympic Coast) and one to Papahānaumokuākea Marine National Monument in the Northwestern Hawaiian Islands. These investigations have vastly improved knowledge of deep-sea habitats in these regions, including the discovery of new species (pages 50–51). In 2019 we plan to continue our work with the West Coast NMS and with American Samoa NMS. Past efforts have focused not only on the biology of deep-sea coral and sponge communities, but also on maritime heritage. Detailed investigations of the World War II aircraft carrier USS *Independence* and the USS *Macon* airship, located in the Greater Farallones and Monterey Bay NMS, respectively, have been particularly fruitful.

Other collaborations, such as with the NOAA's Pacific Marine Environmental Laboratory (PMEL), have resulted in discoveries that led to future focused research. For example, *Nautilus* mapping data collected in 2016 showed that hundreds of methane seeps exist along the Cascadia margin. This new information sparked long-term, multiagency interest in understanding the area between the Straits of Juan de Fuca and Cape Mendocino. During 2016, a series of ROV dives characterized and sampled 10 of the associated cold seep sites, and this partnership with PMEL continued in 2018 with a second expedition to the Cascadia margin (pages 40–41). Other researchers, including those aboard R/V *Falkor*, have continued this exploration (pages 128–137).

Over the years, partnerships with other federal agencies have also helped with the development of new tools, technologies, and ways of exploring. In 2017, OET worked with Peter Girguis of Harvard University to test the NASA-supported ABISS lander, which combines advanced sensor and communication technologies to learn more about deep-sea biogeochemistry. In 2018, OET collaborated with NASA and OER on the SUBSEA expedition to Lōʻihi Seamount off Hawaiʻi's Big Island. This undersea mountain hosts hydrothermal vent systems that are thought to be analogues for others that may exist in our solar system such as on Saturn's moon Enceladus (pages 48–49). OET will continue to collaborate with the SUBSEA team in 2019 on an expedition to Gorda Ridge, part of the mid-ocean ridge system in the Northeast Pacific. Under NASA's Ocean

Aboard *Nautilus*, Robert Ballard briefs the team about deep-sea vents along the Galápagos Spreading Center in 2015.



A spray of bubbles releases over a carbonate crust at the Klamath Knoll methane seep in 2016.

Worlds program, engineers are developing and testing a new diamond drill that is designed to sample vertical rock surfaces and pairs with the microspine gripper (page 28).

Although the new emphasis of the Basic Exploration program, sponsored by OER, is the US EEZ, OER continues to support community workshop-driven programs carried out in international waters. OER supported investigation of the Northern Guaymas Basin in the Gulf of California, where a wide range of hydrothermal vent sites exist along the axis of the sediment-covered East Pacific Rise. There, researchers explored high-temperature black smokers to lower temperature vents and their unique chemosynthetic ecosystems, as well as cold seeps. *Nautilus* also explored the Revillagigedo Archipelago, located 450 km south of Baja California. This area, referred to as "Mexico's Galápagos," was declared a UNESCO World Heritage site in 2016. We explored the sites of submarine volcanic eruptions that took place in 1993 in the deeper regions around the islands of Socorro and San Benedicto, and the impact the oxygen minimum zone has on marine ecosystems on the flanks of the islands.

In 2015, we began a long-term partnership with Ocean Networks Canada (ONC). Based at the University of Victoria, ONC operates the NEPTUNE and VENUS cabled ocean observatories located off the west coast of Canada. VENUS includes three main sites in the Salish Sea, while NEPTUNE's footprint is much larger, and includes nodes off the west coast of Vancouver Island along the Cascadia subduction zone, on the Cascadia Basin abyssal plain, and on the Endeavour Segment of the Juan de Fuca Ridge. Researchers using these networks, which include a wide variety of sensors, are studying deep-sea biodiversity, marine ecosystem function, gas hydrates, hydrothermal vents, sediment and benthic dynamics, and tsunami generation. OET's primary goal is to support maintenance of VENUS and NEPTUNE, as well as the installation of new cables and instrumentation. In 2018, this collaboration with ONC was expanded to include an expedition sponsored by Fisheries and Oceans Canada to explore three seamounts off the coast of British Columbia—SGaan Kinghlas-Bowie, Dellwood, and Explorer—in an effort to manage and protect their unique biodiversity (pages 42–43).

The current supplement to *Oceanography* highlights the 2018 expedition season, as well as the advances in our education and outreach and samples programs. OET has also expanded its reach among researchers and scientists worldwide. Initially, OET worked solely with the Center for Ocean Exploration at the Graduate School of Oceanography at the University of Rhode Island to use the Inner Space Center's telecommunications hub to establish a "Doctors on Call" program, which connected scientists at their home institutions with the field program in real time. The Watch Leader on *Nautilus* was able to call on experts from a broad range of disciplines who had indicated a willingness to be contacted should a new discovery be made in their area of expertise. Within minutes, the Watch Leaders were able to contact experts ashore to assist in the execution of any follow-up work that needed to be done once an important discovery was made. Since 2013, OET has recruited interested scientists for this program, renamed "Scientists Ashore," which has grown to include more than 200 registered participants per year. The program now invites scientists to pre-expedition planning calls to provide input on cruises and allows them to use a chat system to message the watch leaders during dives. Certain experts are also able to talk directly to the team on board *Nautilus* during ROV dives to direct operations and also provide context to the audience on NautilusLive. The growth in this program ensures that the exploration we conduct reaches the global community of scientists and makes the most of the data and samples collected.

THE SECOND TEN YEARS (2019–2028)

OET has learned a great deal over the last 10 years of operating E/V *Nautilus* and looks forward to the next 10 years as our program reaches full maturity. OET is presently seeking to increase its annual at-sea operational tempo from six months to eight to nine months, divided between *Nautilus* and its new mobile systems that are coming online for community use in 2020.

NEW MOBILE SYSTEMS

Having a dedicated exploration vessel has great benefits. This "turnkey" operation permits rapid turn-around between expeditions, and there is less wear and tear on our various supporting technologies and personnel. However, having one ship limits where we can go each year. Given that the Pacific Ocean represents 50% of the world ocean and contains the majority of America's EEZ, OET has decided to spend the next five to 10 years or more in this ocean basin.

OET is now building three mobile systems. These systems can be deployed from a broad range of research platforms, from Global Class research vessels to the new Regional Class research vessels of the US academic research fleet, and will be able to operate at 6,000 m, 4,000 m, and 2,000 m depth ranges. They will share a common series of support facilities, including mobile winches/cable units, a high-bandwidth satellite system, a vehicle support van, a dual-frequency side-scan sonar, a vehicle tracking system, and a portable launch and recovery crane. Other technologies that OET operates or will operate in the future include an autonomous surface vessel, elevators, surface drones, drop cameras, and a cable-following plankton imaging vehicle, all in an effort to expand our present exploratory technology.

Technology

E/V *Nautilus*

E/V *Nautilus* is a fully integrated, turnkey ROV and mapping exploration platform staffed by scientific, operations, and logistics experts organized to reliably produce class-leading structured data. The ship is equipped with a Kongsberg EM 302 multibeam echosounder and two remotely operated vehicles (ROVs), *Hercules* and *Argus*. *Nautilus* has a data lab and wet lab for processing digital data and physical samples. As part of the Ocean Exploration Trust's effort to share expeditions with students, public audiences, and colleagues, we utilize telepresence technology to stream live video from the ROVs and various locations aboard the ship in real time to the Nautilus Live website (https://nautiluslive.org).

GENERAL

BUILT. 1967, Rostock, Germany

LENGTH. 64.23 meters (211 feet)

BEAM. 10.5 meters (34.5 feet)

DRAFT. 4.9 meters (14.75 feet)

TONNAGE. 1,249 gross, 374 net

RANGE. 24,000 kilometers (13,000 nautical miles) at 10 knots

ENDURANCE. 40 days at sea

SPEED. 10 knots service, 12 knots maximum

FUEL CAPACITY. 330 cubic meters

PROPULSION. Single 1,285 kilowatt (1,700 hp) controllable pitch main thruster; 280 kW bow tunnel thruster; 300 kW jet pump stern thruster

SHIP SERVICE GENERATORS. Two 585 kVA generators, one 350 kVA generator

PORTABLE VAN SPACE. One 6.1-meter (20-foot) van

COMPLEMENT. 17 crew; 31 science and operations

FLAG. St. Vincent and the Grenadines

HEAVY EQUIPMENT

- Dynacon 421 ROV winch with Rochester A06063 1.73 centimeter (0.681 inch) diameter cable
- DT Marine 210 winch
- Bonfiglioli knuckle-boom crane, 2–6 ton capacity, two extensions
- Two airtuggers, SWL 900 lbs each
- A-frame, SWL 8 mtns
- Rescue boat davit with SWL 0.9 mtn

TELEPRESENCE TECHNOLOGY

VSAT. 2.4 meter axis stabilized Sea Tel 9711 uplink antenna capable of C- and Ku-band operation of up to 20 Mbps (C-band circular or linear)

REAL-TIME VIDEO STREAMING. Four Haivison X encoders designed for streaming live video via satellite to the Inner Space Center ashore

CAMERAS. Two Sony BZR-H700 high-definition pan/tilt/zoom cameras mounted to view the aft deck and port rail; one BZR-H700 in the control vans; Marshall VS-570 PTZ cameras in the wet lab and in the ROV hanger

COMMUNICATIONS

- Ship-wide RTS Telex intercom system for real-time communications between ship and shore
- Handheld UHF radios are interfaced with the RTS intercom system for deck, bridge, and control room communications
- Telephone interface is available through a Rhode Island exchange for real-time collaboration between scientists ashore and on the ship
- Full Internet connectivity from shipboard LAN and wifi
- KVH TracPhone-v7 for redundant bridge communication, providing telephone and IP service

DATA PROCESSING & VISUALIZATION LAB

AREA. 44.5 square meters (480 square feet)

WORKSTATIONS. Seven workstations for science manager, data loggers, navigators, educators, data engineers, satellite engineer, video engineer; seafloor mapping data processing; flexible bench space

RACK ROOM

AREA. 17.3 square meters (185 square feet)

DATA STORAGE. 32 TB online storage for non-video data; 32 TB disk storage for video data; 2x LTO-8, 2x LTO-6 archive media drives

EMERGENCY COMMUNICATIONS. KVH phone

ELECTRONICS WORKBENCH. 2.3 cubic meters (80 cubic feet) of storage

PRODUCTION STUDIO

AREA. 12 square meters (130 square feet)

CAMERA. Remote controllable high-definition Sony BRC-H700, Canon FX-305 for live deck television broadcasts and interactions

WET LAB

AREA. 19 square meters (204.5 square feet) with 5-meter-long (16-foot) stainless steel worktop

REFRIGERATION

- Panasonic MDF-C8V1 ULT –80°C/–86°C scientific freezer, 0.085 cubic meters (3 cubic feet)
- Science refrigerator, approximately 0.57 cubic meters (20 cubic feet)
- Standard chest freezer

HAZMAT

- Fume hood
- HAZMAT locker for chemical and waste storage
- Carry-on, carry-off chemical policy

ROV HANGAR

AREA. 24 square meters (258.3 square feet)

POWER. 110/60 Hz and 220/50 Hz available

PERSONAL PROTECTIVE EQUIPMENT. Hard hats, PFDs, high voltage gloves

LIFTS. 2 × 2-ton overhead manual chainfall lifts

STORAGE. Storage for spares and other equipment

ROV WORKSHOP

AREA. 18 square meters (193.8 square feet)

TOOLS. Complete set of hand tools, cordless tools, electrical and fiber optic test equipment, mill-drill combination machine

STORAGE. Storage for spares and other equipment

CONTROL VANS

AREA. 28 square meters (301.4 square feet)

WORKSTATIONS. Nine; typical configuration for ROV operations: two to three scientists, data logger, *Hercules* pilot, *Argus* pilot, navigator, video engineer, educator

VIDEO RECORDING AND STORAGE. Two Cinedeck ZX20 units for video recording and an iX Systems TrueNAS for 90 TB video storage capability

Image credit: Ed McNichol

Image credit: Ed McNichol

Acoustic Systems

KONGSBERG EM 302 MULTIBEAM ECHOSOUNDER

The EM 302 is a hull-mounted 30 kHz multibeam echosounder composed of two long transducer arrays mounted in a T-shape on the hull of Nautilus. It was installed on the ship between 2012 and 2013 to collect bathymetric, backscatter, and water column data. This information is useful for identifying areas or features of interest, creating bathymetric maps for ROV dive planning and situational awareness, and locating gas seeps. The EM 302 can map the seafloor in water depths from 10 m to 7,000 m (33 ft to 22,965 ft) at ship speeds of 12 knots.

FREQUENCY. 30 kHz

DEPTH RANGE. 10–7,000 meters (33–22,966 feet)

PULSE FORMS. CW and FM chirp

BEAMWIDTH. 1° × 1°

APPROXIMATE SWATH WIDTH. 3–5 times water depth, up to 8 km (5 miles)

APPROXIMATE GRID RESOLUTION. 10% water depth (e.g., 10 meters [33 feet] at 1,000 meters [3,281 feet] depth)

WATER COLUMN PROFILING

Oceanscience UCTD 10-400 profiling system; max depth 1,000 meters

KNUDSEN SUB-BOTTOM PROFILER AND ECHOSOUNDER

The Knudsen 3260 is a sub-bottom echosounder mounted inside the hull of *Nautilus*. It operates at low frequencies (3.5–210 kHz) so that the sound it emits can penetrate layers of sediment to about 100 m below the surface. The sound that bounces back from each layer is captured by the system, creating a cross section of the seafloor. Scientists can use the data to identify subsurface geological structures such as faults and ancient channels and levees. The Knudsen 3260 can operate in full ocean depths. The Knudsen system also collects 15 kHz single beam echosounder data.

PROFILER. Knudsen 3260 Chirp sub-bottom profiler and echosounder

OPERATING FREQUENCY. Dual frequency, 3.5 kHz and 15 kHz

POWER. 4 kW on Channel 1 and up to 2 kW on Channel 2

RANGE. 50 to 5,000 meters (164 to 16,404 feet)

ULTRA-SHORT BASELINE NAVIGATION SYSTEM

SYSTEM. TrackLink 5000MA system for USBL tracking of ROVs Hercules and Argus

RANGE. Up to 5,000 meters (16,404 feet)

POSITIONING ACCURACY. 1° (~2% of slant range)

OPERATIONAL BEAMWIDTH. 120°

OPERATING FREQUENCY. 14.2 to 19.8 kHz

TARGETS TRACKED. *Hercules*, *Argus*, and two additional transponders are available. With more transponders, up to eight targets including the ROVs can be tracked

Remotely Operated Vehicle *Argus*

ROV *Argus* was first launched in 2000 as a deep-tow system capable of diving to 6,000 meters. More recently, *Argus* is used in tandem with ROV *Hercules*, where it hovers several meters above in order to provide a bird's-eye view of *Hercules* working on the seafloor. Argus is also capable of operating as a stand-alone system for large-scale deep-water survey missions.

GENERAL

DEPTH CAPABILITY. 6,000 meters (19,685 feet), currently limited to 4,000 meters (13,123 feet)

CABLE. 4,500 meters (14, 764 feet), 0.681 electro-optical, 3x #11 conductors, 3x SM fibers

SIZE. 3.8 meters long × 1.2 meters wide × 1.3 meters high (12.5 feet long × 3.9 feet wide × 4.3 feet tall)

WEIGHT. 2,100 kilograms (4,700 pounds) in air, 1,360 kilograms (3,000 pounds) in water

MAXIMUM TRANSIT SPEED. 2 knots

ASCENT/DESCENT RATE. 20–30 meters/minute (65–98 feet/minute) max

PROPULSION. Two Tecnadyne Model 1020 thrusters for heading control

IMAGING & LIGHTING

CAMERAS

- One Insite Pacific Zeus Plus high-definition camera with Ikegami HDL-45A tilt head with Fujinon HA 10 × 5.2 lens, 1080i SMPTE 292M output format, 2 MP still image capable
- Two Insite Pacific standard definition mini utility cameras (fixed mounted) 480 line NTSC format
- One Deep Sea Power & Light Wide-i SeaCam, downward-looking standard definition camera (fixed mounted)

LIGHTING

- Three CathX Aphos 16 LED lampheads, 28,000 lumens each
- Two Deep Sea Power & Light 250 Watt incandescent lights

VEHICLE SENSORS & NAVIGATION

SYSTEM. NavEst integrated navigation system solution

USBL NAVIGATION. TrackLink 5000 system, acoustically triggered

PRIMARY HEADING. Crossbow high-resolution magnetic motion and attitude sensor

SECONDARY HEADING. Lord Microstrain 3DM-GX5-25 Attitude and Heading Reference System (AHRS)

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

ALTIMETER. Benthos PSA-916

FORWARD-LOOKING SONAR. Mesotech 1071, 675 kHz, 0.5–100 meter (1.6–328.1 foot) range typical

SUB-BOTTOM PROFILING SONAR. TriTech SeaKing Parametric Sub-bottom Profiler (10–30 kHz)

SCIENTIFIC INSTRUMENT SUPPORT

POWER. 110 V 60 Hz AC, 24 VDC and 12 VDC power options

DIGITAL DATA CHANNELS. Ethernet

Remotely Operated Vehicle *Hercules*

Since it was first launched in 2003, ROV *Hercules* has been working in tandem with ROV *Argus* to explore the geology, biology, archaeology, and chemistry of the deep sea. *Hercules* is equipped with a high-definition video camera, several LED lights, two manipulator arms, and a variety of oceanographic sensors and samplers, including a suite of high-resolution mapping tools that is available for use upon request. *Hercules* can deliver approximately 68–113 kg (150–250 lbs) of samples or tools to and from the seafloor.

GENERAL

DEPTH CAPABILITY. 4,000 meters (13,123 feet)

TETHER. 30–45 meters (98.4–147.6 feet), 20 millimeters (0.79 inches) diameter, neutrally buoyant

SIZE. 3.9 meters long × 1.9 meters wide × 2.2 meters tall (12.8 feet long × 6.2 feet wide × 7.2 feet tall)

MASS. ~ 2,500 kilograms (5,500 pound) mass in air

PAYLOAD. Up to 113 kilograms (250 pounds)

MAXIMUM VEHICLE SPEED. 0.77 meters/second (1.5 knots) forward, 0.25 meters/second (0.5 knots) lateral, 0.5 meters/second (1 knot) vertical (on site, within tether range)

MAXIMUM TRANSIT SPEED. 1 meter/second (2 knots), no sampling, in layback mode

MAXIMUM ON-BOTTOM TRANSIT SPEED.
0.5 meters/second (1 knot), no sampling

MAXIMUM SAMPLING TRANSIT SPEED.
0.25 meters/second (0.5 knots) on flat seafloor;
< 0.13 meters/second (< 0.25 knots) over featured terrain

ROV CLOSED LOOP POSITION CONTROL. Station Keep, X/Y step, Auto Depth, Auto Altitude, X/Y/Z step and hold velocity control

DESCENT/ASCENT RATE. 30 meters/minute (98.4 feet/minute)/15 meters/minute (49.2 feet/minute), or 20–22 meters/minute (65.6–7.2 feet/minute) average

PROPULSION
- Six hydraulic thrusters powered by 15 kW (20 hp), 207 bar (3,000 psi) hydraulic system
- Fore/Aft & Vertical – Four 27.94 cm (11 inch) ducted thrusters, each providing 900 N (200 lbf) thrust
- Lateral – Two 22.86 cm (9 inch) ducted thrusters, each providing 450 N (100 lbf) thrust

VEHICLE SENSORS & NAVIGATION

SYSTEM. NavEst integrated navigation system solution

HEADING AND ATTITUDE
- Primary Heading – IXSEA Octans III north-seeking fiber-optic gyrocompass (0.1° secant latitude accuracy with 0.01° resolution)
- Secondary Heading – TCM2 solid state fluxgate compass

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

CTD. Sea-Bird FastCAT 49

OXYGEN OPTODE. Aanderaa 3830

TEMPERATURE PROBE. WHOI high-temperature probe (0°–450°C, 0.1°C resolution)

USBL NAVIGATION. TrackLink 5000

DOPPLER NAVIGATION & ALTITUDE. RDI Workhorse Navigator Doppler Velocity Log 600 kHz, 0.7–90 meter range (2.3–295.3 feet)

FORWARD-LOOKING SONARS
- Kongsberg Mesotech 1071 scanning sonar, 300 kHz, 1–200 meter (3–656 feet) range typical
- TriTech Super SeaPrince 675 kHz, 50 meter (164 feet) range

IMAGING & LIGHTING

STANDARD IMAGING SUITE. One high-definition video channel on fiber optic, four standard definition video channels on coax, generally configured as:
- Insite Pacific, 6,000 msw rated, Zeus Plus with 10× zoom lens, Ikegami HDL-45A with zoom/pan/tilt/extend, 1080i SMPTE 292M output format

- Insite Pacific, 6,000 msw rated, Titan Rotate-Tilt standard definition camera (bubble camera) 480 line NTSC format
- Three Insite Pacific NOVA utility cameras, mounted to view the starboard sample box, port rail, and aft region 480 line NTSC format
- One Insite Pacific Aurora utility camera to view the eight-jar suction sampler, NTSC format
- One Deep Sea Power & Light Wide-i-SeaCam to view starboard side sample box, NTSC format

LIGHTING

- Two Deep Sea Power & Light Matrix-3 LED lamps, 20,000 lumens, forward mounted
- Six to twelve Deep Sea Power & Light Sphere LED lamps, 6,000 lumens, mounting configurable

SCALING. Two green Deep Sea Power & Light Micro Sea-Lasers, mounted 10 cm (3.94 inches) apart, HD camera only

HIGH-RESOLUTION MAPPING SUITE

- Available for nonstandard mapping products
- Typical configuration is downward looking; forward-looking configuration possible
- Two stereo Prosilica GT 2750 still cameras, one black & white, one color; 2,750 × 2,200 pixels; 29° × 39° field of view; 2–4 meter (6.5–13 feet) range; 200 watt-second strobe lighting at one image every three seconds
- Structured light laser system with a dedicated Prosilica GC 1380 still camera; runs concurrently with stereo imaging; 532 nanometer, 100 mW coherent laser; 45° line generating head
- System also supports Kongsberg M3 sonar

MANIPULATORS AND SAMPLING

MANIPULATORS

- Kraft Predator: Hydraulic, seven function spatially correspondent, force feedback, 200 lb lift
- ISE Magnum: Hydraulic, seven function, 300 lbs lift

SUCTION SYSTEMS

- Suction sampling system, eight 3-liter discrete samples
- Venturi dredge excavation system

SAMPLING TOOLS. Mission configurable:

- Up to eight 6.35 centimeter (2.5 inch) inner diameter, 28 centimeter (11 inch) long push cores
- Up to six 5-liter Niskin bottles, manually triggered
- Custom tools and sensors can be integrated

SAMPLE STORAGE

- Forward sample tray (inboard): 45 cm × 33 cm × 25 cm (17.7 inches × 13 inches × 9.8 inches)
- Forward sample tray (outboard): 68 cm × 35 cm × 30 cm (26.8 inches × 13.8 inches × 11.8 inches)
- Starboard sample drawer: 65 cm × 50 cm × 30 cm (25.5 inches × 19.7 inches × 11.8 inches)
- Payload: Up to 113 kilograms (250 pounds) depending on sensor package
- Custom configuration of boxes, crates, and containers

ELEVATORS. Mission configurable; free ascent; maximum standard payload 68 kg (150 lb)

SCIENTIFIC INSTRUMENT SUPPORT

SWITCHED POWER

- 110 V, 60 Hz AC
- 24 VDC
- 12 VDC

DIGITAL DATA CHANNELS

- RS-232: 115 Kbauds
- RS-485/422: 2.5 Mbauds
- Ethernet: 10/100/1,000 Mbps links available
- TTL: one TTL link

HYDRAULIC. Proportional and solenoid hydraulic functions:

- 1,150 psi at 5 GPM
- 1,850 psi at 5 GPM
- 3,000 psi at 5 GPM (advance notice needed)

EXAMPLES OF USER-INSTALLED TECHNOLOGY

- In situ mass and laser spectrometers
- Fluorometer, pH sensor, eH sensor
- Kongsberg M3 multibeam sonar
- 18 MP Ethernet connected digital still camera
- Low-light camera
- Modular soft grippers

2018 TECHNOLOGY COLLABORATIONS

- **NATIONAL GEOGRAPHIC SOCIETY.** Deep Ocean Drop Cameras
- **MIT MEDIA LAB.** 360° Camera
- **NASA JET PROPULSION LABORATORY.** ROV Underwater Gripper
- **NOAA PMEL.** Hydrate sampler, Miniature Autonomous Plume Recorders (MAPRs), hydrophone, major sampler
- **UNIVERSITY OF NEW HAMPSHIRE CCOM.** Autonomous surface vehicle
- **UNIVERSITY OF RHODE ISLAND.** Laser mapping system
- **UNIVERSITY OF TEXAS RIO GRANDE VALLEY.** Suspended particulate rosette (SUPR)
- **WOODS HOLE OCEANOGRAPHIC INSTITUTION.** MISO GoPro Camera & Housing, Isobaric Gas Tight (IGT)

Nautilus Samples Program

Documenting the History and Diversity of Our Ocean

By Nicole A. Raineault, Spencer Backus, Andrew Bocklund, Eric Contreras, Marc Fries, Rina Onishi, Bruce Ott, Aaron Parness, and Henry Reiswig

Explorers of our planet—and increasingly of others—require physical specimens to understand and document new environments. The specimens from across the United States collected by Lewis and Clark's Corps of Discovery and from the ocean by those who sailed on the voyages of the United States Exploring Expedition of 1838–1842 form the foundations of great institutions and research centers, providing materials for learning and study. In the last decade, the Ocean Exploration Trust's sampling program has grown in both the number and types of samples collected. Our goal is to provide critical materials from remote deep-sea locations for scientific research through nationally recognized institutions.

During the 2010 and 2011 field seasons, the majority of samples collected by ROV *Hercules* were short sediment cores, rocks, and biological specimens that were frozen because the ship lacked facilities for more sophisticated preservation. Some gas and water samples were also obtained for shoreside analysis by scientists who study the geochemistry of deep-sea volcanic venting in the Mediterranean. During the first phase of *Nautilus* renovations in the winter of 2012, a fume hood and a chemical locker were added to the wet lab, allowing non-cryogenic specimen preservation. The number of samples taken per year has increased from 257 in 2010 to 807 in 2018 (Figure 1). More recently, enhanced ROV *Hercules* sampling capabilities, driven by researchers' needs for samples, has necessitated further wet lab renovations to allow shipboard scientists to analyze or prepare more samples aboard *Nautilus* (Figure 2). This winter, the wet lab will undergo a total overhaul, designed to improve its usability and flexibility for increasingly complex at-sea processing.

Because deep-sea specimens are so precious, OET has also worked to expand the visibility and discoverability of samples. Geological samples have always been housed at the Marine Geological Samples Lab, a national repository for rocks and sediment cores located at the University of Rhode Island's Graduate School of Oceanography. However, biological samples were initially collected for onboard or partnering scientists and housed at each researcher's own laboratory, which limited their availability to other researchers. Starting in 2013, OET partnered with Harvard's Museum of Comparative Zoology (MCZ) for biological sample curation, which allows researchers to request specimens of interest and ensures discoveries will be made years after an expedition (Figure 3). MCZ houses

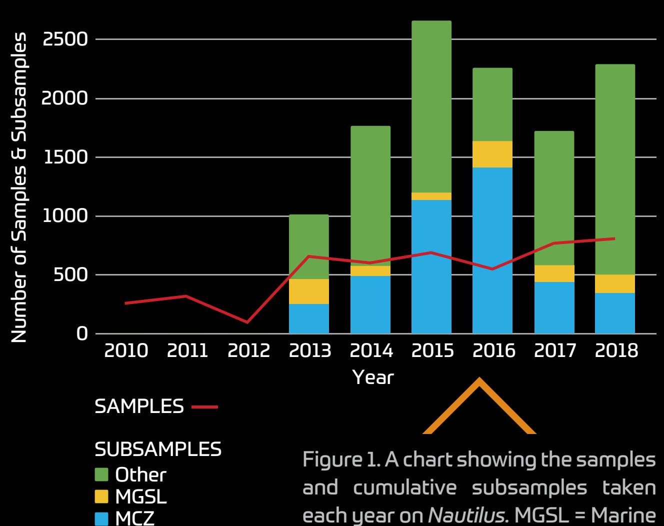


Figure 1. A chart showing the samples and cumulative subsamples taken each year on *Nautilus*. MGSL = Marine Geological Samples Laboratory at the University of Rhode Island. MCZ = Museum of Comparative Zoology at Harvard University.

Figure 2. PMEL scientist Tamara Baumberger in the wet lab holding a gas-tight sampler.

Figure 3. A map showing the locations and number of biological samples collected on *Nautilus* and archived at the Museum of Comparative Zoology, through 2018. *Map data from © 2018 Google Imagery, © 2018 NASA, Terrametrics*

both whole specimen and DNA subsampled material from *Nautilus* expeditions. Select specimens have also been part of museum exhibits to inform the public on topics ranging from chemosynthesis to climate change.

New techniques expand our ability to draw knowledge from something as basic as water or mud. Genetic material in fluid and sediment samples are now analyzed through the emergent technique known as environmental DNA (eDNA). Beginning in 2016, OET partnered with scientists at NOAA's Northwest Fisheries Science Center to collect water near coral and sponge communities, which has led to the advancement of techniques for identifying slow-growing, difficult-to-collect deep-sea corals from one liter of water rather than obtaining direct samples of the corals (Everett and Park, 2017). Water sampling for eDNA has become a standard program on all expeditions and this year expanded to include water collections for NOAA's Pacific Marine Environmental Laboratory scientists who study metagenomics at vent and seep sites. In addition, researchers at Oregon State University have used eDNA from short sediment cores collected near Cascadia margin seeps to study the functional biogeography of seep biota. Finally, this year, scuba divers also took the first sediment core for eDNA analysis within a submerged cave in Southern California. The overarching goal of incorporating eDNA sampling is to learn more about remote deep-sea environments using less invasive and less time-intensive sampling techniques.

Collection of many of the samples during the 2018 expeditions was made possible with the help of specialized sampling tools developed for ROV *Hercules*. A few examples include a magnetic wand created for sampling meteorites (page 28), a methane ice sampler (pages 40–41), and a suspended particulate sampler to capture microbes and localized vent fluids (pages 48–49). Without new innovative technologies to solve challenges in deep-sea sampling, scientists would be unable to gain the necessary materials to further understand Earth and ocean inhabitants, processes, and history. Some recent technological advances, challenges, and discoveries based on *Nautilus* samples are highlighted on the next two pages. Work by Spenser Backus and colleagues demonstrates the complicated nature of obtaining deep-sea material for research, while descriptions of investigations by Henry Reiswig and Bruce Ott and Marc Fries show that sample collection is the important first step in the process of better understanding our ocean.

NASA PROTOTYPES GEOLOGICAL GRIPPER

– Spencer Backus, Rina Onishi, Andrew Bocklund, Eric Contreras, and Aaron Parness

Collecting representative rock samples is key to any geological expedition, but when exploring the deep ocean, the lack of ROV-operated drilling systems limits scientists to collecting loose rocks that can be picked up with the ROV's manipulator. Although still useful, these samples are often more altered and lack the geological context of intact rocks. Thus, researchers have been working toward building an ROV-operated rock drill. The first step was to design and test a microspine rock gripper that latches the drill onto the seafloor and stabilizes it while collecting a sample. The gripper prototype, tested aboard E/V *Nautilus* in September 2018 in Papahānaumokuākea Marine National Monument, consists of 16 radially symmetric digits, with a large metal spine at the tip of each digit (Figure 4). When closed, the digits conform to the rocky surface and the individual spines catch on small features, allowing the gripper to grasp a relatively flat surface as long as it is somewhat rough. During tests, the ROV pilot used the ROV manipulator arm to position the gripper against a cliff face or other feature and engaged the gripper. After latching the gripper to the target, the strength of the grasp was tested by pulling the gripper and bending it back and forth. Successful grasps resisted loads estimated to exceed 30 lbs, which is more than enough to secure and stabilize a drill while collecting a rock sample. Based on these successful test results, we hope to continue developing this system and integrate a sampling drill to collect rock cores on a future cruise.

The research was carried out at the Jet Propulsion Laboratory, California Institute of Technology, under a contract with the National Aeronautics and Space Administration. ©2017 California Institute of Technology. Government sponsorship acknowledged.

Figure 4. The microspine gripper is used to anchor ROV *Hercules* to a rock of interest.

CASCADIA MARGIN METEORITE HUNT

– Marc Fries

E/V *Nautilus* recovered seven samples from a site where a large meteorite fell into the Pacific Ocean on March 7, 2018. During the *Nautilus* search in July 2018, the ROVs recovered one sample with a magnetic collector and six more using a sieve. These samples were provided to the NASA Johnson Space Center for analysis. In a search for "unusual" material, the samples were cleaned and size-sorted, and then examined using an optical microscope (Figure 5a). The unusual samples were set aside for additional analysis.

Most of the seafloor material proved to be native rock that has been broken into small pieces and altered by seawater, and unfortunately often resembles meteorites. Most of the native rocks have a gray-green interior with a thin, partial black crust. Many meteorites look like this, but in this

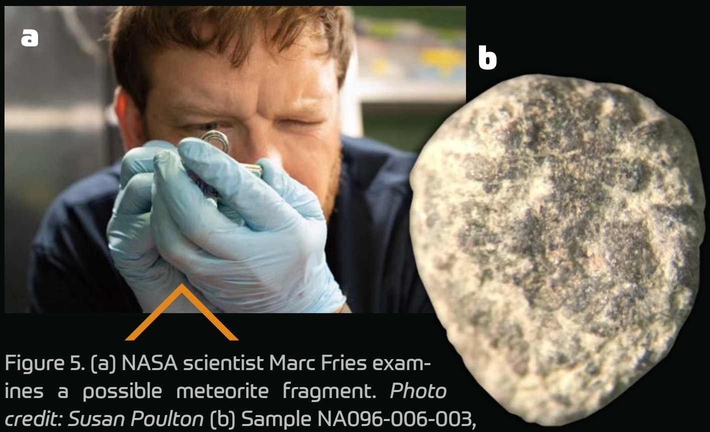


Figure 5. (a) NASA scientist Marc Fries examines a possible meteorite fragment. *Photo credit: Susan Poulton* (b) Sample NA096-006-003, a small (~3 mm) rock with a light gray-green interior and a thin, partial black outer crust is typical of much of the material recovered and bears a passing resemblance to common meteorites. The rock contains quartz and other minerals that are not typically found in meteorites but are common to terrestrial rock. Image contrast adjusted to match naked-eye appearance of the rock.

case, we collected a metamorphic rock containing small, rounded, metallic grains that look like "melt spherules," tiny droplets that form as a meteor "burns" across the sky. However, here, we had sampled small grains of a terrestrial mineral called magnetite that is found in the native rock. Together, these abundant "meteor-wrongs" have made it difficult to analyze the samples (Figure 5b). However, there have been some interesting discoveries. A collection of small, flaky objects turns out to be common rust from man-made steel. A small number of black, spongy things turned out to be charcoal with its original wood structure intact, perhaps arising from forest fires in the Pacific Northwest. One small (~3 mm) piece of anthracite coal may come from the wreck of SS *Ferndale*, a schooner that carried Australian coal from Newcastle, New South Wales, in 1892. Pieces of coal from this wreck still wash up on local beaches.

There remain two further lines of evidence to pursue. One it to examine a ~2 mm sphere that clearly melted and is composed primarily of magnetite along with what may be a heat-altered form of a mineral called pentlandite, a nickel-bearing sulfide, which would be consistent with a molten fragment from a meteorite fall. The second is to dissolve the material in acid and examine the remaining, tough grains for isotopes consistent with a meteorite fall. This process is slow, and will commence in early 2019. The samples have proven to be difficult to study, but not impossible. The final word on whether meteorite fragments are in the samples will be forthcoming soon.

NEW SPONGE SPECIES DISCOVERED OFFSHORE CALIFORNIA AND GALÁPAGOS ISLANDS

– Henry Reiswig and Bruce Ott

Researchers who participated on *Nautilus* expeditions from the equatorial Pacific to northern Canada have discovered many new sponge species and two new sponge genera. All specimens from the glass sponge class Hexactinellida, as well as demosponges, collected during three *Nautilus* cruises have been studied, and work is in progress on specimens from three others. The Galápagos seamounts cruise (NA064) collected 18 specimens comprising 11 identifiable demosponges and four hexactinellids; of these, 13 are new species, including two new genera. Specimens collected at Grays Canyon, Washington (NA072), comprised two demosponges and seven hexactinellids, of which one demosponge is a new species. The expeditions within West Coast national marine sanctuaries have also produced several new species. A cruise to Greater Farallones National Marine Sanctuary (NMS) in California (NA077) collected six specimens, including two new species and one known homonym, allowing correction of the species name. The Cordell Bank NMS expedition off central California (NA085) collected five sponge specimens, including two new species. The Olympic Coast NMS off Washington (NA086) collected 53 sponge specimens, 37 of which were demosponges and 14 hexactinellids. So far, these specimens include two new hexactinellid species, but many still need species-level determination. Research on specimens collected from the Canadian seamounts (NA097) is just beginning; the one specimen examined at the time of this writing proved to be a new species of hexactinellid. Overall, from these six cruises, researchers have identified 21 new species and two new genera, but work is far from complete for some collections. The most interesting discovery among these collections was a new genus and species of the family Phellodermidae from the Galápagos seamounts (Figure 6).

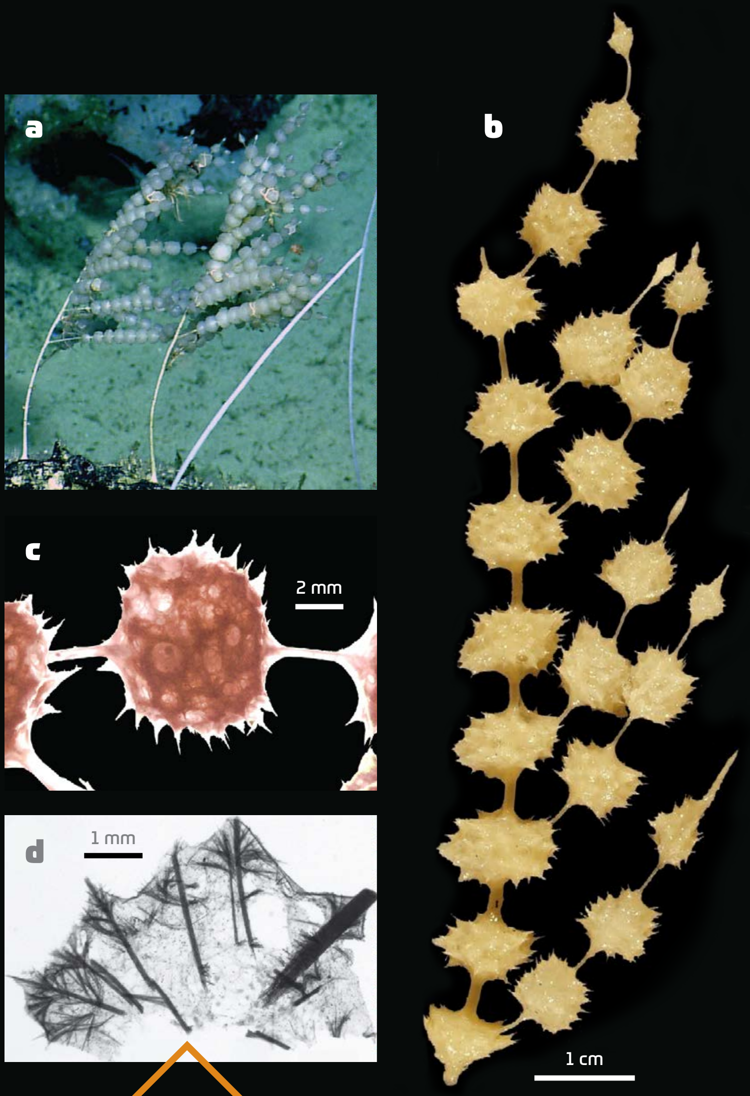


Figure 6. The new as yet undescribed species of Phellodermidae from Galápagos: (a) In situ image of several specimens. (b) The collected sample. (c) One of the body spheres in dark-field illumination. (d) A thick section showing the arrangement of the skeletal spicule bundles.

A Decade of Engaging Students, Educators, and Global Audiences in Deep-Sea Expeditions

By Allison Fundis, Megan Cook, Samantha Wishnak, Kelly Moran, Timothy Burbank, and Michael Viveiros

Inspired by the thousands of letters he received from students seeking an opportunity to join an expedition following his discovery of the wreckage of RMS *Titanic*, Robert Ballard's vision for the mission of the Ocean Exploration Trust was that it would increasingly connect exploratory expeditions beyond the scientific community and into classrooms and living rooms. His goal in this was, and continues to be, to encourage the next generation of explorers to follow educational pathways into the STEM (science, technology, engineering, and mathematics) workforce. OET has maintained this mission since Dr. Ballard founded the organization in 2008 and has since connected tens of millions of members of the public to ocean exploration. Additionally, OET has provided professional development and authentic career exploration opportunities to more than 400 students and educators aboard E/V *Nautilus* through scholarship and fellowship programs over the last decade.

Role modeling has been the keystone of OET's educational and outreach program since its inception. Each year, members of the Corps of Exploration—which includes everyone from crew members, to students, to lead scientists who sail aboard *Nautilus*—come from academia, industry, schools, federal agencies, the military, and nonprofit organizations. As we introduce each Corps member aboard the vessel to global audiences, we aim to showcase the vast breadth of vocations and pathways possible within STEM-related disciplines. We also strive to ensure that the demographics of the Corps—specifically, representation of women and historically underrepresented minorities in STEM—reflects the diversity of the United States, allowing a greater number of children to recognize opportunities for themselves in these career pathways.

While emphasizing role modeling and mentoring, OET has developed a suite of programs over the last decade to engage educators and students of all ages, including: (1) outreach to inspire the online public through 24/7 connectivity to explorers at sea; (2) immersive, hands-on opportunities for students and educators to participate in *Nautilus* expeditions shoulder-to-shoulder with professionals in the field; (3) professional development opportunities for educators on shore; and (4) ocean exploration-themed STEM curricular materials.

OET engages students nationwide with classroom and community visits, like this event in Sulphur, Louisiana. Professional development workshops and the Nautilus Ambassador Program also build and celebrate STEM education leaders, supporting their teaching with ocean exploration lesson plans and digital resources. *Image credit: Dennis Pevey*

The Nautilus Patch Design contest solicits original art from students ages 6–18 around the world. Bella Miller, age 14, from Washington state, USA, created the winning hydrothermal vent-inspired design worn by all explorers who joined *Nautilus* this year.

For Global Audiences

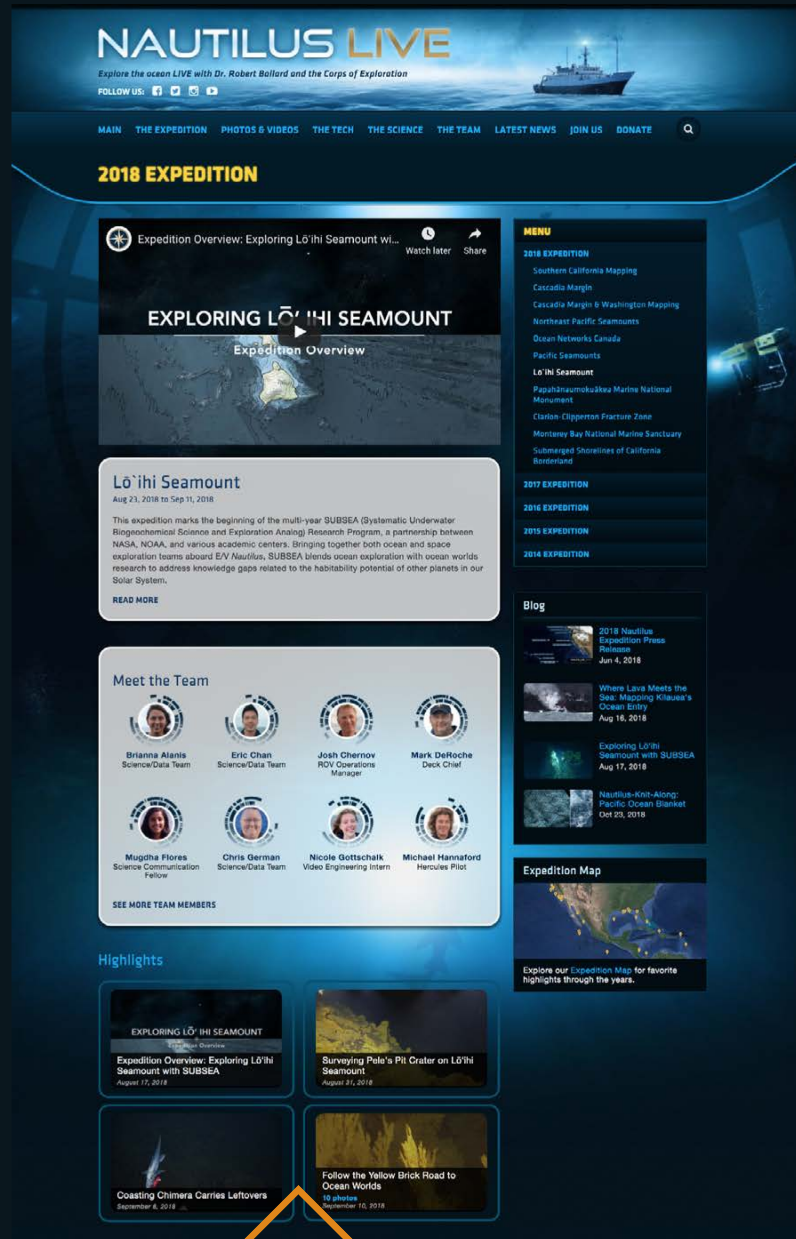
DIGITAL OUTREACH

As the central portal into ocean exploration aboard *Nautilus,* the Nautilus Live website continues to evolve to provide a real-time educational experience for students, educators, scientists ashore, and the general public that mirrors our shipboard operations. Featuring live-streaming video from underwater ROV cameras and topside shipboard cameras, paired with audio commentary from scientists, engineers, educators, and interns, these streams have drawn more than 16.6 million views from over 130 countries since 2010. Development and release of content for the Nautilus Live website, social media, and newsletter is structured around individual expeditions to help the public and educational groups follow along during our operating seasons.

During the six-month 2018 expedition, live shipboard and underwater video feeds drew more than 1.9 million views, with 6.6 million minutes watched by viewers from around the world. This year, we incorporated additional situational awareness into the streaming video and audio experience. The real-time data interface, with vehicle depths, water temperature, and recent scientific log entries, now includes the ability to rewind the live feeds up to four hours, giving users more autonomy over their viewing experiences. The latest tweets are embedded to provide glimpses behind the scenes, highlighting team members, shipboard roles, and innovative technologies.

Beyond the live video channels, our most visited web resource is the team page. Updated for each expedition, it features all 48 science and engineering team members and professional maritime crew aboard *Nautilus*, and acts as a permanent archive for the hundreds who have participated in the Corps of Exploration. Biographical profiles for scientists, engineers, educators, and interns highlight individual career paths, areas of study, and advice for following similar opportunities. One of the primary outlets for students and general viewers to connect directly with these explorers at sea is the "Submit a Question" feature, which received over 23,400 questions during the 2018 expedition.

Restructuring the Nautilus Live website around the expedition pages—comprising all team member biographical profiles, highlight videos, photo albums, and blogs associated with an expedition—offers a new way for students and the public to follow individual expeditions and search through expedition seasons. A new map feature that includes location pins on a searchable Google map, as well an expedition season index, further enhances the interactive capabilities of our website for virtual explorers during and after expeditions.



New expedition pages on NautilusLive.org encapsulate and archive the story of each mission, featuring team member biographical profiles, highlight videos, photo albums, and blogs.

Social media, a parallel and complementary branch to OET's outreach via telepresence and the Nautilus Live website, continues to be an entry point for many new viewers. Since 2012, we have engaged with people directly on social media, and have integrated social media links into our website. Adding dedicated production and digital media team members to edit video highlights and manage our social media presence has allowed our reach to expand to over 295,000 followers across the platforms of Facebook, Twitter, Instagram, and YouTube.

Among all Nautilus Live social media platforms, YouTube continues to have the most rapid subscriber growth. High engagement and views on this platform often result in a highlight "going viral," with a majority of press inquiries to our team noting YouTube as a source. Total views of video highlights during the six-month season reached over 5.1 million, with 8.9 million minutes of our archived video highlights watched. The single, short video highlight of a gulper eel inflating its balloon-like body was viewed over 2 million times over two weeks and led more than 11,000 new viewers to subscribe to the Nautilus Live YouTube channel during the Papahānaumokuākea Marine National Monument expedition.

The number of Instagram followers continues to grow rapidly as well, with a 61% increase since 2017 and rising popularity in Instagram Stories, a feature that allows photos and videos to be annotated and shared temporarily. Members of the Corps of Exploration were encouraged to devote a day to sharing personal experiences via Nautilus Live Instagram Stories. By saving these temporary stories on our Instagram profile we can showcase Nautilus STEM role models in another shared venue.

PRESS

While the Nautilus Live website and social media platforms are the primary way in which we share our most surprising sightings with the public, coordinated media efforts among the OET team and partners resulted in over 670 *Nautilus*-related news reports in print, radio, television, and online media, with an estimated reach of more than 40 million people. Several opportunistic sightings became viral news stories across the world, including the discovery of more than 1,000 brooding octopuses near fluid seeps in Monterey Bay National Marine Sanctuary, a ghostly *Grimpoteuthis* octopus before Halloween, and a gulper eel inflating in Papahānaumokuākea Marine National Monument. As increasingly frequent press headlines that mention our team's reactions suggest, Nautilus Live is becoming more recognizable in the online ocean space for highlighting surprising, fun, and accessible human experiences that demystify deep-sea research and exploration.

Working with NASA research teams three times this season, *Nautilus* hunted for meteorites off the Washington coast, explored Lōʻihi Seamount off Hawaiʻi, and tested a new geological gripper in the Papahānaumokuākea Marine National Monument. This work captured the attention of ocean and space exploration enthusiasts, and was reflected in a surge of media stories highlighting the unique partnership between NASA, NOAA, and OET. Additionally, many educators and students who participated in 2018 aboard *Nautilus* as Science Communication Fellows and Science & Engineering Interns, as well as researchers and explorers aboard, were featured in media stories in the *Washington Post*, *Los Angeles Times*, *Smithsonian* magazine, *National Geographic*, *Forbes*, *Boston Globe*, *Popular Science*, Space.com, Science Friday, on the BBC and CNN, and in many more local, national, and international outlets.

SHIP-TO-SHORE CONNECTIONS

Telepresence technology installed on *Nautilus* allows onshore audiences to engage in a unique, two-way dialogue with onboard team members. Over the last decade, OET has conducted more than 4,700 live ship-to-shore interactions with K–12 classrooms, universities, museums, science centers, and out-of-school programs. Audience members learn about *Nautilus* expeditions and ocean exploration directly from the at-sea team and address questions to those aboard. These sessions are a popular way to showcase the many professions needed to conduct an ocean exploration expedition and, as such, are a key component of the role modeling aspects of OET's program.

In 2018, the Corps of Exploration conducted 257 live ship-to-shore interactions reaching over 12,000 students and community members. More than half of these connections went directly into K–12 schools, offering students an engaging outlet for curiosity about the ocean and a direct connection with role models among the scientists, interns, educators, and engineers aboard *Nautilus*. Over the past several years, OET has partnered with NOAA's Office of National Marine Sanctuaries to connect NOAA scientists to the communities local to their sanctuaries. This effort was expanded in 2018 to include live interactions with those living near Papahānaumokuākea Marine National Monument in Hawaiʻi. In the past three years, OET has conducted 96 ship-to-shore interactions in partnership with the National Marine Sanctuaries.

Ship-to-shore interactions connect members of the Corps of Exploration with learners around the world, from classrooms and museums to public citizen science events like Science Hack Day. *Image credit: Matt Biddulph*

For Students

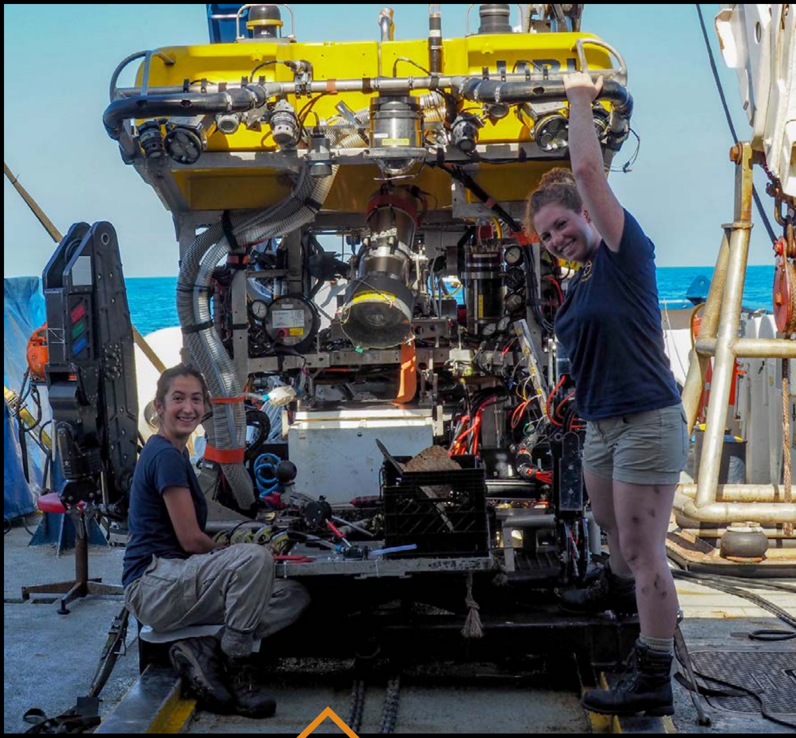
SCIENCE & ENGINEERING INTERNSHIP PROGRAM

OET's Science & Engineering Internship Program (SEIP) provides opportunities to deepen students' understanding of ocean science and engineering by fostering teamwork, developing skills, and applying their growing knowledge to real-world problems. Through two- to five-week internships aboard *Nautilus*, the program provides hands-on experiences for students studying ocean science, engineering, and video/film. Interns can work as data loggers, seafloor mappers, navigators, ROV pilots, or video engineers. Interns come from a variety of stages in their professional training. They may be students at community colleges and undergraduate institutions, graduate students, or early-career professionals. All interns spend their time at sea working with a wide array of scientists, engineers, students, and educators to gain experience in communication and leadership, including participating in educational outreach activities.

The current five internship tracks in the program—ROV Engineering, Ocean Science, Seafloor Mapping, Navigation, and Video Engineering—are modeled to expand students' depth and breadth of academic learning and relevant skill sets. Each internship is crafted around both general skills development and personal development goals. In 2014, the program expanded to its current form with the additions of seafloor mapping and navigation internships. Offered in partnership with the United States Naval Academy and the United States Coast Guard Academy, the navigation internship provides operational experience for cadets and midshipmen to use their course instruction, critical thinking, and problem-solving skills to support at-sea operations and deep-sea exploration.

OET has provided training for students in exploration fields since 2011. SEIP has trained 114 interns from 24 states and Washington, DC, as well as Puerto Rico, and Canada. Working to be inclusive, since 2014, OET has seen a steady rise in the percentages of applications from students who have been historically underrepresented in STEM fields. In 2015, 24% of the total applications for SEIP were from minority groups, rising to 35% in 2018. The percentage of applications received from groups historically underrepresented in STEM is now equivalent to the percentage of representation for these groups in public, four-year colleges. Women also remain underrepresented in the science and engineering workforce. Through the internship program, OET has worked to ensure women are equally represented. Since 2014, the percentage of female SEIP applicants has remained at 50% or higher in the sciences and video engineering tracks and has increased by more than 20% in the ROV engineering-focused internship track.

ROV Engineering Intern Leonardo Castro Sitiriche became an ROV pilot from day one aboard *Nautilus*. Interns learn to operate and maintain the ROV systems, sensors, and samplers from professional technicians and engineers in the Corps of Exploration.



Role modeling is the keystone of OET's education and outreach programs, specifically, representation of women and historically underrepresented minorities in STEM. Since 2014, the percentage of female applicants for engineering-track internships has risen more than 20%. *Image credit: Jenny Woodman*

For Educators

SCIENCE COMMUNICATION FELLOWSHIP

The Science Communication Fellowship (SCF) invites formal and informal educators to participate in the Nautilus Exploration Program to help share the excitement of exploration and research with students and public audiences in their communities and around the world. The Science Communication Fellowship includes participating in a science communication training workshop alongside the OET team; sailing for one to three weeks as expedition interpreters aboard *Nautilus*; collaborating with OET, STEM professionals, and fellow educators for one year; and developing STEM lessons or outreach materials as a summative deliverable.

Participation in the program provides Fellows with a variety of experiences within professional settings and, importantly, helps develop their skills in public speaking and strengthens their ability to communicate STEM concepts to a variety of audiences. Program implementation focuses on increasing Fellows' exposure to and understanding of a variety of STEM careers through interactions with the Corps of Exploration and increasing Fellows' proficiency and understanding of STEM concepts. All of these experiences combine to support an essential goal of the SCF program: to impart the significance of ocean exploration and the variety of STEM fields to the students of the participating educators.

The 2018 Science Communication Fellowship cohort included 17 Fellows from 11 US states, the District of Columbia, and Ontario, Canada. Formal educators participating in the program varied in professional experience and student populations, from those just completing secondary certification, to instructors specializing in learning disability equity, to senior vocational-technical instructors. The cohort also had a wide diversity of educators who reach students informally beyond classroom walls. Fellows included a citizen science advocate, the founder of an afterschool program that boosts the involvement of young black women in marine science, museum and aquarium interpreters, a writer, and a storytelling consultant.

The Science Communication Fellowship has grown to be OET's premier educator professional development program. Since 2011, 117 educators have participated from 34 US states and seven countries—Australia, Canada, Ireland, Wales, Jamaica, New Zealand, and Venezuela. Fellows have supported many months of live broadcasting and have become favorite voices within discovery highlight videos that distill the enthusiasm and mission of the Nautilus Exploration Program. As the program moves forward, with support from partners nationwide, the focus of the SCF program will be to reach educators who engage students traditionally underrepresented in STEM fields to help inspire and motivate them on paths toward careers in science, technology, engineering, mathematics, and exploration.

NAUTILUS AMBASSADOR PROGRAM

The Nautilus Ambassador Program brings educators selected for their leadership in STEM teaching onto *Nautilus* for a short expedition to introduce them to the field of ocean exploration. For educators with limited previous experience, this program provides a strong foundation in ocean literacy and exposes the Ambassadors to career pathways in STEM and maritime industries. Ambassadors are involved in all aspects of the Nautilus Exploration Program while on board. They gain familiarity with ocean science, technology, and engineering, and receive training in science communication. The program also includes professional development using the inquiry-based STEM Learning Modules and Digital Resource Library, experience making scientific observations, and standing watch in the control van and assisting in the wet lab. After the at-sea experience, Ambassadors return home as strong role models for students and their education peers, ready to share

Science Communication Fellow Mugdha Flores stands watch in the control van, fielding questions from global audiences who join the Corps of Exploration live on the seafloor via NautilusLive.org. *Image credit: Ed McNichol*

Nautilus Ambassadors like Jeff Brown and Terri Miller bring their expertise as STEM educators to *Nautilus* where they learn new applications of technology, participate in exploration, and train with STEM lesson plans so that they can successfully connect from the ship to their high school and elementary school classrooms ashore.

OET conducts professional development workshops for educators across the nation, providing inquiry-based activities aimed at inspiring students' curiosity and honing their problem-solving skills. Since 2015, OET trained more than 470 educators, including these participants in Lake Charles, Louisiana.

the excitement of ocean exploration and research with their schools and communities. The collaborative format and teaching/learning style of this program has profound impacts on educator's teaching practices.

This year, five Nautilus Ambassadors from Louisiana, Texas, Illinois, and New York sailed on two seafloor mapping expeditions along the California and Oregon coastlines. Ambassadors conducted nine live interactions with their communities during the cruises. Since 2014, 28 different educators have sailed as Nautilus Ambassadors representing their schools and the states of California, Connecticut, Florida, Illinois, Louisiana, Texas, and New York. Ambassadors have remained highly engaged role models for other educators, promoting live ship-to-shore interactions and classroom resources. Participants have organized a series of local student workshops and STEM Night events featuring OET staff that have reached over 2,000 K–12 and 1,100 community members to date.

EDUCATIONAL RESOURCES & PROFESSIONAL DEVELOPMENT WORKSHOPS

OET offers a suite of education resources designed to link classroom STEM content and twenty-first century skills with the real-world applications of concepts fundamental to deep-sea exploration. OET has a collection of inquiry-driven lessons, called STEM Learning Modules, aligned to and guided by the performance expectations of the Next Generations Science Standards, Common Core State Standards, and Ocean Literacy Principles. The STEM Learning Modules collection has grown since 2015 and now includes 26 stand-alone and freely available lessons. OET has also built a Digital Resource Library of over 60 unique resources to equip educators with introductory and instruction-enhancing material geared toward students of all ages.

Developed alongside OET's education resources, professional development workshops provide formal training for educators and give them time to work with OET staff in building connections between their classroom content and real-world exploration. Workshops have been designed for a variety of durations, from after-school sessions to full-day STEM Academy trainings, and they are crafted to address variable levels of educator familiarity with ocean science and STEM connections to ocean exploration. OET staff also provide educator coaching to encourage implementation of new materials in classrooms beyond the workshop events.

Each workshop is taught by OET staff and members of the Corps of Exploration who sail aboard *Nautilus*, bringing authenticity to the instruction along with experience in applying OET resources to formal and informal education. Since 2015, OET has led 18 workshops and STEM Academies, directly involving 471 educators. Attendees are from all levels, working in early childhood education, college prep, nonprofit organizations, education publishers, and community institutions. In 2018, five workshops were led in Texas, Louisiana, and Illinois for 111 educators with a reach of over 6,900 students.

Through this suite of programs and outreach efforts, we hope to motivate more students and members of the public to be lifelong learners and to gain exposure to opportunities and careers they may otherwise not know about. It is our goal to use the Nautilus Exploration Program to inspire future explorers, innovators, policymakers, and the STEM workforce while ensuring any child can find a role model aboard a *Nautilus* expedition.

Nautilus Field Season Overview

By Nicole A. Raineault

The year 2018 marks one decade since the Ocean Exploration Trust began conducting expeditions aboard E/V *Nautilus*. For a review of our program's history, please read "The First Ten Years" by founder and President, Robert D. Ballard (pages 14–19). This year was distinguished by an extremely successful nearly seven-month expedition season that brought strengthened partnerships with researchers at NASA, NOAA's Pacific Marine Environmental Laboratory, and the National Geographic Society, and the formation of new partnerships, including with Fisheries and Oceans Canada, Papahānaumokuākea Marine National Monument, and the US Geological Survey's Hawaiian Volcano Observatory. This tenth year was also remarkable in that *Nautilus* ventured the furthest north and west it has ever traveled, completing expeditions to western Canadian seamounts (pages 42–43) and Papahānaumokuākea Marine National Monument (pages 50–51). We mapped more this year than any on record, over 107,000 km^2—including more than a dozen previously unmapped seamounts (pages 38–39). *Nautilus* operated 174 days between late May and mid-November and logged a total of 82 ROV dives.

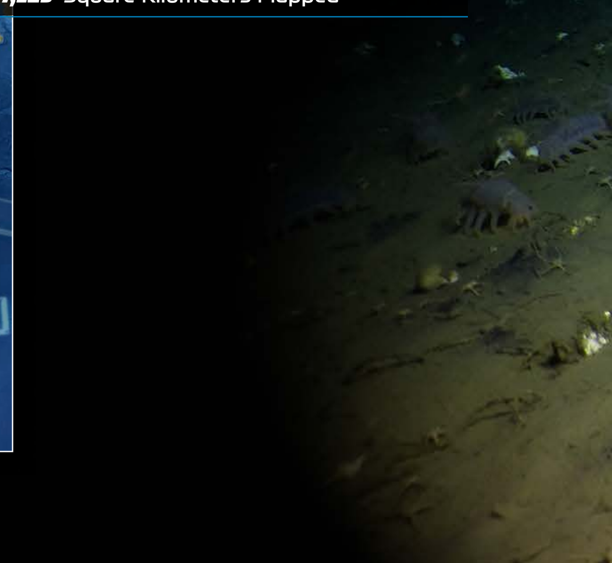
Between May and November 2018, the Nautilus Corps of Exploration mapped new territory, tested new technologies, and engaged students and the public through expeditions ranging from the west coasts of Canada and the United States to Hawaiʻi. Over 190 people participated on board and more than 70 researchers participated from shore, adding their expertise to the exploration.

After mobilization and a shakedown cruise off the coast of San Pedro, California, *Nautilus* embarked on a West Coast mapping cruise in preparation for a follow-up to our 2016 methane seep exploration of the Cascadia margin with researchers from NOAA's Pacific Marine Environmental Laboratory (pages 40–41). *Nautilus* mapped areas in the Southern California and Cascadia region and even conducted a brief ROV dive in search of meteorite fragments from an impact within the Olympic Coast National Marine Sanctuary (pages 28–29).

Exploration of seamounts with scientists from Fisheries and Oceans Canada improved maps of undersea features and provided stunning imagery and information on the diversity and abundance of deep-sea inhabitants in this potential marine protected area (pages 42–43). ROV work completed during the Ocean Networks Canada expedition doubled the amount of instrumentation at the incredible Endeavour hydrothermal vent site (and Canada's first marine protected area), including the installation of

2018 At a Glance

12	Cruises
174	Days
82	ROV Dives
877	Hours in Water (36.5 Days)
807	Samples Collected (2,297 Subsamples)
107,125	Square Kilometers Mapped



additional seismometers to provide critical warning in advance of large earthquakes and tsunamis (pages 44–45).

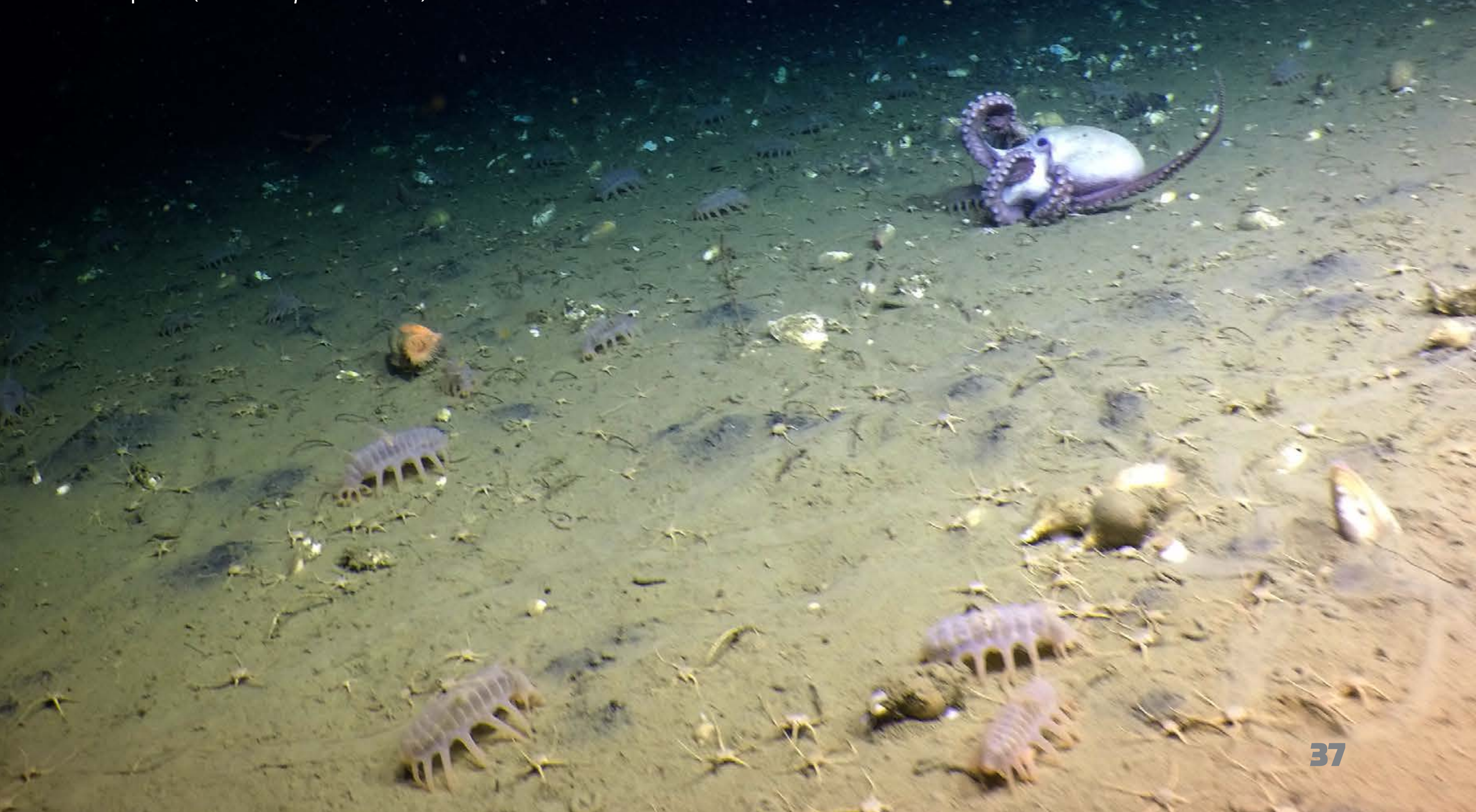
Nautilus mapped important seafloor regions in remote areas of the Pacific between British Columbia and Hawai'i, including several previously unmapped seamounts and new seafloor off Hawai'i created by the 2018 Kīlauea Volcano eruptions (pages 46–47). ROV *Hercules* examined new lava flows on the NASA SUBSEA expedition, which also included studies of Lō'ihi Seamount via telepresence-led dives by scientists based at the University of Rhode Island Graduate School of Oceanography's Inner Space Center (pages 48–49).

An expedition to the remote expanded area of the Papahānaumokuākea Marine National Monument, the largest contiguous marine protected area in the United States, contributed significantly to our knowledge of 10 enigmatic seamounts and their sponge, coral, and other associates, including one surprising visit by a gulper eel (pages 50–51).

The voyage across the Pacific from Hawai'i to California was an excellent opportunity to map and collect National Geographic Deep Ocean Drop Cam footage of organisms living on or near the seafloor at the Clarion-Clipperton Fracture Zone, an area that contains polymetallic nodules and other rare earth deposits that are the target of international seabed mining (pages 38–39).

Although brief, the expedition in the Monterey Bay National Marine Sanctuary photographed what may prove to be the largest grouping of brooding cephalopods (*Muusoctopus robustus)* ever observed. Even more intriguing is their apparent association with a low-temperature hydrothermal system—more than enough reason to return next year for follow-up exploration (pages 52–53). Finally, the Southern California Borderland expedition continues two years of research into the region's submerged shorelines by focusing on offshore banks and collecting valuable samples to constrain the ages of the paleoshorelines (pages 54–55).

Next year, over a six-month field season, *Nautilus* will venture even further west to US territories, including American Samoa, Baker and Howland Islands, and Johnston Atoll. Many cruises will test new technologies such as the new mobile ROV system, which will be jointly owned and operated by the Ocean Exploration Trust and the National Deep Submergence Facility located at Woods Hole Oceanographic Institution, with funding from NOAA's Office of Ocean Exploration and Research and the National Science Foundation. We also plan to expand our program with NOAA's Office of National Marine Sanctuaries to include the Great Lakes, where we will continue our use of an autonomous surface vehicle for seafloor mapping. We look forward to beginning work with researchers to build field programs in the far western Pacific, where there are little-explored US territories that contain critical information to help better understand our planet.



Contributing to Global Seabed Mapping Initiatives: *Nautilus* Maps Remote Pacific Areas

By Lindsay Gee, Larry Mayer, Erin Heffron, Nicole A. Raineault, Alan Turchik, Eric Mittelstaedt, Thomas Hourigan, and Marie-Helene Cormier

Between August and October 2018, E/V *Nautilus* moved from the west coast of North America to the Hawaiian Islands, with expeditions to Lōʻihi Seamount and the Papahānaumokuākea Marine National Monument. The transit across the North Pacific Ocean provided the opportunity to fill in gaps in seabed mapping coverage, add data for the US Extended Continental Shelf (ECS) Project, and map the lava ocean entry sites from the 2018 eruption of Kīlauea Volcano. *Nautilus* also completed targeted mapping of seamounts and mapped a section of the Area of Particular Environmental Interest One (APEI-1) in the Clarion Clipperton Fracture Zone (CCFZ) designated by the International Seabed Authority (ISA).

During NA099 and NA102, *Nautilus* mapped approximately 63,300 km^2 of seafloor with 8,965 km of trackline (Figure 1). The depths ranged from just under 50 m on the southeast flank of the island of Hawaiʻi to over 6,500 m on the Clarion Fracture Zone. In addition, 15 seamounts were mapped along with more than 20 other structures that did not meet the definition of a seamount but displayed similar features and rose >500 m above the surrounding seabed.

Although systematic mapping of the seafloor by echosounder commenced nearly a century ago, more than 80% of the world's seafloor remains unmapped, even at a resolution of 1 km. The eastern Pacific Ocean is no exception. In 2016, the Nippon Foundation-GEBCO Seabed 2030 project was initiated under General Bathymetric Chart of the Oceans (GEBCO) with the goal of having 100% of the world's seafloor topography mapped by 2030. The mapping goals of NA099 and NA102 align with the goals of Seabed 2030, and also contribute to this global initiative by making the *Nautilus* mapping data publicly available.

The route for NA099 from Sidney, BC, Canada, to Honolulu, Hawaiʻi, commenced with passage across the Mendocino Fracture Zone, collecting data in support of the US ECS Project. Multibeam mapping filled in gaps in coverage in the vicinity of Mendocino Ridge, and the new sub-bottom profiler data helped to further illuminate the complex geologic relations between mass wasting, constructional volcanic, and sedimentation processes in this region.

The transit then proceeded southwest, mapping the summit of Agerholm Seamount (34°23.60'N, 135°30.24'W), prior to mapping a linear chain of seamounts to the south of the Murray Fracture Zone called the Moonless Mountains (30°45'N 139°15'W). Three seamounts were completely mapped from base to summit, with depths ranging from about 5,000 m to 1,400 m (Figure 2). The new mapping provides vivid details of the seamounts' structures and

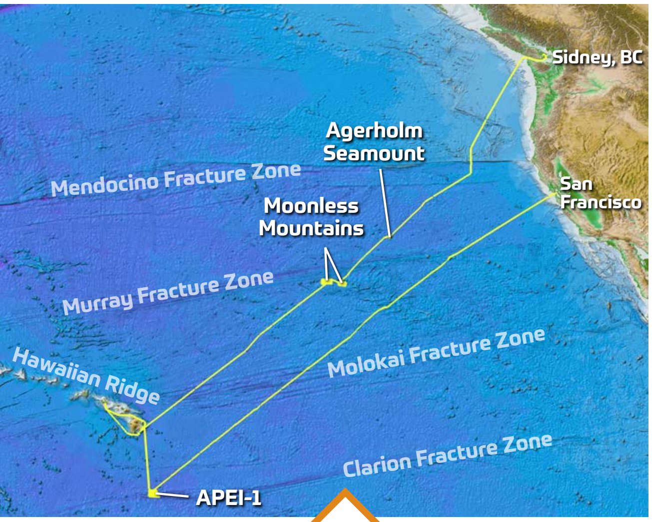


Figure 1. Overview of areas mapped on E/V *Nautilus* Pacific transits NA099 and NA102.

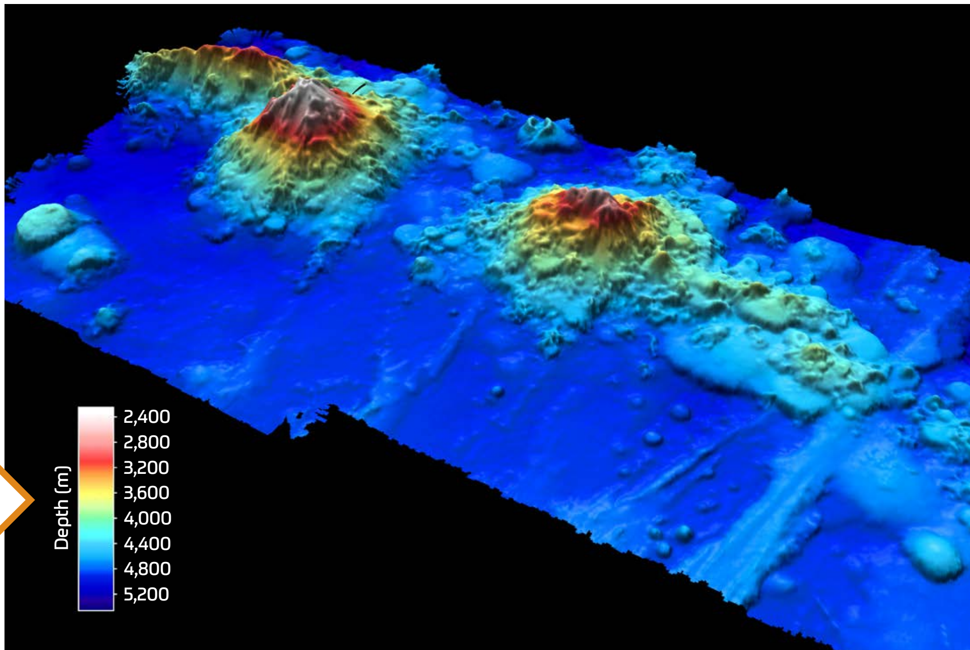


Figure 2. Image of Moonless Mountains western mapping area of 105 km × 45 km at three times vertical exaggeration.

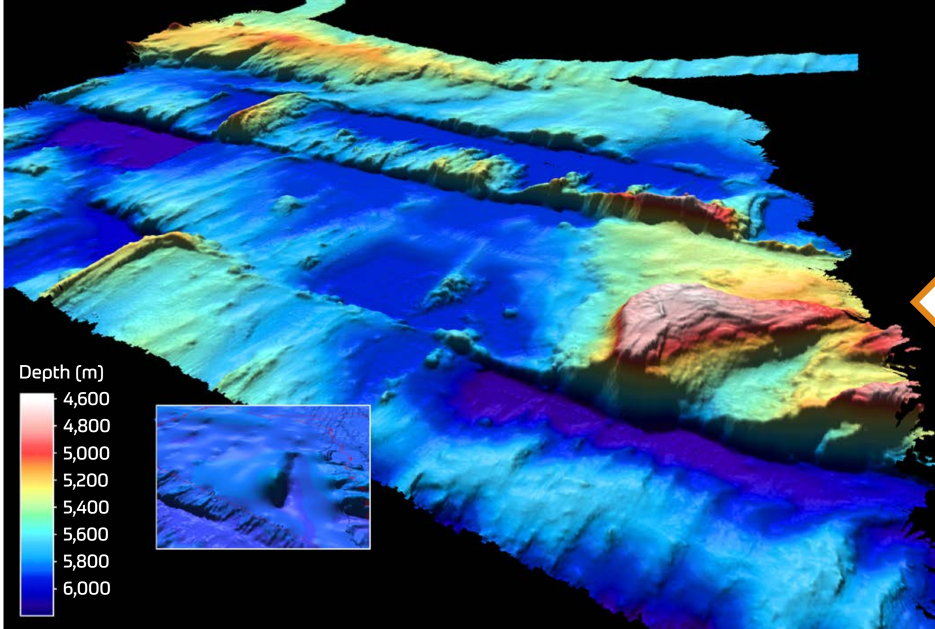


Figure 3. Mapped area of APEI-1 at three times vertical exaggeration, with preexisting bathymetry in the bottom left. The area mapped is approximately 90 km × 55 km.

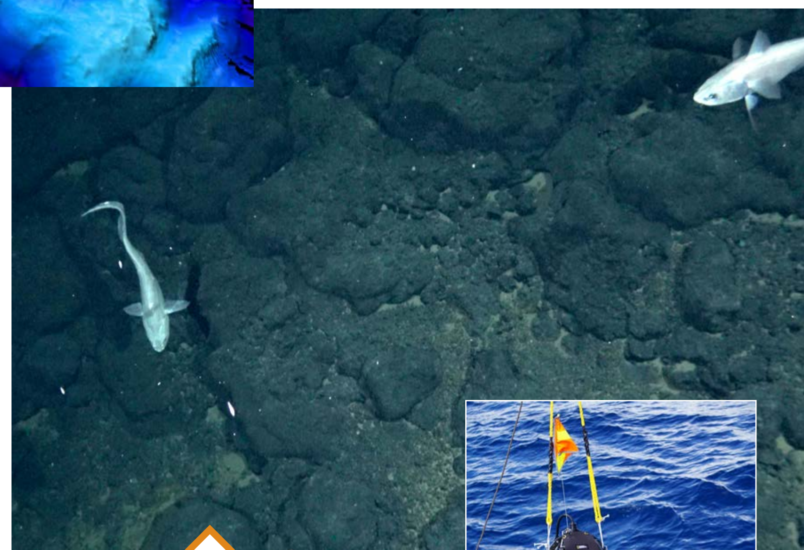


Figure 4. National Geographic Society's Deep Ocean Drop Cam (right) and seabed image (above) from the CCFZ deployment at 5,400 m depth.

their relationships to the adjacent fracture zone. North Pacific seamounts with summits shallower than 1,500 m are potential targets for deep-sea bottom fishing. The new surveys also help ensure that protection is provided for vulnerable marine ecosystems. The remainder of the transit continued to the southwest over unmapped areas, before mapping the lava ocean entry sites from the eruption of Kīlauea Volcano (pages 46–47).

The primary goal of the NA102 return transit from Honolulu to San Francisco was to cover areas of unmapped seabed, following a final remapping of the Kīlauea ocean entry sites. The initial phase of the expedition transited over 300 nm southeast from Hawai‘i to map a section of APEI-1 (14°10′N, 154°05′W) in the CCFZ that is adjacent to areas designated for seabed mining of polymetallic nodules under the ISA. The principal function of the ISA is to regulate deep seabed mining on the high seas and also to ensure that the marine environment is protected from any harmful effects that may arise during mining and resource exploration activities. Little information or data is available related to the habitat in the CCFZ, primarily because of the remoteness of the region. In order to protect and preserve habitats of a significant size in this vast area, an ISA environmental management plan for the CCFZ identifies nine APEIs where extraction of marine minerals is prohibited. The area *Nautilus* mapped covers the full fracture zone in the north and adjacent to existing mapped areas, and provides significant new details compared to gravity-derived predicted seafloor bathymetry (Figure 3).

The transits were conducted with a reduced science team and thus no ROV dives for seafloor observations and sampling. However, a collaboration between the Ocean Exploration Trust and National Geographic Society allowed use of their Deep Ocean Drop Cam. Drop Cams are relatively small, self-contained deep-ocean imaging systems outfitted with high-efficiency LED lighting, a 4k resolution camera capable of recording up to six hours of footage, and depth and temperature sensors. Baited to attract wildlife, they can be deployed to depths of up to 6,000 m.

During NA102, the Drop Cam was deployed four times. The first deployment was to a depth of ~1,000 m near the base of the recent Kīlauea lava flow. The camera recorded footage of a sediment-draped seafloor, an abundance of sediment or marine snow in the water column, and visits from shrimp and grenadiers. The other three deployments were during the CCFZ mapping in depths of 4,600–5,300 m. These deployments yielded footage of exposed rocky terrain interspersed with sediment. Much less marine snow and sediment was observed in the water column compared with near the Kīlauea flows, and individual plankton, small nekton, shrimp, and grenadiers were visible at APEI-1 in the CCFZ (Figure 4). The Drop Cam operations complemented the mapping by allowing direct observation of geology and biology in these deep and remote areas of the Pacific Ocean without significant delay to the mapping program.

Further Exploration of Methane Seeps on the Cascadia Margin

By Tamara Baumberger, Susan Merle, Camilla Wilkinson, Kevin Roe, Nathan Buck, Robert Embley, Nicole A. Raineault, Sarah Seabrook, and Rebecca Crawford

Systematic efforts to map the distribution of methane seeps along the Cascadia Margin began in 2016 during E/V *Nautilus* expedition NA072. Since then, a large database of unexplored seeps has been generated, setting the stage for further exploration of seep sites on the seafloor. Expedition NA095 in 2018 made use of this database and focused on extensively surveying and characterizing selected methane seeps between Cape Mendocino and Astoria Canyon off the west coast of the United States. Most of the expedition was devoted to dives with ROV *Hercules*.

ROV *Hercules* explored 12 bubble emission sites on the seafloor located between 40°N and 46°N at 100–1,810 m depth (Figure 1). These dive sites were chosen to maximize collection of samples over the full depth range of methane seeps along the Oregon and Northern California margins. Major working areas were located south of Coquille Bank, Heceta Bank, and Astoria Canyon/Nehalem Bank, as well as at a carbonate ridge off the Oregon-California border and Eel River, a previously known seep site with exposed hydrate.

In addition to the ROV dives, 3,525 km^2 of seafloor were mapped with the ship's EM 302 multibeam echosounder. During those surveys, 96 bubble streams were identified from midwater multibeam data (blue circles in Figure 1). Where possible, the rise height of each bubble stream was determined, with some observed reaching into the surface water layer (Figure 2).

At the ROV dive sites, a large number of samples, such as gas bubbles, hydrates, fluids, sediments, rocks, and fauna, were collected for further characterization. A Miniature Autonomous Plume Recorder (MAPR) collected optical backscatter and oxidation-reduction potential data in the water column during dives.

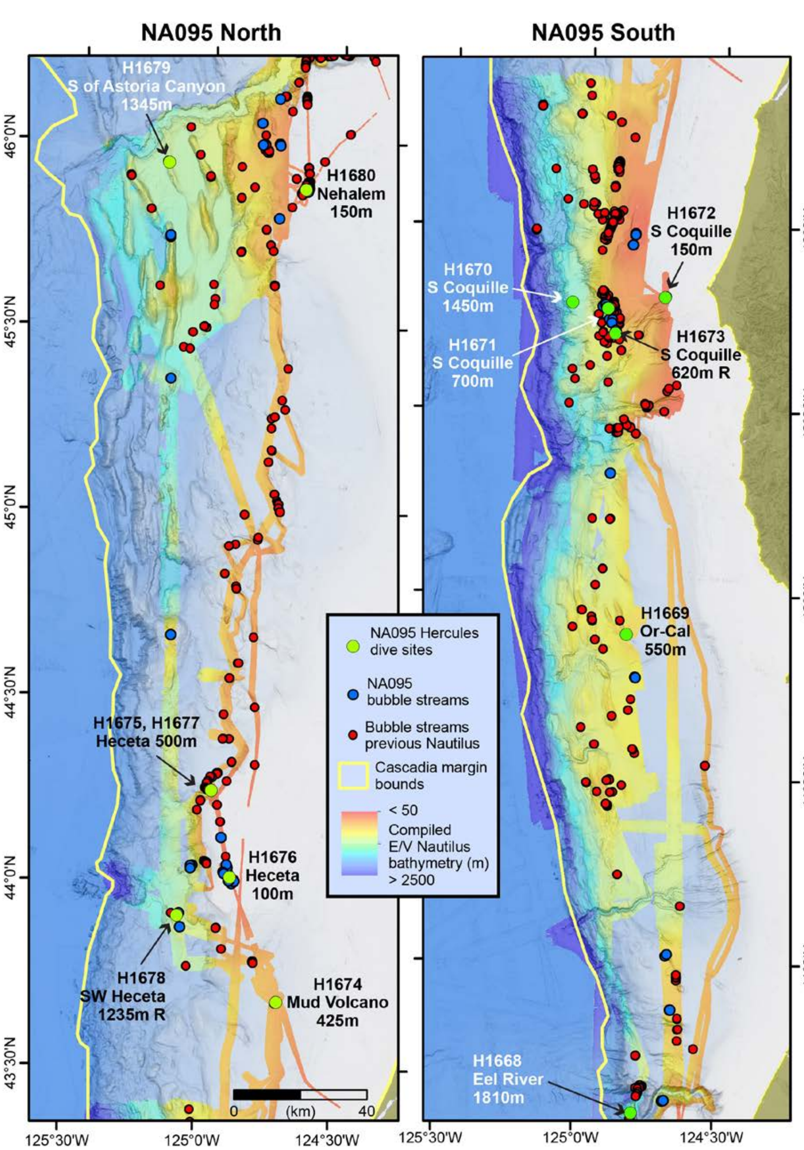
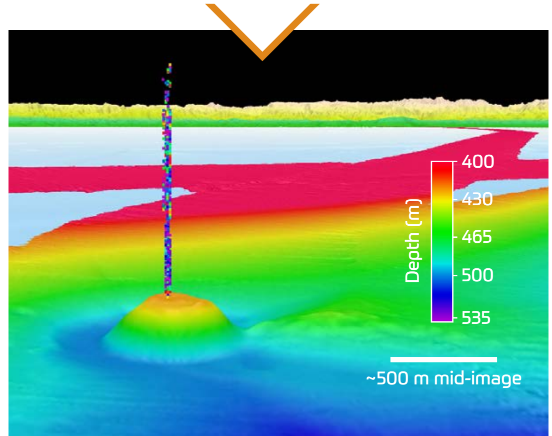


Figure 1. Compiled E/V *Nautilus* bathymetry collected on the US Cascadia Margin, overlaid with bubble stream and NA095 ROV dive locations.

Figure 2. Three-dimensional view of the mud volcano site explored during Dive H1674. Vigorous bubble streams are illustrated by three-dimensional point cluster objects, created using the Fledermaus FMMidwater software module. Vertical exaggeration is 3x. Created by Susan G. Merle, Oregon State University, NOAA EOI.



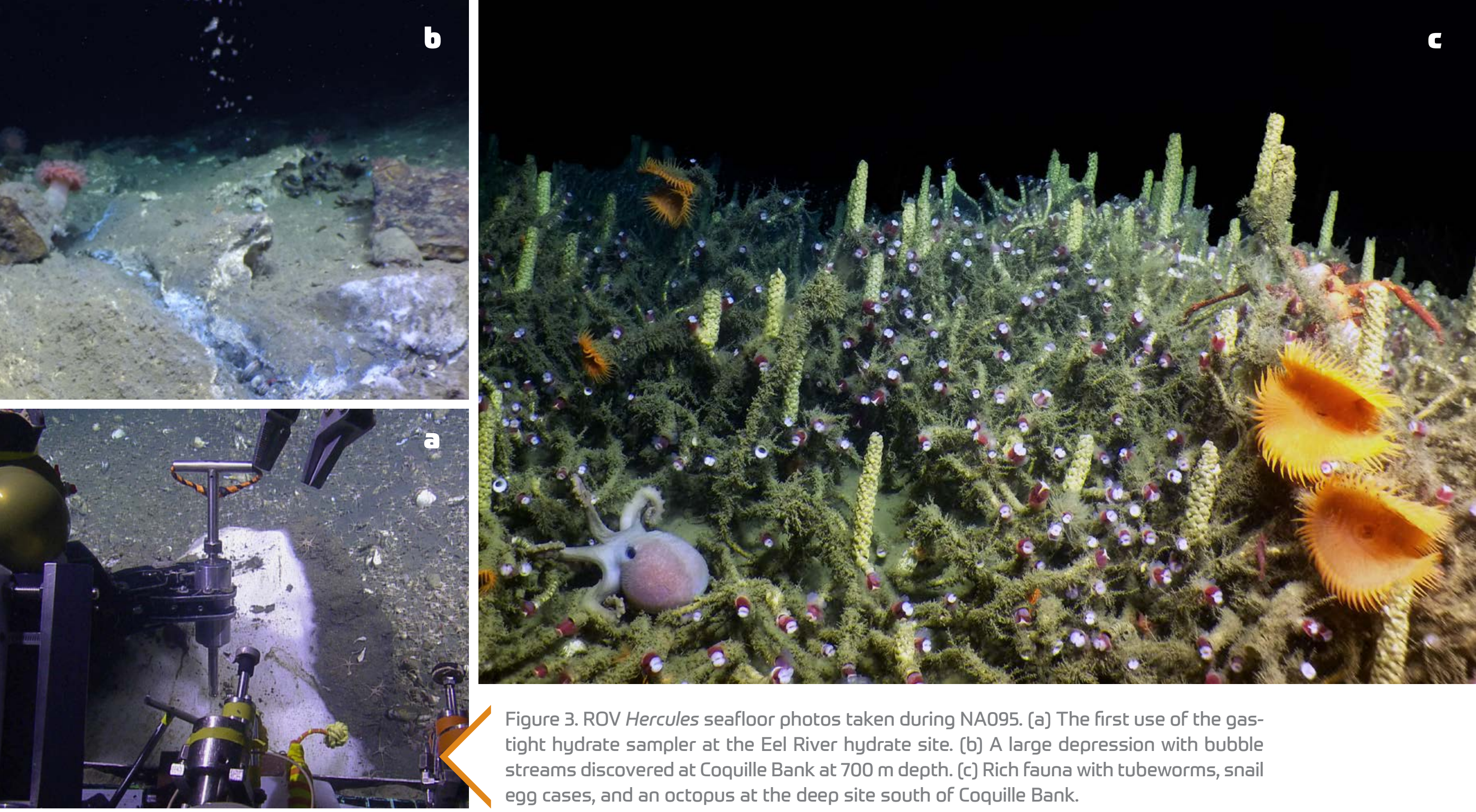


Figure 3. ROV *Hercules* seafloor photos taken during NA095. (a) The first use of the gas-tight hydrate sampler at the Eel River hydrate site. (b) A large depression with bubble streams discovered at Coquille Bank at 700 m depth. (c) Rich fauna with tubeworms, snail egg cases, and an octopus at the deep site south of Coquille Bank.

Two hydrate samples were successfully collected at Eel River (1,810 m depth; H1668) and at Heceta (1,235 m; H1678) during the first field test of a newly developed hydrate sampler (Figure 3a). Its gas-tight design permits retention of sample integrity while the pressure increases within the sampler as the hydrate dissociates. A high vacuum line on board *Nautilus* was used to directly subsample the gas phase without air contamination or gas loss.

At the Oregon-California site (H1669), a carbonate ridge that formed along a strike-slip fault ridge was investigated in detail. Large collapsed carbonate blocks were observed and bubble streams aligned with cracks alongside the carbonate cap were found at the ridge's summit. Diffuse methane flow from the cracks was abundant, and bacterial mats and clams were present (Figure 3b).

Numerous vigorous bubble streams were located at the Heceta Canyon Head site (500 m; H1675 and H1677), several of which may reach the sea surface as suggested from the midwater sonar data. In addition to sampling at this site, an acoustic experiment was conducted over two tidal cycles, with the aim of relating bubble formation to the prevalent methane flux rates.

Revisiting the 2016 dive locations at Southwest Heceta (1,235 m; H1678,) and Southwest Coquille (620 m; H1673) showed evolution of seepage and associated ecosystems over the two-year time window. At Southwest Heceta, the bubble stream sampled in 2016 was inactive, although there were traces of previous active seepage. Coquille had active bubble streams and large clam beds.

South Coquille (1,450 m; H1670) was the deepest site visited along the Oregon margin. No bubble streams were located during this dive, but the site revealed dense aggregations of tube worms associated with anemones, snail egg casings, and an octopus (Figure 3c).

Another deep methane seep site was located south of Astoria Canyon (1,345 m; H1679). Several bubble streams and associated microbial mats, clam beds and tubeworms were discovered. The last dive of the expedition (H1680) was conducted in shallow water on Nehalem Bank (150 m). This site was associated with orange and white bacterial mats and intermittent low intensity bubble streams.

NA095 significantly expanded the number of investigated and sampled bubble emission sites along the US Cascadia Margin. The sampling strategy allowed geochemical and biological comparisons between a variety of depths and latitudes. Revisiting selected sites revealed that methane seep evolution varies over time and can change quickly, and that bubble streams can turn on and off within a local area. A large part of the Cascadia Margin remains unexplored. Further water column surveys and ROV dives will be necessary to understand regional seep-related impacts on climate, biological habitat, and ocean chemistry.

NA095 involved collaborations at sea and on shore with NOAA Pacific Marine Environmental Laboratory, Oregon State University, University of Washington, NOAA Northwest Fisheries Science Center, Olympic Coast National Marine Sanctuary, and Monterey Bay Aquarium Research Institute. The expedition was funded by the NOAA Office of Ocean Exploration and Research through the Ocean Exploration Trust.

Northeast Pacific Seamount Expedition: Exploring Canada's Seamounts

By Tammy Norgard, Cherisse Du Preez, Jaasaljuus Yakgujanaas, Molly Clarkson, Lais Chaves, Robert Rangeley, Alessia Ciraolo, Katie S.P. Gale, Dana Haggarty, James Pegg, Caroline McNicoll, Shelton Du Preez, Brett Jameson, Mandy Leith, S. Kim Juniper, Leslie Elliot, Candice St Germain, Jennifer Whyte, Allison Fundis, and Renato Kane

The Offshore Pacific Bioregion off the west coast of British Columbia, Canada, is a mosaic of mountainous terrain, valleys, ridges, and basins that reflect its intense nearshore tectonic activity. The bioregion is thought to contain 52 underwater mountains (called seamounts) with elevations over 1,000 m, as well as hundreds of smaller knolls and hills. All known seamounts in the waters surrounding Canada are found off the Pacific coast, a region that includes the SGaan Kinghlas-Bowie Seamount Marine Protected Area (SK-B MPA). This bioregion also includes a large Area of Interest (AOI) designated in 2017 for marine protection. At approximately 140,000 km^2, the AOI covers almost the entire southern half of the region, contributing significantly to the Government of Canada's goal to protect 10% of the country's ocean by 2020.

In an effort to better understand the ecology of this unique AOI, Fisheries and Oceans Canada (DFO), Oceana Canada, Ocean Networks Canada (ONC), and the Haida Nation formed the Northeast Pacific Seamounts Partnership to explore the Offshore Pacific Bioregion. The partnership's 16-day expedition in July 2018 traveled 2,500 km along the full length of the British Columbia coastline to seamounts near the islands of Haida Gwaii, *Nautilus'* northernmost destination to date (Figure 1), and completed 10 dives on six different seamounts using ROVs *Hercules* and *Argus*.

In addition to collecting high-resolution underwater video and photographs, the team collected over 300 specimens, some of which are likely new species. Twenty-four long-term monitoring sites were established using physical markers, and photo mosaics were made of 10 m^2 areas. Using the ship's multibeam echosounder, all three seamounts within SK-B MPA (Figure 2) and two AOI seamounts were mapped in high resolution. Because offshore bathym-

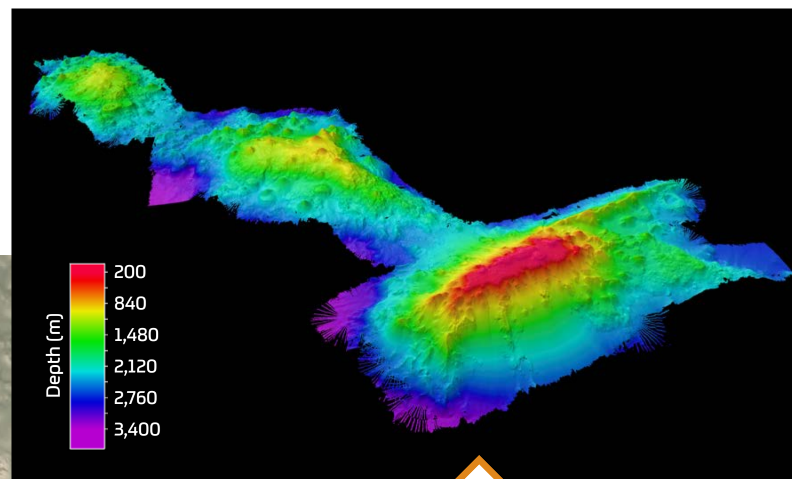


Figure 2. Multibeam image of the three seamounts within SGaan Kinghlas-Bowie Seamount Marine Protected Area. *Image credit: OET, Northeast Pacific Seamount Expedition Partners*

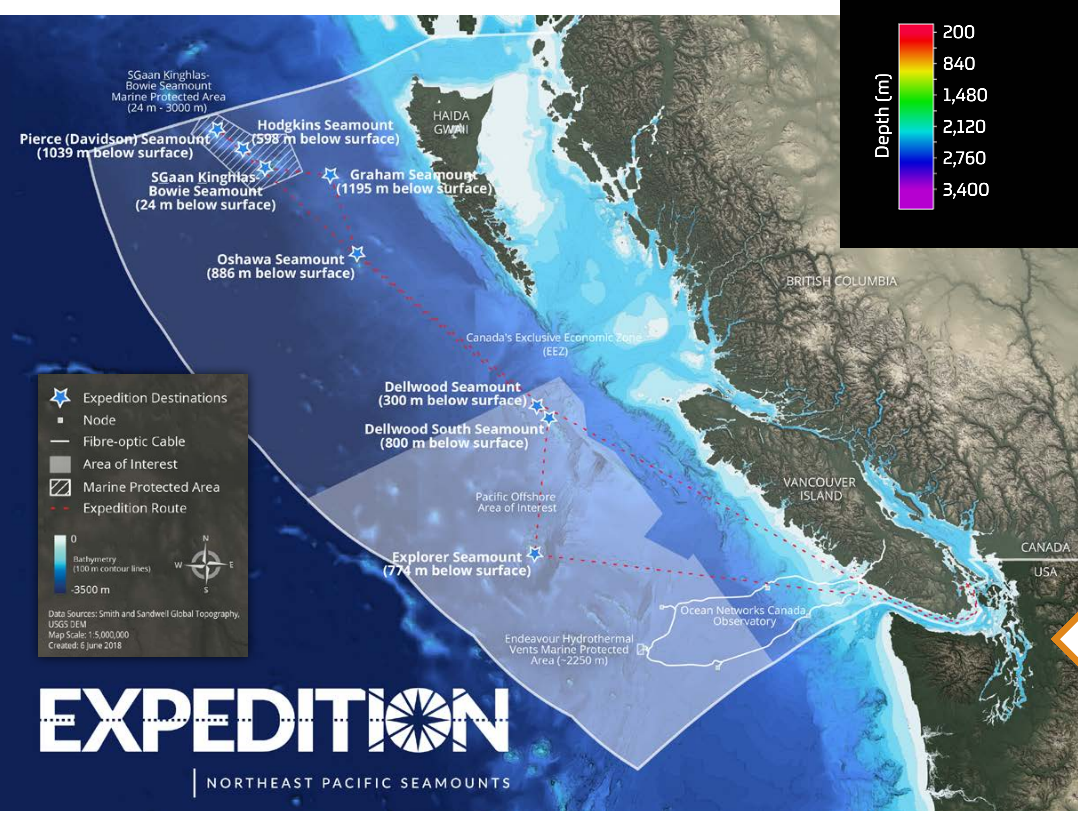


Figure 1. The Northeast Pacific Seamounts Expedition was a 16-day, 2,500 km voyage to explore and map little-known underwater volcanoes in order to inform future marine protection measures.

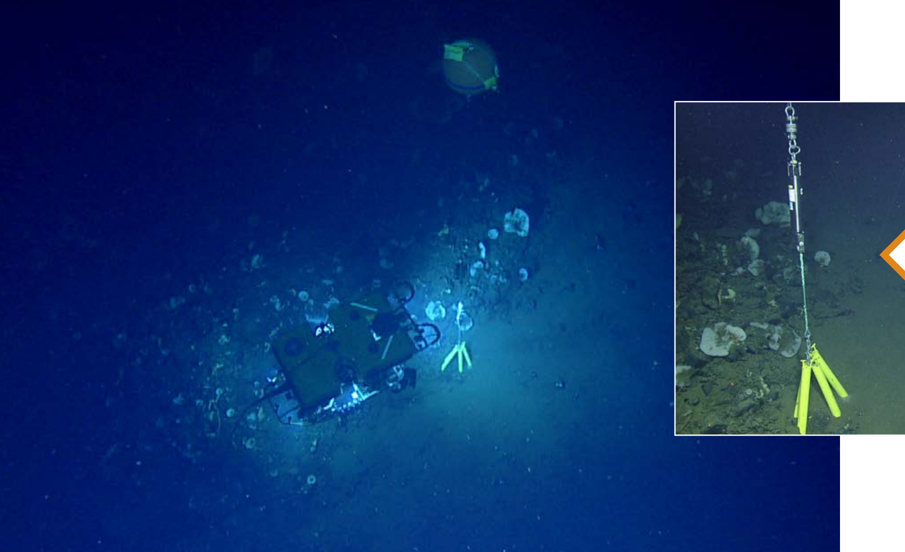


Figure 3. ONC's oceanographic mooring was deployed on the slopes of Dellwood Seamount at 825 m depth. *Image credit: OET, Northeast Pacific Seamount Expedition Partners*

Figure 4. ROV *Hercules* sampling sponges on top of Explorer Seamount at 800 m depth. *Image credit: OET, Northeast Pacific Seamount Expedition Partners*

etry data are limited, transits between dive locations were planned to pass over a further 13 predicted seamounts to confirm their elevations and classification as seamounts.

The first stop was Dellwood Seamount, surveyed by DFO in 2017 using a towed camera. Near the seamount's summit, *Hercules* took in situ temperature readings and water samples to investigate an area with suspected low levels of hydrothermal venting that were observed in 2017. It was determined the site was likely historically active but currently dormant. In addition, two near-bottom moorings were deployed on the seamount, a hydrophone to record marine mammal and fish noises and an oceanographic mooring in an area of high sponge and coral concentration to gather continuous data on seawater properties and near-bottom currents (Figure 3). Both moorings will be recovered after one year, at which time ONC plans to make these data freely available. The data will enable DFO and other researchers to understand how habitat conditions vary throughout the year, in particular, how future ocean change might affect coral and sponge communities.

At Explorer Seamount, the team was surprised to see a dense underwater sponge garden extending in every direction (Figure 4) and exhibiting a different species composition from those found on other seamounts surveyed. This seamount range represents geological, ecological, and oceanographic anomalies that will require future investigation.

SK-B MPA, designated in 2008, lies within Haida territory and is co-managed by DFO and the Haida Nation. On this expedition, research was planned to expand our understanding of the SK-B MPA and to map all three seamounts within it. Four dives were completed on SK-B Seamount, which rises within just 24 m of the surface, and is the most-surveyed seamount in Canada. One dive each was also conducted on Hodgkins and Davidson/Pierce Seamounts. These SK-B MPA dives established 14 long-term monitoring sites. This expedition surveyed deeper than ever on SK-B and Hodgkins Seamounts, made the deepest specimen collections (2,044 m) within the MPA, and conducted the first dive ever on Davidson/Pierce Seamount.

Sharing the beautiful imagery from this underwater world and communicating the science being done aboard the ship were expedition priorities. The *Nautilus* team worked with onshore teams to set up live "Seamount Viewing" events on Haida Gwaii, led by the Haida Nation and ONC. The live-streaming video provided community members in Skidegate and Old Massett with the opportunity to see the diversity of deep-sea marine life within Haida territory. More broadly, the onboard team connected daily from ship to shore, engaging online with students, summer camps, museums, and the general public. The livestream was viewed a total of 1.02 million minutes, generating 213,000 views. More than 33,000 users visited the interactive website and social media generated a reach of over two million impressions via the hashtag #PacificSeamounts2018.

The Northeast Pacific Seamounts Expedition, made possible through the contributions of all of the partners, provided information that will enhance understanding of the Offshore Pacific Bioregion's unique ecosystems.

Deep Space Meets Deep Sea on Expedition 2018: Wiring the Abyss

By Adrian Round, Fabio De Leo, Martin Scherwath, Karen Douglas, Samantha Lacy, and Mandy Leith

The deep sea holds answers to many questions about our changing ocean, the origins of life on Earth, and even outer space. During Expedition 2018: Wiring the Abyss, Ocean Networks Canada (ONC) successfully expanded infrastructure to help us understand both the deep sea and deep space, as it reached new milestones in the development of Canada's offshore observatory in the Northeast Pacific.

During Wiring the Abyss Leg 1 (June 21–July 3), 40 instruments were deployed from Canadian Coast Guard Ship *John P. Tully*. Leg 1 accomplished much of the heavy lifting in preparation for Leg 2 (July 21– August 3) aboard E/V *Nautilus*, where ROVs *Hercules* and *Argus* completed installations and connected them to the ONC network, while also collecting samples and mapping the seafloor.

With the help of the two ROVs, the final offshore seismometers for British Columbia's earthquake early warning system were successfully deployed during Leg 2. Over the last three years, ONC has installed a total of eight strong motion sensors along the Cascadia subduction zone at Cascadia Basin, Clayoquot Slope, and Barkley Canyon. Two different types of Canadian-built sensors—a Nanometrics Titan strong motion accelerometer (Figure 1) and an RBR tiltmeter—add redundancy and permit better signal comparison. The proximity of these sensors to a megathrust earthquake could provide crucial seconds of warning.

The expedition successfully doubled instrumentation at the Endeavour Hydrothermal Vent Field, Canada's first marine protected area (Figure 2). New infrastructure includes two new platforms at Main Endeavour Field to monitor vent flow and a string of three cabled Guralp

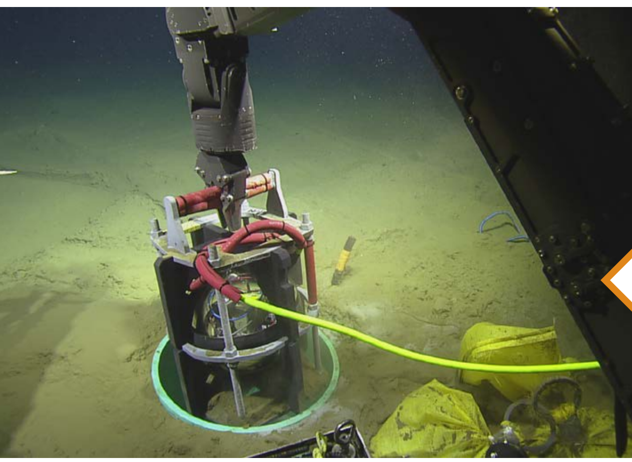


Figure 1. ROV *Hercules* carefully submerges an accelerometer inside the buried green caisson at Barkley Canyon, the final installation of Ocean Networks Canada's offshore earthquake early warning system.

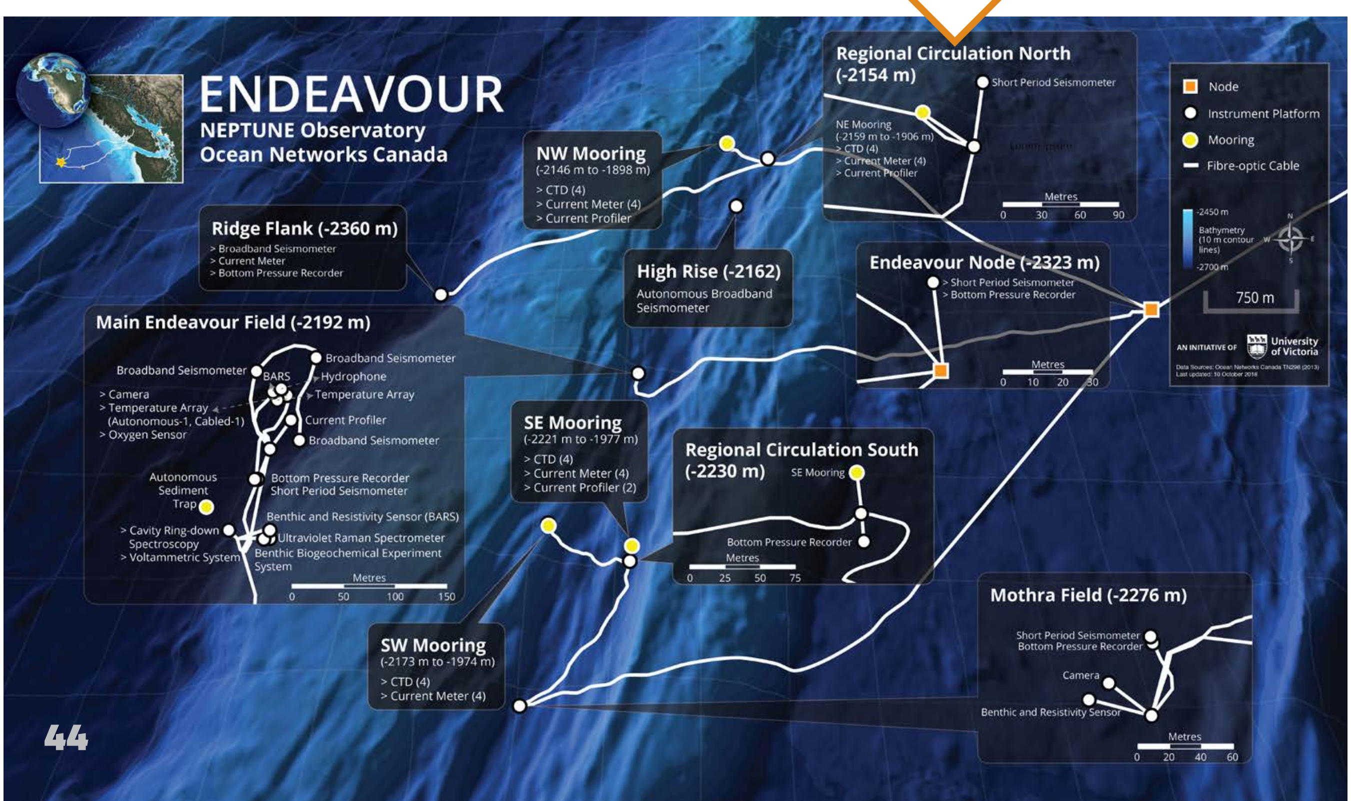


Figure 2. Endeavour is the world's most international deep-sea cabled observatory site, with instruments from Canada, United States, United Kingdom, and France connected to Ocean Networks Canada's data management system, Oceans 2.0.

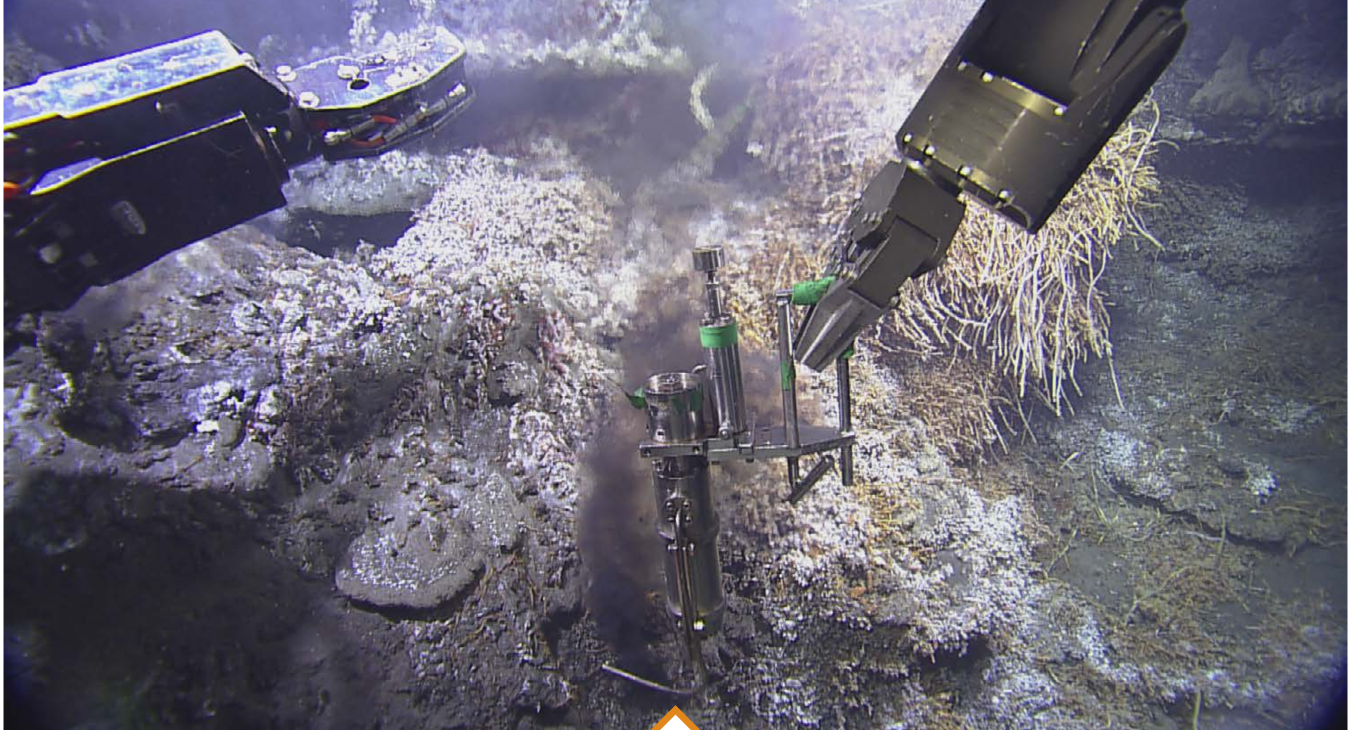


Figure 3. Sampling ~300°C hydrothermal vent fluid with a gas-tight bottle.

Maris ocean bottom seismometers to record activity at this mid-ocean ridge spreading center. A hydrophone was installed near venting activity, and three benthic resistivity sensors were added at Mothra and Main Endeavour Field to monitor super-heated hydrothermal vent fluid and chloride concentrations. An autonomous seismometer was added to High Rise vent and the two northern Regional Circulation Moorings were replaced. Data from the new instruments at Endeavour will help us to better understand the links among geological, chemical, biological, and oceanographic processes operating at mid-ocean ridges.

Other maintenance highlights include installation of a refurbished vertical profiling system and new cameras that turn on at intervals throughout the day to monitor experiments, instruments, and diverse marine life.

While diving to complete infrastructure maintenance and upgrades, the ROVs collected 80 samples, including sediment, benthic megafauna, water, hydrothermal vent fluid, and methane gas hydrate bubbles. Sediment push core samples taken at various sites support a range of research projects, including documenting the region's little-known benthic organisms living in the sediment.

As part of a new collaboration with scientists from the Natural History Museum of London, benthic megafauna samples—organisms that inhabit the sediment-water interface—were collected at Endeavour. Samples of other invertebrates such as polychaete worms, crustaceans, corals, sea anemones, and brittle stars were also collected for taxonomical identification in an ongoing partnership with the Royal BC Museum in Victoria, British Columbia.

Methane gas and fluid samples were collected at the Endeavour Hydrothermal Vent Field and Barkley Canyon using a "gas-tight" bottle held over hot fluids (Figure 3) and cold methane bubble streams, respectively, at these locations. These samples are key for determining the biogeochemical nature of the vent fluids and measuring the rates and amount of methane emanating from the seafloor.

To help answer astrophysical questions about the Big Bang and supernovae, a neutrino experiment was deployed at ONC's deepest site, Cascadia Basin (2,700 m depth). Neutrinos are subatomic particles that can provide insight into the origin and evolution of the universe. The two specialized moorings contain three photon-emitting and five photon-detecting optical modules for assessing the transparency and darkness of seawater at Cascadia Basin over a two-year period. These photomultipliers produce and receive short-lived bursts of light that simulate the detection of neutrino interactions with other particles in the water column.

During Leg 2, the expedition also took advantage of the multibeam echosounder aboard *Nautilus* to map the ocean floor in areas of interest. Two surveys—between Endeavour and Clayoquot Slope and northwest of Barkley Canyon—mapped the lower portion of the continental slope around the subduction deformation front. These maps are valuable for determining future seafloor changes caused by the next Cascadia megathrust earthquake.

Despite the challenges of working 2.5 km beneath the waves in one of the harshest environments on Earth, Wiring the Abyss 2018 achieved over 90% of its expedition goals, enabling an international group of scientists to better understand the mysteries of the deep sea and deep space.

Mapping the Lava Deltas of the 2018 Eruption of Kīlauea Volcano

By Adam Soule, Erin Heffron, Lindsay Gee, Larry Mayer, Nicole A. Raineault, Christopher R. German, Darlene S.S. Lim, Michael Zoeller, and Carolyn Parcheta

Kīlauea on the Island of Hawaiʻi is one of the most active and well-monitored volcanoes in the world. Its most devastating eruption of the last 200 years occurred in 2018, destroying more than 700 homes and other structures and displacing thousands of residents (Hawaiian Volcano Observatory Staff, 2018). As is common for Hawaiian eruptions, the lava flows from the 2018 lower East Rift Zone reached the coastline, where they produced prodigious plumes of toxic, corrosive steam and several spectacular hydrovolcanic explosions. As activity progressed, a significant volume of lava entered the ocean and was deposited on Kīlauea's submarine slopes, where it formed a lava delta. Through funding provided by NOAA's Office of Ocean Exploration and Research and the National Science Foundation's Ocean Sciences Division, scientists aboard E/V *Nautilus* mapped the south flank of Kīlauea with the ship's EM 302 multibeam echosounder to characterize this and other recently formed lava deltas.

Three bathymetric surveys conducted between late August and early October 2018 captured the morphology of the volcano's submarine flanks from depths of 4,000 m to 50 m (Figure 1). By comparing the new bathymetric surveys to those collected in 2006, we were able to determine the location and volume of lava deposited subaqueously during the 2018 East Rift Zone eruption. Unsurprisingly, the areas of greatest deposition coincided with locations where the coastal plain expanded seaward, in places up to 1 km (Figure 2). As much as 2.5 km^2 of new land was added during the 2018 eruption. Surveys also captured lava deltas offshore from the Puʻu ʻŌʻō eruption, which was active

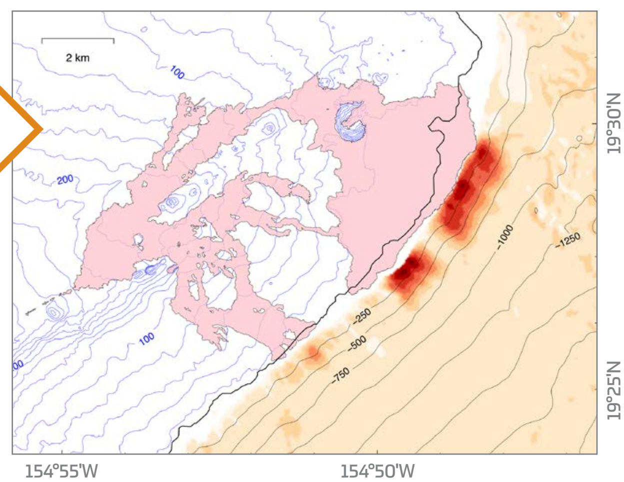
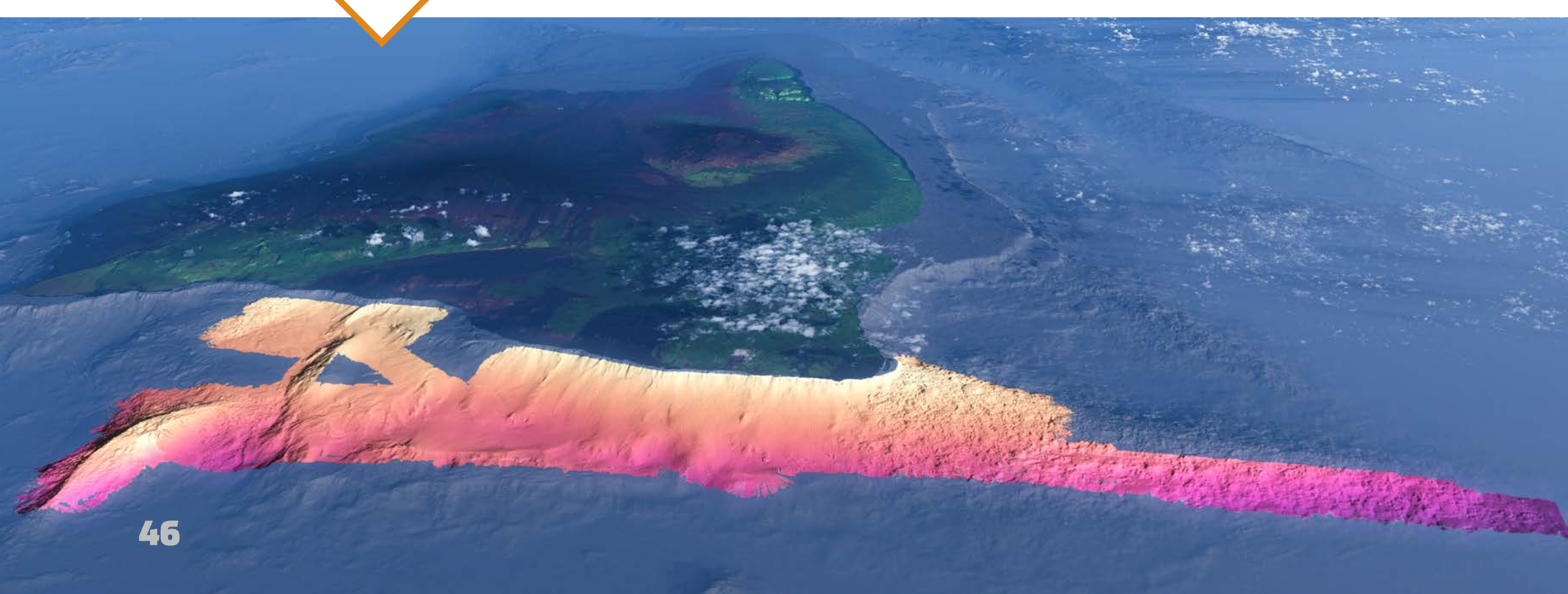
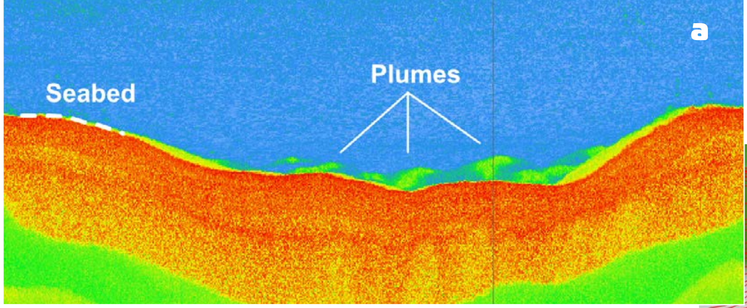


Figure 2. Bathymetric difference map between the E/V *Nautilus* 2018 surveys and 2006 surveys by R/V *Kilo Moana* shows the location of lava delta deposition offshore of the 2018 lower East Rift Zone lava flows (pink). Black contours indicate water depth in meters and blue contours indicate elevation in meters. The deltas coincide with the areas of greatest coastline addition, shown by the extension of the 2018 lava flows from the pre-eruption coastline (solid black line). Deltas extend ~1 km offshore from the new coastline to water depths greater than 750 m.

Figure 1. Three bathymetric surveys conducted by E/V *Nautilus* between late August and early October 2018 captured the morphology of Kīlauea's submarine flanks from depths of 4,000 m to 50 m.





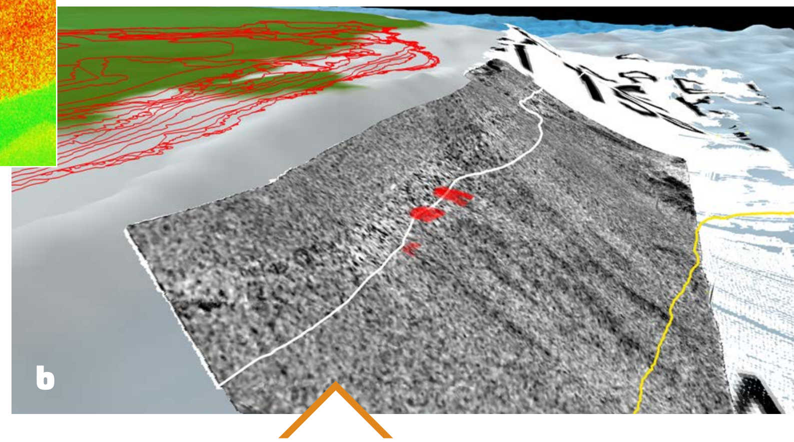


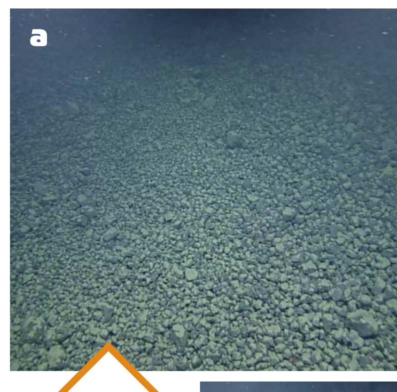
Figure 3. (a) Green plumes ascending a few meters above the seabed reflect low-lying water column anomalies imaged by the EM 302 multibeam echosounder. (b) Three water column targets (red dots) located along the 300 m depth contour (white line) superimposed on seafloor backscatter data from the EM 302 multibeam echosounder (the yellow line is 700 m contour, and red lines represent coastline growth as determined by US Geological Survey unmanned aircraft system flights).

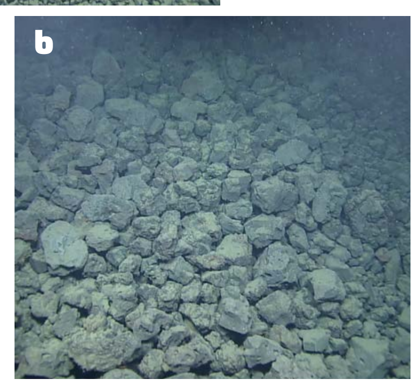
from 1983 to 2018, revealing areas of both deposition and removal due to delta collapses over the last 12 years.

Echosounder recordings during surveys over the lava deltas formed in 2018 also revealed water column anomalies that might reflect active fluid circulation, steam generation, or particle entrainment (Figure 3). These anomalies were ephemeral, appearing and disappearing from the same area as the ship traversed the coastline.

The SUBSEA program aboard *Nautilus* that followed the initial lava delta mapping (pages 48–49) diverted from its activities at Lōʻihi Seamount to investigate the water column anomalies. An ROV *Hercules* dive transect at ~300 m depth across a portion of one of the lava deltas observed a diverse array of fragmental lava. The clastic material ranged in size from a few centimeters in diameter to more than a meter and was well sorted within lobes, indicative of downslope transport (Figure 4). A second transit conducted at ~1,500 m depth across the delta encountered a series of intact lava flows. Following one of these flows upslope, diffuse hydrothermal venting, 1°–2°C above ambient, was discovered to have already been colonized by yellow-orange microbes. Rock, fluid, and microbiological samples were collected on the dive for onshore analysis.

Concurrent analysis of the bathymetric data, ROV imagery, and samples will allow us to address fundamental questions regarding the processes of deposition and remobilization as subaerial lava flows cross the coastline. Evaluating the volume of lava deposited on the submarine flanks will provide key data for understanding the integrated effects of this eruption as recorded by subaerial geophysical monitoring and observations. Further, ocean entries of active Hawaiian eruptions are known to be among the most hazardous locations on the volcanoes. In addition to persistent corrosive plumes and hydrovolcanic explosions, large collapses can occur that enhance explosivity and cause local tsunamis. Such collapses are difficult to predict without greater knowledge of the physical characteristics of the material deposited in the submarine environment and the manner in which deposition alters seafloor slopes. The ability of *Nautilus* and ROV *Hercules* to quickly respond to the volcanic crises at Kīlauea has provided critical data and observations to help address key questions at ocean entries, one of the most frequently visited, yet potentially dangerous, regions on ocean island volcanoes.





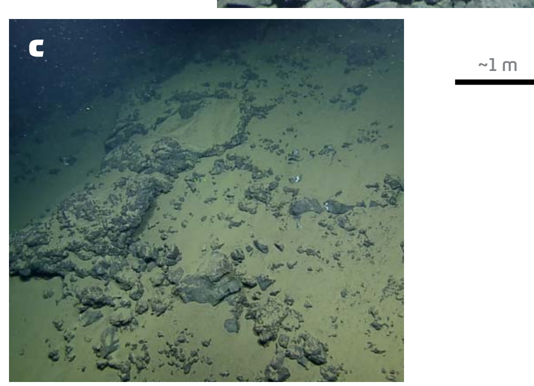


Figure 4. Photos showing materials that comprise the new lava delta, including (a) fine-grained clastic material (295 m depth), (b) coarse-grained blocks (303 m depth), and (c) intact lava flows (692 m depth). The black bar indicates ~1 m scale for each image derived from 10 cm spaced lasers mounted on ROV *Hercules*.

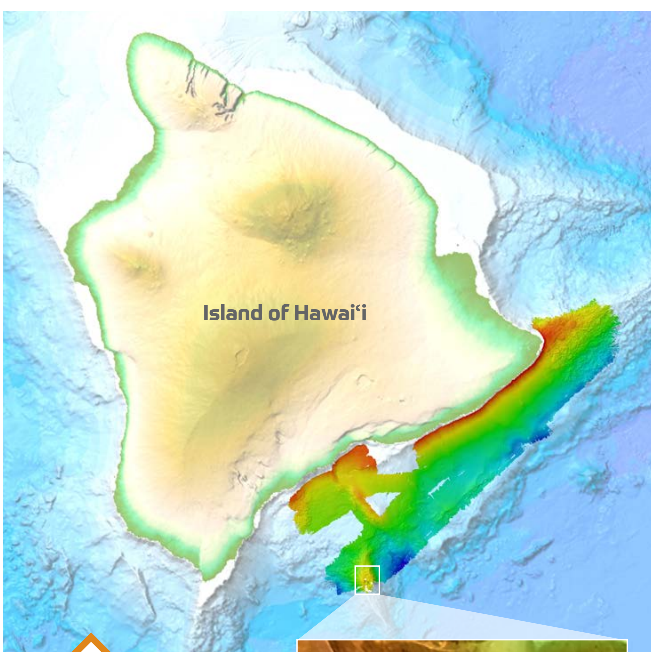
SUBSEA 2018 Expedition to Lōʻihi Seamount, Hawaiʻi

By Darlene S.S. Lim, Nicole A. Raineault, Briana Alanis, John A. Brier, Eric Chan, David Emerson, Angela Garcia, Christopher R. German, Julie A. Huber, Shannon Kobs Nawotniak, Vincent Milesi, Ashley Shields, Everett Shock, Amy Smith, Jeffrey S. Seewald, Elizabeth Trembath-Reichert, Zara Mirmalek, Matthew J. Miller, Tamar Cohen, David Lees, and Matthew Deans

Work aboard E/V *Nautilus* and at the Inner Space Center in 2018 may assist in the search for extraterrestrial life, as exploration of iron-rich hydrothermal vent systems on Lōʻihi Seamount (Figure 1) informs the design of future science-focused missions across our solar system. From August 21 to September 12, 2018, this research program was conducted by the SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) team, which is supported by NASA's Science Mission Directorate and NOAA's Office of Ocean Exploration and Research. Our mission comprises three research elements: science, operations, and technology. Both natural and social sciences anchor the SUBSEA program, providing the basis for the operations and technology domains to design and implement their studies and supporting capabilities.

SUBSEA scientists study seafloor fluid venting in Earth's deep ocean as analogs to environments on other ocean worlds in the outer solar system that could host similar chemosynthetic ecosystems (Hendrix et al., 2019). Lōʻihi Seamount is located off the coast of Hawaiʻi's Big Island more than 1 km beneath the ocean surface. It was chosen as the focus of the expedition because it hosts a distinct class of low-temperature (<100°C) and shallow depth (hence, low pressure) fluid flow that might provide a particularly relevant analog for seafloor hydrothermal conditions (T = 50°–200°C; P = 10–50 MPa) inferred for Enceladus, one of the highest priority known ocean world candidates (Figure 2). While major elements, inorganic vent fluid chemistry, and the associated microbial mats at Lōʻihi have been investigated several times since their first discovery, novel approaches during this cruise included dedicated sampling for dissolved gases and organic species in the vent fluids, microbiological sampling of those same fluids, and detailed mapping of both the flow fields and the geological formations that make up the summit of Lōʻihi (see pages 46–47).

Despite a series of hurricanes that affected the cruise, the team completed nine dives to Lōʻihi, plus one to the ocean entry site associated with the 2018 Kilauea Volcano eruption on Hawaiʻi's Big Island. The standard payload of ROV *Hercules* for these dives was augmented with a Suspended Particulate Rosette (SUPR) and Isobaric Gas-



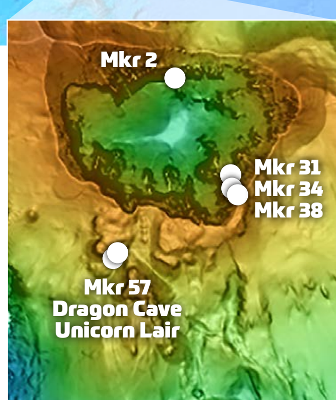


Figure 1. Map of the Lōʻihi Seamount summit and location of six vent sites that were sampled (bottom: bathymetry published in Clague et al., 2019).

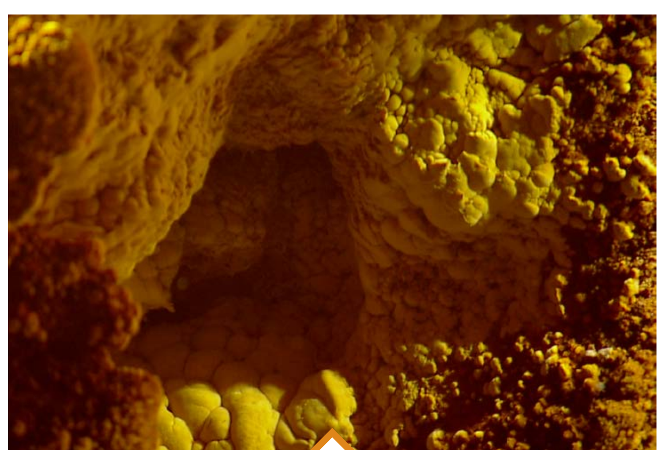


Figure 2. Interior of the "Dragon's Cave" vent (Pohaku Site, Lōʻihi Seamount) immediately prior to sampling. Fluid temperatures reached a maximum of 18°C. Individual microbial "spherules" lining the floor and walls of the cave measured up to 1 cm across.

Figure 3. On board *Nautilus* southwest of the Big Island of Hawaiʻi, SUBSEA and OET teams included scientists and engineers collaborating with scientists located at the ISC in Rhode Island (Figure 4.)

Figure 4. A selection of the SUBSEA scientists at the Inner Space Center during *Nautilus* dive operations, representing microbiology, geochemistry, and geology interests in Lōʻihi Seamount.

Tight (IGT) sampling devices. Five geologic transects were completed across the summit, including multiple high-resolution mapping surveys of lava morphologies. In parallel, the ROV sampled rocks, vent fluid, and plumes at five vent sites, two of which were also mapped in detail for areas of seafloor fluid flow. At the ocean entry site, a single ROV dive completed a systematic reconnaissance of the fresh lava flows, sampled fresh lavas, and sampled an area of already-colonized low-temperature diffuse flow for fluid geochemistry and microbiology.

Temperatures measured at vent fluid sites across Lōʻihi Seamount (in the range 15°–41°C) were ~5°–10°C cooler than when the same sites were investigated in 2013. Shipboard analyses of samples for pH, alkalinity, H_2, CH_4, H_2S, and Fe will be followed up with more detailed analyses for major elements, trace metals, and stable isotopic compositions. Theoretical modeling of water-rock interaction throughout the cruise predicted higher temperatures for fluids deep in the system before being diluted with cold seawater during subsurface circulation.

Shipboard microbiological analyses focused on components of the fluid community and their capacity to fix carbon and cycle nutrients such as nitrogen, sulfur, and iron using the energy made available as a result of water-rock reactions. A variety of shipboard experiments and cultures to target key metabolisms included NanoSIMS, RNA Stable Isotope Probing (RNA-SIP), and culturing of autotrophs. Organisms were targeted that use hydrogen or cycle nitrogen, iron, and sulfur. Although the measured temperatures of venting fluids rarely exceeded ~40°C at the seafloor, because our working model suggests that they may reach much higher temperatures at depth, microbial enrichment experiments exhibited growth at incubation temperatures of 30°C, 55°C, and 80°C. On shore, our team is also determining biomass and conducting metagenomic, metatranscriptomic, and metabolomic analyses on our vent fluid samples.

The SUBSEA Operations research team leveraged the *Nautilus* telepresence mission architecture and science activities at Lōʻihi to gain operational knowledge of the existing ocean exploration telepresence model. The SUBSEA project provides operations researchers the opportunity to study non-simulated operations with low-latency telepresence systems for planetary sciences, exploration, and microgravity environs. The SUBSEA team aboard *Nautilus* (Figure 3) and on shore at the Inner Space Center (Figure 4) were simultaneously studied during daily science data collection activities. Data collected using ethnographic and cognitive systems research methodologies will inform the construction of an information flow model and designs of workgroup environments for future human spaceflight concepts of operations. Resulting analysis will inform the upcoming 2019 SUBSEA cruise, which will be conducted in accordance with NASA spaceflight operational conditions.

During the expedition, the SUBSEA Technology team studied mission operations activities and capabilities at the Inner Space Center in preparation for the forthcoming deployment of their Exploration Ground Data Systems (xGDS) open source software to support shore-side activities for the 2019 SUBSEA cruise. xGDS is a set of web tools that support planning, situational awareness, and data visualization for remote field science and mission operations. xGDS has been developed, tested, and matured across multiple NASA analog science campaigns with humans, rovers, and ROVs. During the cruise, the technology team began the process of tailoring xGDS to support *Nautilus* data types and formats.

The SUBSEA team looks forward to work in 2019 in the Gorda Ridge area of the Northeast Pacific Ocean, which will serve to evolve and broaden the knowledge gained during the 2018 Lōʻihi expedition.

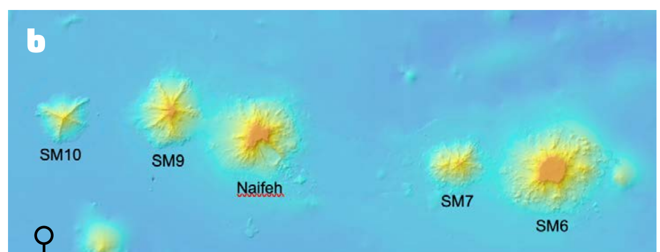
Enigmatic Seamounts Exploring the Geologic Origins and Biological Communities in Papahānaumokuākea Marine National Monument

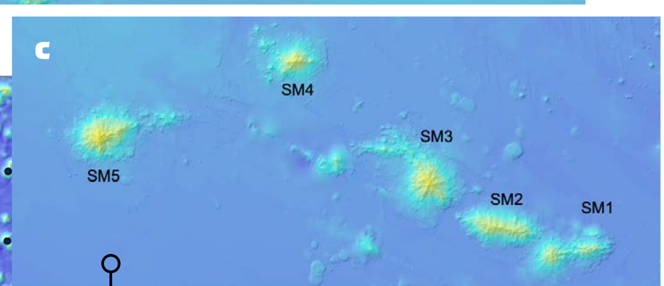
By Christopher Kelley, Thomas Hourigan, Nicole A. Raineault, Andrea Balbas, Dorsey Wanless, Leigh Marsh, Rebecca Wipfler, Lila Ardor Bellucci, and Renato Kane

The Papahānaumokuākea Marine National Monument (PMNM) was established in 2006 to protect all emergent land (i.e., islands, atolls, pinnacles) in the Northwestern Hawaiian Islands (NWHI) as well as the seas extending 50 nautical miles (nm) out from these features. In 2016, the boundary was expanded to the full 200 nm US Exclusive Economic Zone, making PMNM the largest contiguous marine protected area in the country. Since the expansion occurred only two years ago, previous deepwater research in the monument was focused almost entirely within the original 50 nm boundaries. Submersible and ROV dives had only been conducted on five of the 88 seamounts in the "expansion area." Providing PMNM's management with more information on the resources in this part of the monument was the main driver for E/V *Nautilus* cruise NA101, conducted from September 15 through October 2, 2018.

The NA101 dives focused on two clusters of enigmatic seamounts located north of Gardner Pinnacles (Naifeh cluster) and Necker Island (unnamed cluster) (Figure 1) that had not previously been mapped or explored. Their location north of the NWHI chain and lineation may indicate they formed by "arch volcanism." This type of volcanism occurs along a flexural bulge that forms due to loading of the oceanic plate by an adjacent large volcanic edifice, in this case Gardner. This poorly understood process has been linked to the formation of a large lava field north of the Big Island of Hawai'i. If they were formed by arch volcanism, then Gardner and the seamount chains should have formed contemporaneously. Thus, the primary geologic objectives of the cruise were to determine the age of the seamount lavas using $^{40}Ar/^{39}Ar$ dating methodologies and analyze the geochemical constituents to better understand volcanic dynamics and origins.

The primary biological objectives were to determine if high-density, filter-feeding communities were present on these seamounts and to survey for new species or new records of species for this area of the Pacific. Prior to this cruise, 14 spectacular communities of deep-sea corals, sponges, and their associates had been found in PMNM at depths of over 1,500 m. Only one of these is located within the expansion area, although many more are believed to exist. Such communities represent hotspots of biological diversity in the deep sea and are thus principal targets for conservation. The primary mapping objectives were to





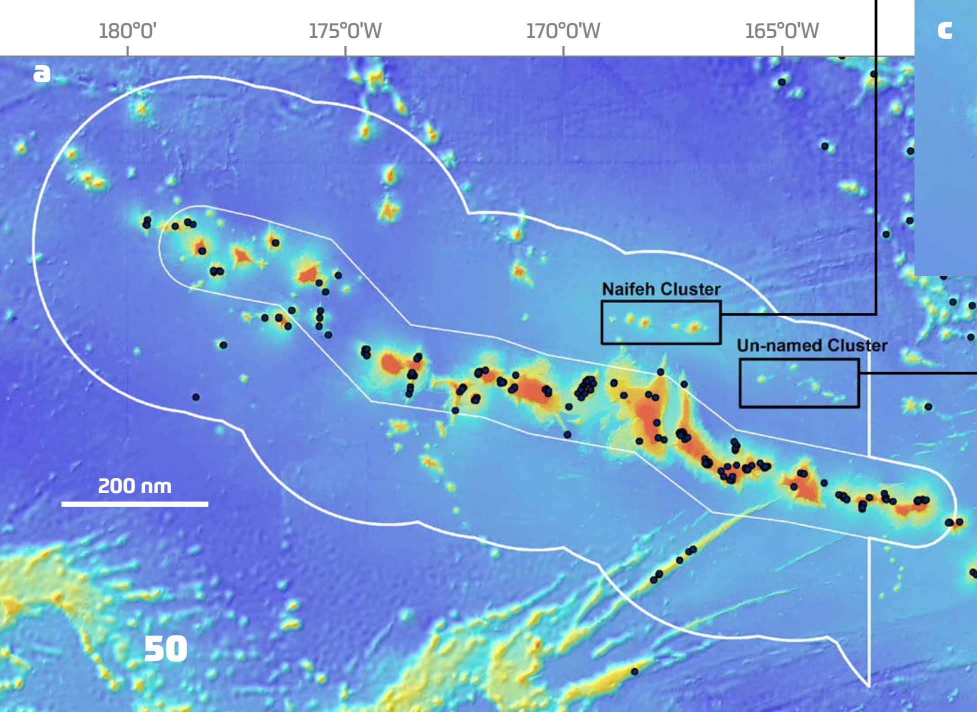


Figure 1. (a) Map of the Papahānaumokuākea Marine National Monument showing both original and new boundaries (thin and thick white lines, respectively), locations of all previous deepwater dives (black dots), and the two clusters of seamounts targeted during this cruise. Multibeam bathymetry of the (b) Naifeh seamount cluster and the (c) unnamed seamount cluster collected during NA101. Basemap source: GMRT (Ryan et al., 2009).

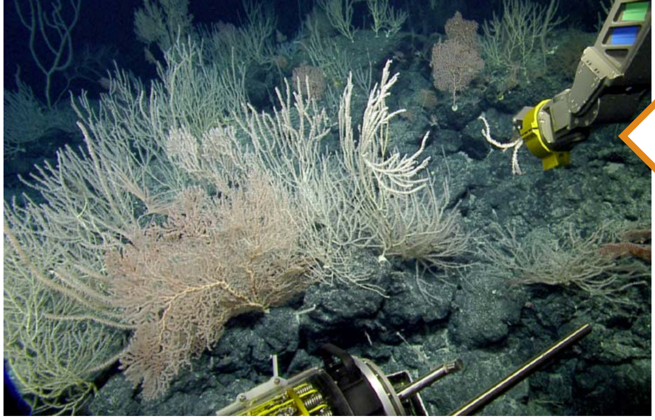


Figure 2. Image of the high-density coral and sponge communities found on seamounts.

Figure 3. Two potentially new species of squat lobsters collected during NA101.

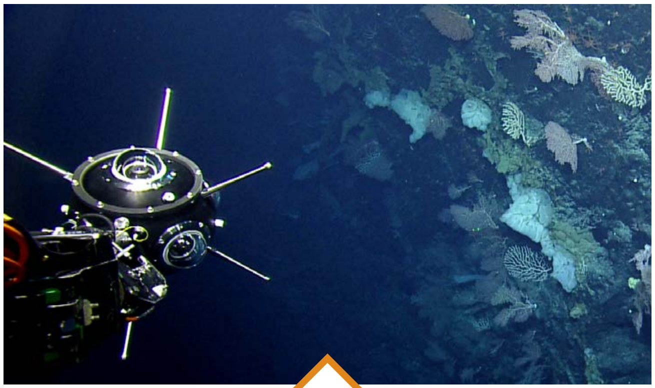


Figure 4. The MIT 360° camera being tested during an NA101 dive.

acquire from all these seamounts high-resolution bathymetry, backscatter, and sub-bottom data, which are essential for interpreting both geological and biological data, as well as for dive planning.

All of the mapping, geological, and biological objectives were achieved during the cruise. Bathymetry collected on the two seamount clusters and during transits totaled 16,594 km^2 (Figure 1b,c). The newly collected bathymetry indicates that five of the seamounts in the unnamed cluster are elongate ridges or conical, the shallowest of which reached a summit depth of 1,676 m. Three of five seamounts in the Naifeh cluster were revealed to be guyots, indicating they had once reached the ocean surface. Naifeh Seamount had the shallowest summit at a depth of 723 m. The abyssal seafloor beneath Naifeh cluster was shallower than that of the unnamed cluster, which is consistent with these seamounts being situated on the Hawaiian Arch.

Eleven ROV dives were successfully completed during the cruise, one dive on each of the seamounts in both clusters along with a second dive on the largest seamount (SM6). Eight of the dives were conducted on rift zone ridges, two on summits, and one on an off-slope cone. Dive depths ranged from 1,243 m to 2,844 m. Fifty-six rocks were collected from all 10 seamounts. From initial examination, at least one rock from each of the Naifeh cluster seamounts and from three of the unnamed cluster seamounts are believed to be dateable. Rocks from the other two seamounts (SM3 and SM5) appeared to be too altered for dating purposes. Rocks from the Naifeh cluster seamounts looked younger, which would be consistent with arch volcanism origin, but further geochemical analyses to be completed following the cruise should help determine their genesis.

High-density coral and sponge communities were discovered on four of the 10 seamounts (SM4,6,8,9) at depths between 1,548 m and 2,420 m. These communities varied in both diversity and dominant species (Figure 2) and all were found on rift zone ridges, which supports past work indicating that ridge topography is conducive to high-density community development.

The 46 biological specimens collected potentially include two new species of arthropods (Figure 3), one new tunicate species, one new hexactinellid sponge species, two new species of mollusks, three potential new species of sea stars, six potential new species of holothuroideans, a new species of urchin, and a number of new species of cnidarians that included both hexacorals and octocorals. All of the specimens are now at Harvard's Museum of Comparative Zoology for long-term curation and study by taxonomic researchers. In addition, 25 water samples were taken for environmental DNA analysis by Meredith Everett at the NOAA Northwest Fisheries Science Center toward understanding coral and fish distributions.

Finally, two new instruments were successfully tested during the cruise: a 360° camera developed at the Massachusetts Institute of Technology and a rock "gripper" developed at NASA's Jet Propulsion Laboratory for possible future use in horizontal drilling in the deep sea (Figure 4; see page 28 for details). Both of these instruments have the potential to revolutionize deep-sea research, the camera to immerse scientists and the public in deep-sea exploration via virtual reality, and the gripper (with the addition of a drill) to allow precision core sampling never before possible on difficult terrain.

Corals, Sponges, and an Octopus Garden in Monterey Bay National Marine Sanctuary

By Chad King and Jennifer Brown

Davidson Seamount is an inactive volcanic undersea mountain 120 km off the coast of central California that last erupted approximately 9.8 million years ago. It is 42 km long, 13 km wide, and 2,280 m tall, and its summit is still 1,250 m below the sea surface (McClain et al., 2009; Castillo et al., 2010). The seamount is home to large coral forests, vast sponge fields, crabs, deep-sea fishes, shrimp, basket stars, and a variety of rare and unidentified benthic species (DeVogelaere et al., 2005). As part of the 2008 management plan for Monterey Bay National Marine Sanctuary (MBNMS, 2008), a boundary change included the undersea mountain as the Davidson Seamount Management Zone (DSMZ).

Multibeam data collected during 2017 E/V *Nautilus* cruise NA080 were used to identify dive targets southeast of Davidson Seamount in a previously unexplored deep-water (>3,000 m) region of basaltic rocky reef. Objectives of the 2018 NA103 cruise included: characterization of the rocky reef area and documentation of the distribution and abundance of corals, sponges, fishes and other biota; collection of biological samples of corals, sponges, and associated species for identification; exploration of previously unseen areas of Davidson Seamount; documentation of associations of fishes, corals, sponges, and rocky substrate; collection of sediment and water samples to analyze for the presence of persistent organic pollutants (POPs); and mapping along the Big Sur coast and the southwest corner of the DSMZ. Unfortunately, due to technical issues and weather, NA103 only completed two ROV dives.

The first dive was conducted at a deep (3,100–3,420 m) unexplored area southeast of Davidson Seamount characterized by muddy sediments overlying what is assumed to be basalt (Figure 1). Much of this area consisted of "stepped" plateaus and landslide scarps over 100 m in height. Few corals and sponges were seen, with the exception of one vertical wall that featured hundreds of sponges and dozens of smaller corals. The largest geologic feature at this site was a volcanic dome about 230 m in height. Numerous hexacorals and octocorals were observed, including the primnoid *Calyptrophora* sp. A "dumbo" octopus (*Grimpoteuthis* sp.) was seen at 3,200 m depth (Figure 2).

The highlight of this dive and of this expedition came within the last hour of the dive. We discovered aggregations of over 1,000 brooding female octopuses (*Muusoctopus robustus*). This genus has an unusual "upside-down" brooding posture, with the underside of the arms exposed and the mantle toward the eggs, which are cemented to bare rock (Figure 3). A large gathering of brooding *Muusoctopus* sp. (only 100 individuals) was described once before at a hydrothermal system near Costa Rica (Hartwell et al., 2018). The geographic extent and total abundance of this much larger *M. robustus* population could not be determined, but clusters of octopods were visible in the distance.

Examination of two groups of 20+ brooding individuals revealed shimmering water, indicative of a fluid seep.

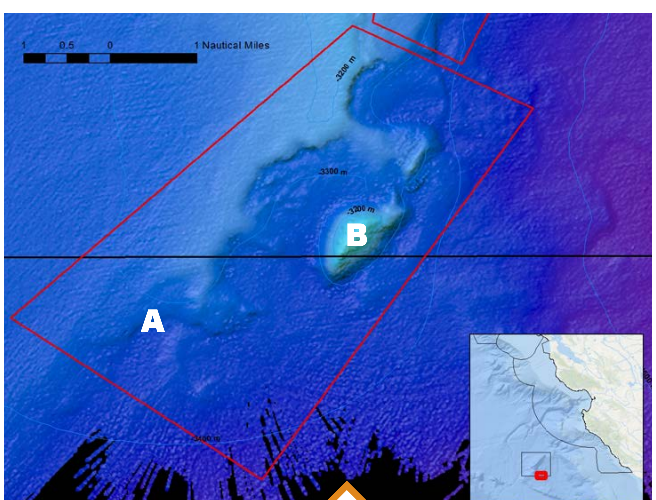


Figure 1. The boundary of the first dive site is indicated by the red polygon. Northeast-trending scarp features were explored (A), along with a prominent volcanic cone that rises over 200 m (B).

Figure 2. Dumbo octopus (*Grimpoteuthis* sp.) observed near Davidson Seamount at 3,200 m depth.

Figure 3. Female octopuses (*Muusoctopus robustus)* in their unique brooding posture within a fluid seep at 3,100 m depth near Davidson Seamount.

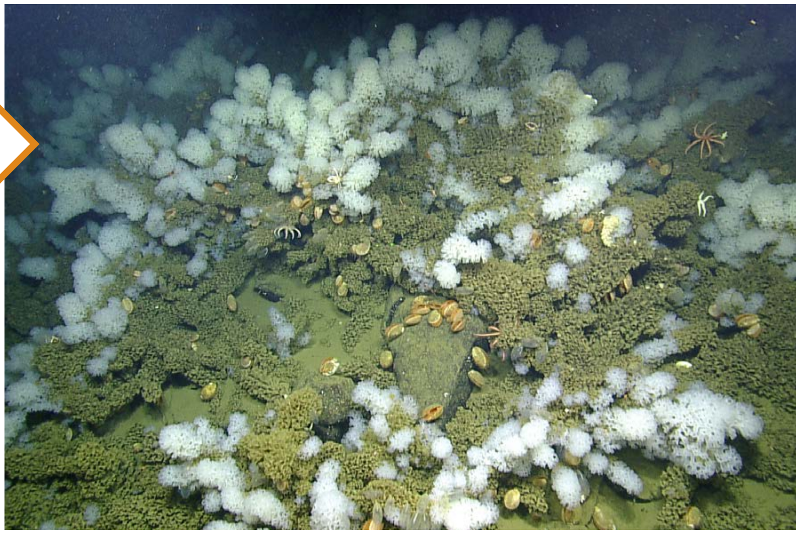


Figure 4. Sponge reef observed during a dive south of Anacapa Island.

The rock surface in these two seeps areas was bare, but they were surrounded by rocks with light sediment cover. Several species abundant in the seeps, including whelks, amphipods, shrimp, and anemones, were not observed elsewhere. We assume that other groupings and lines of individual octopods that followed fissures in the rock were there because of fluid seepage.

We were unable to obtain a temperature reading or water sample to determine the characteristics of the shimmering water, but likely causes include warmer water than the surrounding area and/or enrichment with hydrocarbons. Twenty-four samples were collected, including rocks from several locations, a push core into a clay landslide, carnivorous sponges, several unidentified sponges, a stalked crinoid, a whelk, a xenophyophore, and corals.

Bad weather drove us to seek the relative shelter of the Channel Islands, so the last ROV dive of the expedition occurred approximately nine nautical miles south of Anacapa Island, just outside of Channel Islands National Marine Sanctuary. The ROVs traversed a scarp where large sponge reefs dominated the benthic landscape (Figure 4). Conspicuous species included *Farrea* sp., *Heterochone* sp., *Staurocalyptus* sp., and species from the family Acanthascinae. Overall, six samples were collected, including rocks, sponges, a file clam, and water samples for environmental DNA analysis.

We successfully mapped 2,107 km^2 of ocean floor in the DSMZ's southwest corner and along the Big Sur coast. Initial data show a rich complex of small volcanic and sedimentary features to the southwest of Davidson Seamount.

National Geographic's baited Deep Ocean Drop Cam was deployed once southeast of Davidson Seamount and once in Mill Creek Canyon off the Big Sur coast. Each deployment recorded six hours of video. Grenadiers and cusk eels were observed at the Davidson Seamount site at a depth of 3,400 m. The Mill Creek Canyon deployment reached 550 m, revealed a turbulent environment, and recorded a sleeper shark and many benthic jellies.

The Ocean Exploration Trust assisted MBNMS and Office of National Marine Sanctuaries press teams by providing materials, sending media alerts, and organizing a dozen interviews aboard *Nautilus*. This media coverage resulted in hundreds of stories about dumbo octopus sightings and octopod brooding grounds. The onboard team conducted 60 ship-to-shore interactions with schools and public audiences in 11 states, Canada, Ireland, and Colombia. The total reach for live interactions during NA103 was approximately 3,200 people.

Although NA103 did not fulfill all of the planned objectives, the discovery of the "octopus garden" is a significant find. This gathering of brooding females was unknown to science just a couple of years ago, but could be an important nursery. The full extent of this population and the cause for the fluid seeps are yet to be determined.

Funding for the expedition was provided by the National Marine Sanctuaries Foundation.

"Walking with the Ancients" in the Southern California Continental Borderland

By Robert D. Ballard, Larry Mayer, Kenneth Broad, Dwight F. Coleman, Erin Heffron, and Val Schmidt

"Walking with the Ancients" was the fifth in a series of E/V *Nautilus* expeditions to the Channel Islands and the Southern California Continental Borderland that began in 2016. Cruise sponsors were NOAA's Office of Ocean Exploration and Research, the Office of Naval Research, the National Geographic Society, and the Lounsbery Foundation.

The primary focus of the five expeditions was to discover and investigate submerged caves carved by the sea since the Last Glacial Maximum (LGM) some 19,000 years ago. When the great continental ice sheets began to melt, sea level rose discontinuously, creating a series of paleo-shorelines. A reconstruction using regional sea level data shows breaks in sea level rise, called still stands, at about 120 (corresponding to the LGM), 110, 100, 70, 35, and 10 meters below current sea level (e.g., Liu et al., 2004; Chaytor et al., 2008). At the time of these still stands, high-energy coastal processes created wave-cut terraces that characterize these paleo-shorelines, creating an environment that may have led to cave development within the folded and fractured rock formations that make up the regional geologic structure. It has been suggested that humans occupied some of these sea caves, including during the period when humans first left Beringia to populate the rest of the Western Hemisphere (e.g., Erlandson et al., 2011; Reeder-Myers et al., 2015).

Scuba divers have identified numerous submerged caves in water depths of 35 m or less (Ballard et al., 2018). The fundamental question we are addressing is: are there still any sea caves along the paleo-shorelines at depths below 35 m that represent the time of the earliest human settlement into western North America?

In 2016 and 2017, the E/V *Nautilus* Kongsberg EM 302 multibeam echosounder was used to map the seafloor around many of the Channel Islands, locating all six of the paleo-shorelines at their predicted depths (Figure 1). In 2017, divers explored a known cave complex along the 10 m paleo-shoreline off Santa Cruz Island. In addition, the University of New Hampshire's (UNH) autonomous surface vehicle (ASV) *BEN* was used to collect high-resolution bathymetric data to locate potential caves for subsequent verification by scuba divers and ROVs *Argus* and *Hercules* (Ballard et al., 2018).

In 2018, scuba divers explored one of the caves discovered by *Hercules* the year before at 70 m depth on Osborn Bank. They swam the cave's 25 m length and exited from a separate entrance. A team of divers also revisited Seal Cove cave off Santa Cruz Island and used a hand-held MNEMO cave mapping system (Kister, 2018) to construct a three-dimensional map of the cave's interior (Figure 2).

The primary objectives of the 2018 *Nautilus* exploration were to: (1) continue to map regions of the US Exclusive Economic Zone within the Continental Borderland from Santa Barbara to Los Angeles using *Nautilus*' echosounder;

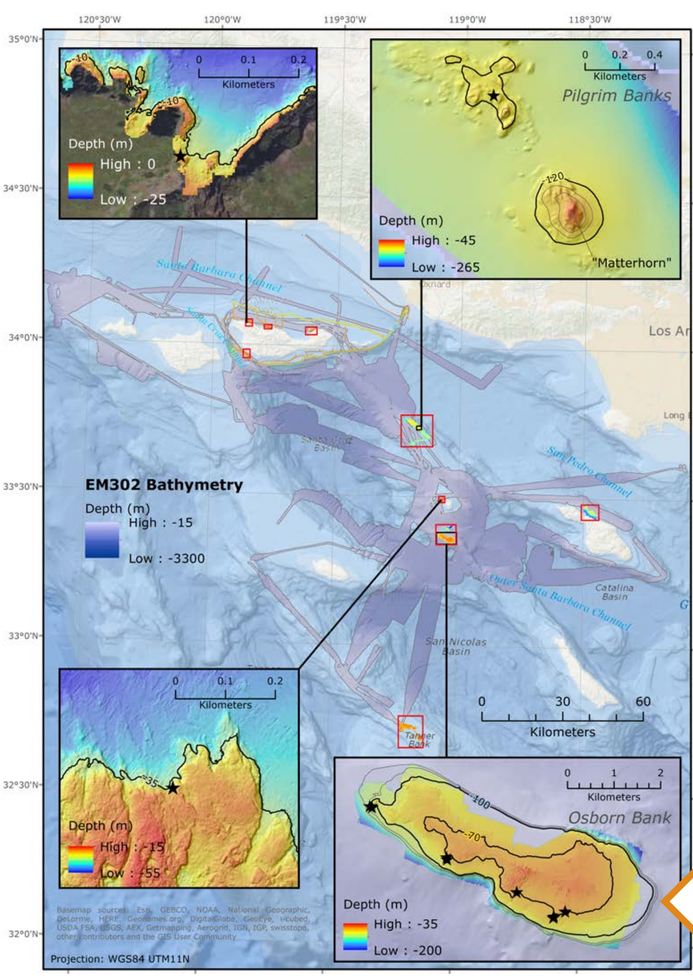


Figure 1. Map of locations for this project. Blue bathymetry: *Nautilus* EM 302 multibeam data collected during NA074, NA083, and NA104. Rainbow bathymetry: ASV *BEN* EM2040 and R/V *Shearwater* NORBIT data collected in 2017 and 2018. Red boxes: locations of high-resolution, focused ASV EM2040 surveys. Inset maps: EM2040 and NORBIT bathymetry shown using rainbow colormap, EM 302 bathymetry in blue, cave locations marked as black stars, paleo-shoreline contours shown as black lines with contour nearest to cave depths shown in bold. The inset map at the top right shows the location of the "Matterhorn" feature shown in Figure 4b.

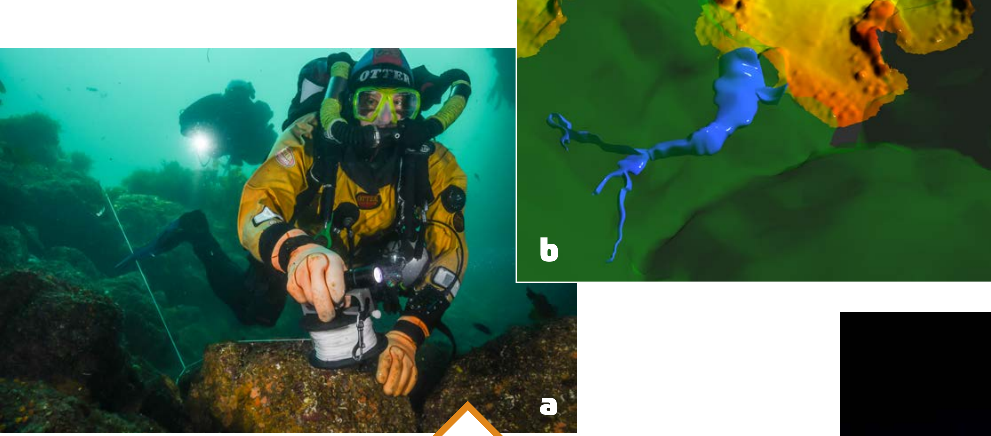


Figure 2. (a) Dive team explores interior of Seal Cove cave off Santa Cruz Island. (b) Three-dimensional map of the cave made using the hand-held MNEMO system, revealing over 280 m of passageways.

(2) use the UNH ASV to collect high-resolution bathymetric and backscatter data of Osborn, Tanner, Nidever, and Pilgrim Banks, and conduct additional mapping off Santa Cruz Island; and (3) use the ROVs to explore the paleo-shorelines mapped by *Nautilus* and the ASV. The objectives of the ROV dives were to locate and document the paleo-shorelines of these banks, including paleo-sea caves; to assess area marine life and, in some cases, collect biological samples, including shells, primarily of ancient oysters, scallops, and abalone, for subsequent carbon-14 age dating; and to collect rock samples along the paleo-shorelines, especially around caves.

At Tanner Bank, which is a beveled sandstone anticline, we found numerous overhanging ledges, but none at sufficient depths to qualify as sea caves. Nidever Bank, also formed of sandstone and other sedimentary rocks, had no sea caves. The paleo-shorelines of both these banks were dominated by sandstone and mudstone concretions, indicating an energetic environment but the lack of a geologic framework to sustain cave formation (Figure 3).

In contrast to these banks, all of the submerged paleo-sea caves discovered to date have been within volcanic terrains of Santa Cruz and Santa Barbara Islands as well as on Osborn and Pilgrim Banks. The best developed deep caves were found in volcanic bedrock that is significantly faulted and fractured. Although Santa Rosa Island also contains volcanic rocks, the area investigated was on the eastern tip of the Island, which is characterized by thick layers of volcanic ash. Within the ash, only small caves were mapped by the multibeam sonar and visually verified by ROV *Hercules*.

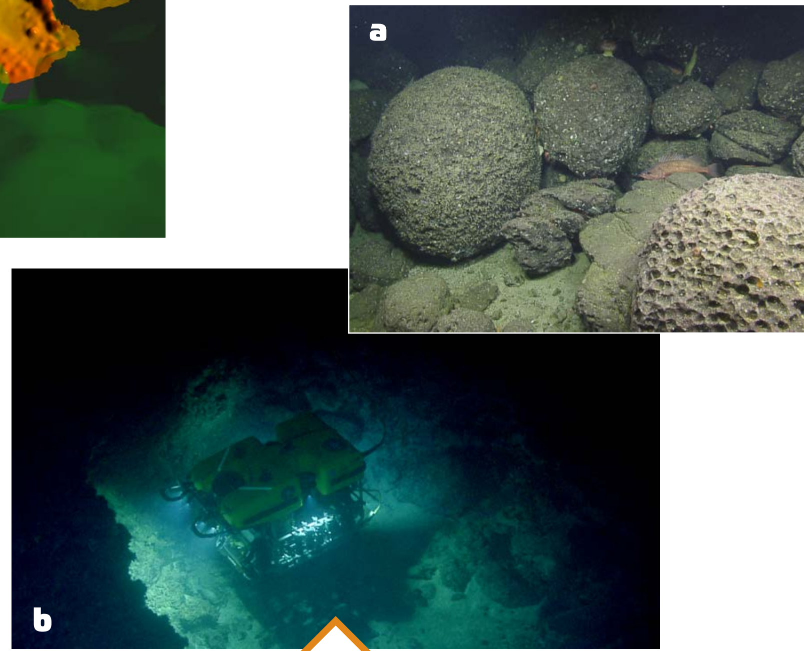
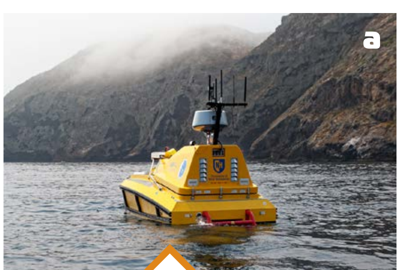


Figure 3. (a) Sandstone concretions located along paleo-shorelines on Tanner and Nidever Banks. (b) ROV *Hercules* exploring the entrance to one of the submerged caves.

The search for caves along Pilgrim Banks also provided an opportunity to map and investigate a remarkable pinnacle feature known to the local scuba diving community as the "Matterhorn" (Figure 4), characterized by a rich concentration of marine life, in particular, cup corals. Adjacent smaller pinnacles were also mapped, imaged, and sampled using our vehicle systems.

The combined 2017 and 2018 efforts resulted in the location of cave entrances along each of the six paleo-shorelines. Age dating of shells and rock samples collected next to the entrances of all of the caves will provide important temporal and geological context and constrain the ages of the paleo-shoreline and paleo-sea cave formation. Most importantly, these efforts have allowed us to develop a series of tectonic, geologic, environmental, and mapping criteria to optimize our search for potential archives of human history. Our team plans to return in 2019 to continue mapping these cave systems, including using ROV *Hercules* and the AUV *Sunfish* built by Stone Aerospace, to prepare for exploring caves that are beyond diver depth.



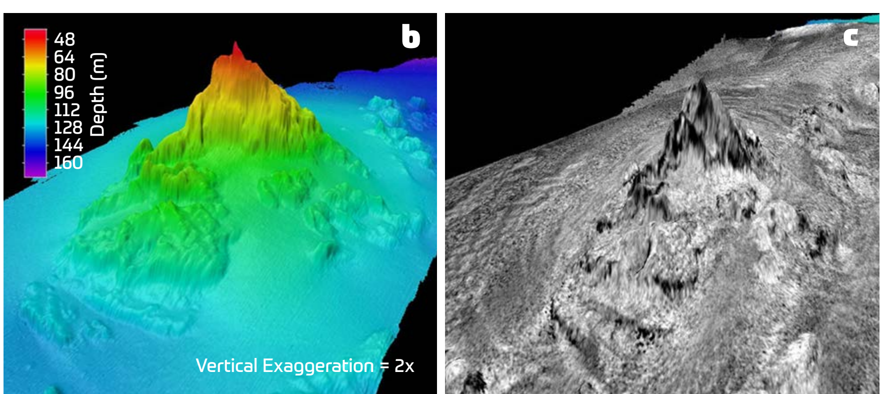
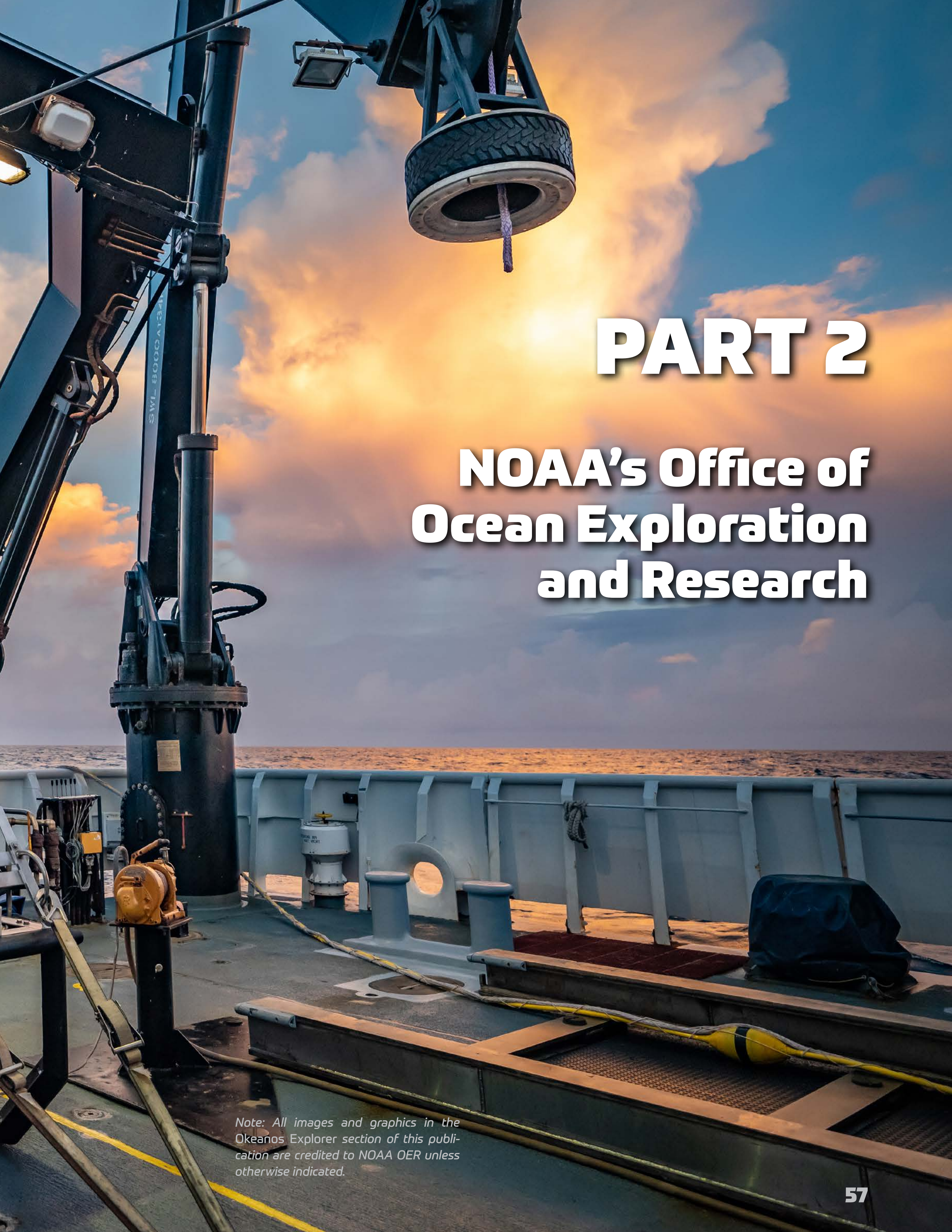


Figure 4. (a) University of New Hampshire ASV *BEN* deployed from E/V *Nautilus*. (b) Bathymetry and (c) backscatter of "Matterhorn" peak on Pilgrim Banks.

The ROV team prepares the ROV camera sled *Seirios* for deployment during the Océano Profundo 2018 expedition aboard NOAA Ship *Okeanos Explorer*. *Image credit: Art Howard, GFOE*



PART 2

NOAA's Office of Ocean Exploration and Research

Note: All images and graphics in the Okeanos Explorer *section of this publication are credited to NOAA OER unless otherwise indicated.*

Ten Years of Ocean Exploration with NOAA Ship *Okeanos Explorer*

Taking the Risk to "See Through New Technological Eyes"

By Paula Keener, David McKinnie, and Emily Crum

THE CALL FOR AN INNOVATIVE AND BOLD APPROACH TO OCEAN EXPLORATION

In 2000, a Presidential panel issued *Discovering Earth's Final Frontier: A US Strategy for Ocean Exploration* (President's Panel for Ocean Exploration, 2000), a timely, compelling and moving call for an "innovative and bold" US ocean exploration program in which "discovery and spirit of challenge are the cornerstones." As part of this national exploration program, the Panel envisioned a "flagship" dedicated to voyages of discovery that centralized "data collection and outreach technologies on a dedicated platform."

In keeping with the Panel's vision, the National Oceanic and Atmospheric Administration (NOAA) commissioned NOAA Ship *Okeanos Explorer* in 2008 as America's first civilian agency ship dedicated to ocean exploration (Figure 1). Since its first voyage in 2009, *Okeanos Explorer* has served as the "new technological eyes" that allow NOAA's Office of Ocean Exploration and Research (OER) to pursue the Exploration Objectives described in the Panel's report:

- **Mapping at New Scales.** Find and explore archaeological sites, expand understanding of marine resources, characterize ocean ecosystems, discover new species, and map the seafloor—all to show others what lies beyond our current understanding.
- **Exploring Ocean Dynamics and Interactions at New Scales.** Discover new oceanographic features, reveal oceanographic and atmospheric changes, and unravel the processes that connect living and non-living systems in the ocean.
- **Developing New Technologies.** Invent, build, and adapt remote and in situ tools for measuring, mapping, and exploring all aspects of the ocean, and create new ways to visualize ocean data.
- **Reaching Out in New Ways.** Deliver ocean expeditions to schools and informal science centers around the nation; develop new technologies to connect scientists and explorers with students, educators, and the public; and expand the reach of ocean exploration data to include business and industry partners.

These Exploration Objectives set the stage for 10 years of innovative, exciting, and far-reaching ocean exploration aboard *Okeanos Explorer*, as we outline below.

Figure 1. NOAA Ship *Okeanos Explorer*.

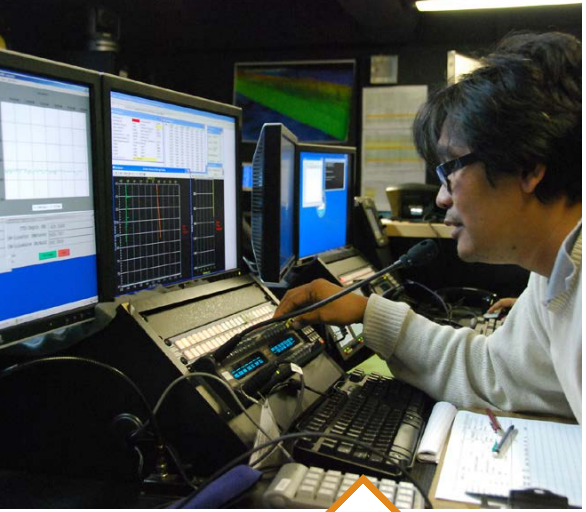


Figure 2. Indonesian scientist, Michael Purwoadi, makes the first "call" using telepresence from *Okeanos Explorer* to colleagues in the newly established Jakarta Exploration Command Center.

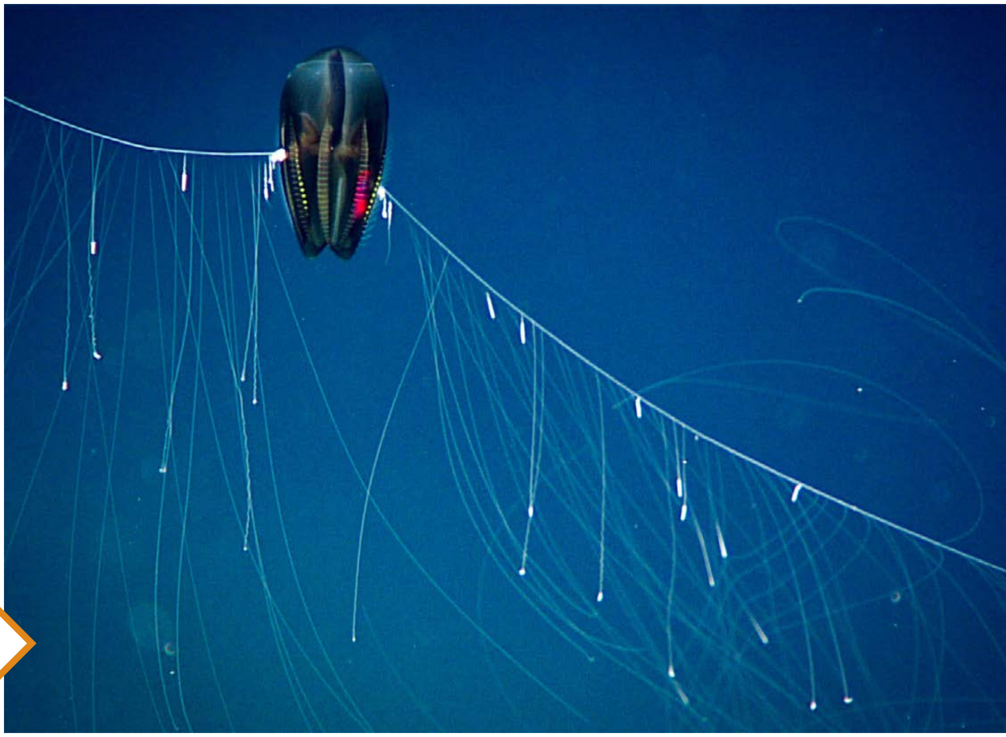


Figure 3. This dark ctenophore was observed with its tentacles fully extended at ~1,460 m depth.

MAPPING AT NEW SCALES

Since 2008 when *Okeanos Explorer* was commissioned, the ship has traveled the globe, exploring the ocean and seafloor from as far away as Indonesian waters and the Central and Western Pacific, to the Gulf of Mexico and Atlantic. During these voyages of discovery, telepresence allowed the science teams on the ship and on shore to work together in real time to map, or characterize, unknown and little known areas of the world ocean.

In 2010, the now fully operational *Okeanos Explorer* set sail for Indonesia to explore the deep waters of the Sangihe Talaud region, in the heart of the Coral Triangle (Figure 2). The Indonesia-US Sangihe Talaud (INDEX-SATAL) expedition was bold and risky. In this early demonstration of telepresence, *Okeanos Explorer* transmitted imagery captured by the remotely operated vehicle (ROV) *Little Hercules* from the seafloor to scientists at organized Exploration Command Centers (ECC) in the United States and Indonesia within seconds. During the expedition, the first-ever deepwater dives in Indonesia's Sulawesi Sea revealed previously unknown seamounts and as many as 50 previously unknown species, while the Indonesian research vessel *Baruna Jaya IV* mapped potential ROV targets for *Okeanos Explorer* and collected geological and fisheries samples near ROV dives. The result was a successful partnership of two maritime nations working together to document the extraordinary biodiversity of the Coral Triangle Region. The INDEX-SATAL expedition set the stage for OER's efforts via *Okeanos Explorer* to characterize the world ocean at new scales, from the seafloor to the water column, to discover new species, and to understand seemingly otherworldly deep-sea environments.

In 2014, *Okeanos Explorer* passed the 1,000,000 km^2 milestone of seafloor area mapped using the vessel's high-resolution multibeam sonars. Much of the mapping was within the US Exclusive Economic Zone (EEZ). OER's continued seafloor mapping is contributing to the US Extended Continental Shelf Project, a multi-agency partnership to establish the full extent of the continental shelf over which the United States can exercise sovereign rights. These new high-resolution seafloor maps display previously unknown deep-sea features and enable a better understanding of the little-known, likely resource-rich deep ocean realm.

Okeanos Explorer's sonars also revealed dense layers of marine life and plumes of bubbles rising through the water column. An ROV was deployed to systematically explore these and other features in water column in more detail (Figures 3 and 4). A relatively recent addition to *Okeanos Explorer* operations, midwater ROV transects were conducted for the first time in 2012, and OER has now explored the water column at a total of 42 sites (Ford and Netburn, 2017; Netburn et al., 2018), most within the last four years. Each midwater dive has been a first for the site, with many likely new species observed and unexpected biodiversity and abundance discovered at many areas.

Virtually every OER expedition aboard *Okeanos Explorer* has yielded new biological and geological insights, helping us to better understand and appreciate marine resources and characterize deep ocean ecosystems. From 2015 to 2017, OER and partners executed the Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE) to explore the deepwater areas of US marine protected areas in the Central and Western Pacific. CAPSTONE findings include the first documentation of precious corals in seven regions of the Commonwealth of the Northern Mariana Islands and the identification of over 70 high-density deep-sea coral and sponge communities. Discovery of the largest sponge known to date (Figure 5) within Papahānaumokuākea Marine National Monument and the first observation of a living member of the fish family Aphyonidae (Figure 6), deep-sea eel-like fishes, both made during CAPSTONE expeditions, demonstrate why these areas need protection. Prior to CAPSTONE, little to no data were available about most of these areas because of their remoteness. Yet, they are of high interest to federal and state agencies with research and management responsibilities due to the vulnerability of their marine habitats, the presence of high concentrations of commercially valuable deep-sea minerals, and the need to more fully understand deep-sea biogeographic patterns across the region.

Site characterizations conducted by *Okeanos Explorer*

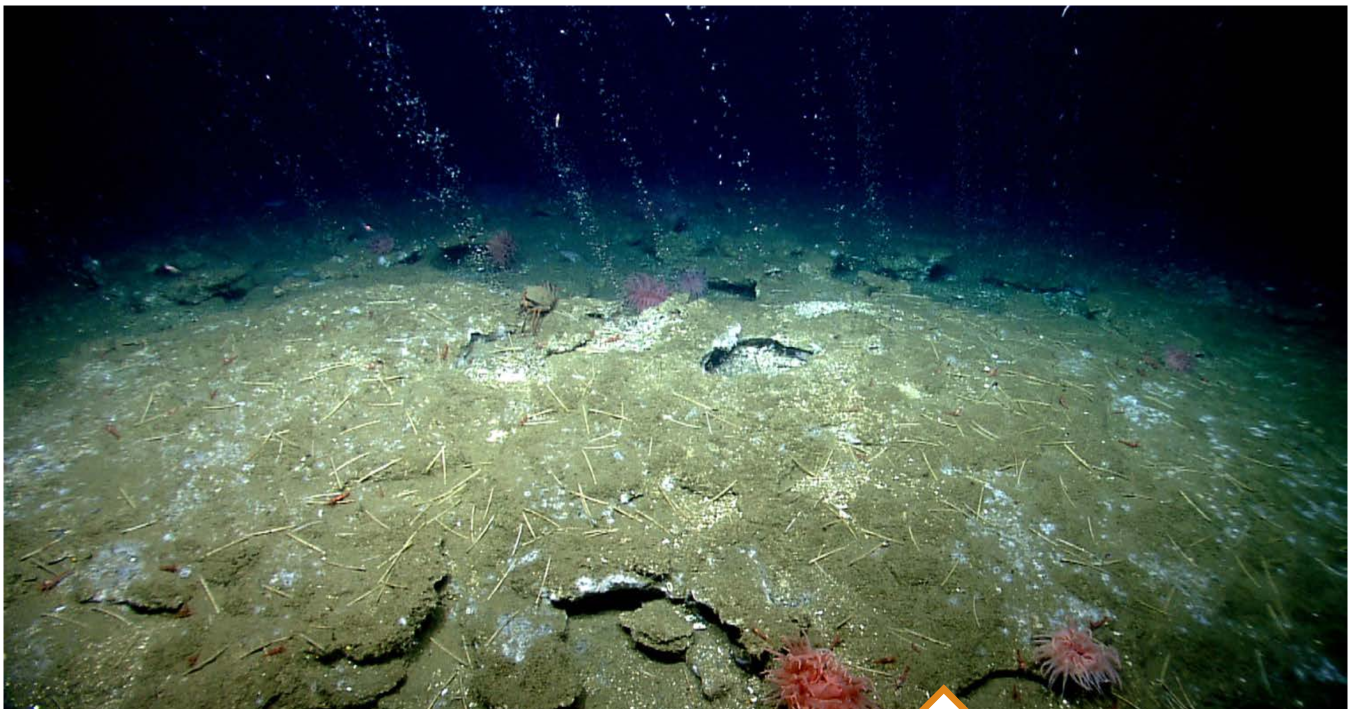
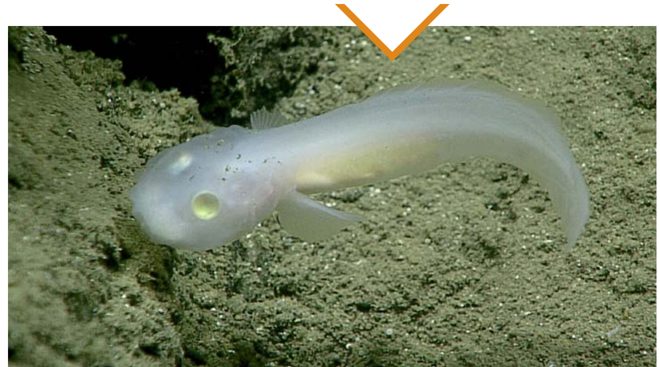


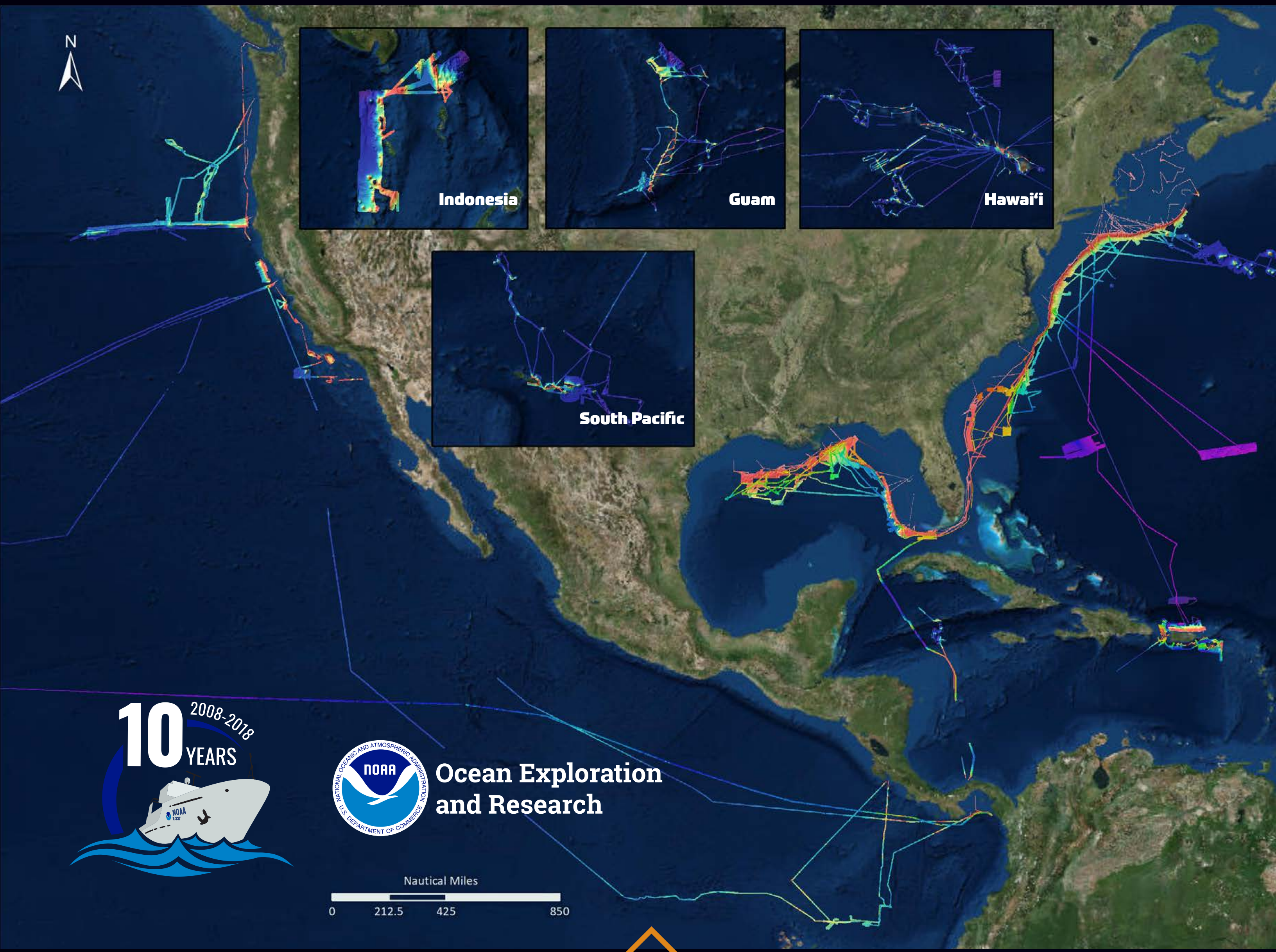
Figure 4. Authigenic carbonates pave the seafloor in the foreground at a seep site on the Virginia margin at ~425 m water depth. At least nine methane bubble streams can be seen in the background.

Figure 5. Massive sponge photographed at 2,117 m depth within Papahānaumokuākea Marine National Monument.

Figure 6. First observation of a living member of the family Aphyonidae (ghostfish), deep-sea eel-like viviparous fishes, many species of which have features that are more similar to fish larvae than adults. Seeing this individual in its natural habitat increases our understanding of its unique, and curious, life history.



10 Years of High-Resolution Seafloor Mapping



From 2008 to 2018, NOAA Ship *Okeanos Explorer* mapped more than 1.5 million square kilometers of ocean floor globally. These baseline data were used to select ROV dive sites for further characterization of the seafloor and to choose locations for collection of water column temperature and salinity information. These data have also been used externally by managers, scientists, educators, and other entities. OER's community-driven approach to site selection, combined with the open availability of these mapping data, have opened the deep waters of the US Exclusive Economic Zone and areas of interest to the US Extended Continental Shelf Project to further research.

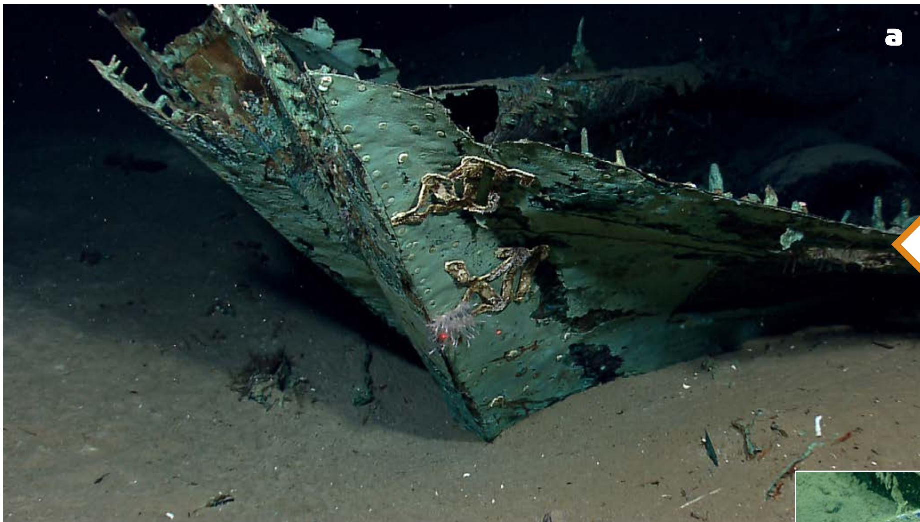


Figure 7. (a) Copper sheathing covers the stern post and aft part of the lower hull of this wreck (Site 15577) discovered in the Gulf of Mexico. The rudder attached to the stern post has been twisted around to the left, or port side, making it difficult to see in this image. This type of damage suggests the vessel impacted the seafloor stern-first, displacing the rudder. Two draft marks made of lead are visible on the stern post. (b) Transferware teacup and open end of a glass bottle found toward the stern.

Figure 8. This aircraft is one of many lost in the vicinity of Tinian and Saipan. The B-29 Superfortress was one of the largest aircraft flown by the United States in World War II.

have also added to our understanding of America's maritime heritage. A significant chapter in this story lies in the discovery and investigation of three nineteenth century shipwrecks in the Gulf of Mexico by OER and partners during expeditions conducted from 2012 to 2014 (Figure 7a,b). Artifact assemblages suggest that the three vessels may have been lost together during the first decades of the nineteenth century, at a time when communities in the region were transitioning from colonies to independent counties. These wrecks thus offer a snapshot of a formative time in US history and are a significant contribution to our understanding of Gulf of Mexico maritime heritage.

In 2016, OER and partners worked with the Department of Defense POW/MIA Accounting Agency on the discovery of a World War II B-29 Superfortress bomber in the channel between Tinian and Saipan. This was the first B-29 crash site discovered of over one dozen American B-29s lost in the area while flying missions against Japan. The sites represent America's final push to end the war, a historically significant time in US history, and are of interest to multiple management groups and several universities and foundations working to identify crash sites for the families of lost service members (Figure 8).

EXPLORING OCEAN DYNAMICS AND INTERACTIONS AT NEW SCALES

Exploration technologies on board *Okeanos Explorer*, including telepresence, have enabled in situ exploration of ocean dynamics and interactions at new scales—as they are unfolding and at new depths—including current flow, seepage out of the subsurface, underwater volcanic eruptions, and organisms' interaction on and within the seafloor, to name a few. These observations of ocean dynamics and interactions at new scales, although still "snapshots in time," expand our scientific understanding of ocean properties, biogeochemical processes, and interactions taking place within the ever-changing, larger Earth system.

Some of the most dynamic—and unusual—ecosystems within which to observe ocean dynamics and interactions at new scales can be found at hydrocarbon seeps. OER expeditions on *Okeanos Explorer* in the Gulf of Mexico between 2012 and 2018 have uncovered many previously unknown seep sites, allowing scientists to document the chemosynthetic communities that often live there and the geologic processes at work (Figure 9). Although these seep discoveries have added much to what we know about chemosynthetic communities, the importance of these

Figure 9. A dense cluster of *Escarpia* sp. chemosynthetic tubeworms at a cold seep, accompanied by an *Alvinocaris* sp. shrimp and a chaetopterid polychaete waving its pair of feeding palps from its slender bamboo-like tube.

ecosystems remains largely unknown. Because seeps can be an indicator of the presence of undiscovered petroleum deposits and may be potential sites for exploratory drilling and offshore oil wells, building our understanding of these dynamic systems is critical to properly managing them.

Understanding and establishing baseline characterizations of deep-sea coral ecosystems are critical to determining possible effects of environmental changes as we learn more about the role(s) these dynamic ecosystems play in the deep ocean. For example, deep-sea corals in the Gulf of Mexico provide habitat for other animals, add structure and complexity to the ocean floor, and may produce compounds important to human health; these ecosystems are also highly vulnerable to, and slow to recover from, environmental change. Prior to the Deepwater Horizon oil spill, OER sponsored 11 expeditions in the Gulf of Mexico, several within a few kilometers of the Deepwater Horizon platform; following the event, *Okeanos Explorer* dedicated ROV dives in the vicinity. The combined data are helping us to document the condition of deepwater coral communities before and after the spill and assisting with the continuing assessment of the potential impacts of Deepwater Horizon on these important ecosystems (Figure 10a,b).

In 2012, capitalizing on the complementary capabilities of five NOAA ships, including *Okeanos Explorer*, NOAA embarked on the Atlantic Canyons Undersea Mapping Expeditions (ACUMEN) project to map all or part of every

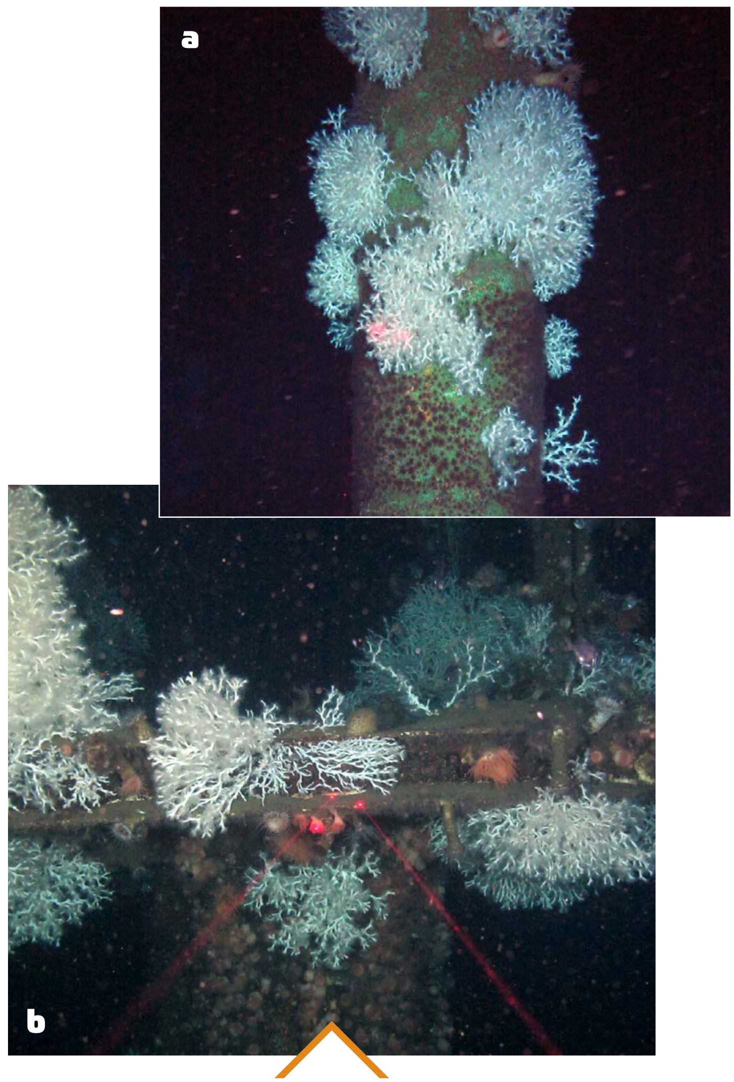


Figure 10. (a) A possible rare (for the Gulf of Mexico) orange *Lophelia* colony seen during an ROV dive near the Joliet Platform. (b) Colonies of *Lophelia pertusa* grow on a test piling at a subsea well installation in Mississippi Canyon.

Figure 11. Often multiple species of invertebrates are found co-occurring on rock ledges and canyon walls. Here, a brisingid sea star, an octopus, bivalves, and several individuals of the cup coral, *Desmophyllum*, are found in close proximity to one another.

submarine canyon in the US EEZ from the US-Canada border to North Carolina. Over 70 submarine canyons are located off the Atlantic coast, providing refuge for a variety of fauna (Figure 11). While some of these canyons had been studied previously, most were poorly understood yet of high interest to federal and state agencies with research and management responsibilities. The ACUMEN campaign led to the discoveries of rich and diverse deep-sea ecosystems within several hundred kilometers of some of the most densely populated regions off the US east coast. These scientific discoveries were used to support the establishment of the Frank R. Lautenberg Deep-Sea Coral Protection Area, which protects more than 100,000 km^2 of seafloor habitat in the Mid-Atlantic region. OER led the ACUMEN campaign with support from other NOAA offices, in collaboration with the Bureau of Ocean Energy Management and US Geological Survey, and key state and regional constituents.

Explorations such as these, which allow investigation of ocean dynamics and interactions at new scales, have led to new scientific understanding of deep-sea species assemblages at previously unexplored hydrothermal vents, canyons, seamounts, and cold seeps. We have witnessed feeding, swimming, and mating behaviors not previously observed in the deep sea and have uncovered unusual burrows in places never seen before. With continued exploration via *Okeanos Explorer*, OER is expanding our understanding of the ocean's complex and dynamic ecosystems.

DEVELOPING NEW TECHNOLOGIES

During *Okeanos Explorer* expeditions, OER's dual-bodied ROV system, composed of *Deep Discoverer* and *Seirios*, provides scientists with unprecedented access to the deep ocean. The design and build of this system and its final integration with *Okeanos Explorer* in 2013 opened new exploration territory for OER. These ROVs, combined with *Okeanos Explorer*'s ability to deliver high-quality imagery within seconds of its capture from the seafloor to any Internet-enabled device, revolutionized the concept of ocean exploration. Scientists were no longer required to physically be on a research vessel or even at a dedicated Exploration Command Center. Now, due to advancements in telepresence technologies, video and other data are transmitted from the ship to shore in real time, opening the door for anyone, anywhere on the planet with Internet access, to participate in our expeditions. The result is not only more robust engagement of multidisciplinary science teams in ROV dives, greatly expanding the available scientific expertise when making discoveries, but also a major shift in OER's methods of engaging the public. Via online tools such as the OceanExplorer.NOAA.gov website and social media, the public can watch scientists from around the world exploring, in real time, unknown areas of the deep ocean.

In recent years, OER has extended telepresence capabilities to engage shore-based teams in *Okeanos Explorer* seafloor mapping expeditions. In 2016, shipboard and shore-based teams used a combination of existing telepresence technologies in a new way to successfully execute a multibeam mapping expedition within the Wake Island Unit of the Pacific Remote Islands Marine National Monument. The overall result was faster data processing, quality control, production of value-added products, public archiving, and secure backup of data, as well as more efficient management of personnel time.

Okeanos Explorer's technological demonstration platform capabilities were also realized when its EM 302 multibeam sonar led to yet another unexpected discovery in the deep ocean—the detection of gas plumes rising 1,400 m from the seafloor along the northern California margin (Gardner et al., 2009). Since then, several hundred methane cold seeps have been discovered along the Atlantic Ocean margin of the United States in an area previously believed to be devoid of such features (Figure 12), according to a study published in *Nature Geoscience* and based on data collected on *Okeanos Explorer* missions (Skarke et al., 2014). The discovery of these gas seeps, along with others discovered by E/V *Nautilus* along the Cascadia margin (Embley et al., 2016), suggests that natural methane leakage from the seafloor is far more widespread than previously thought. Scientists now estimate that tens of thousands of seeps could still be discoverable in the region.

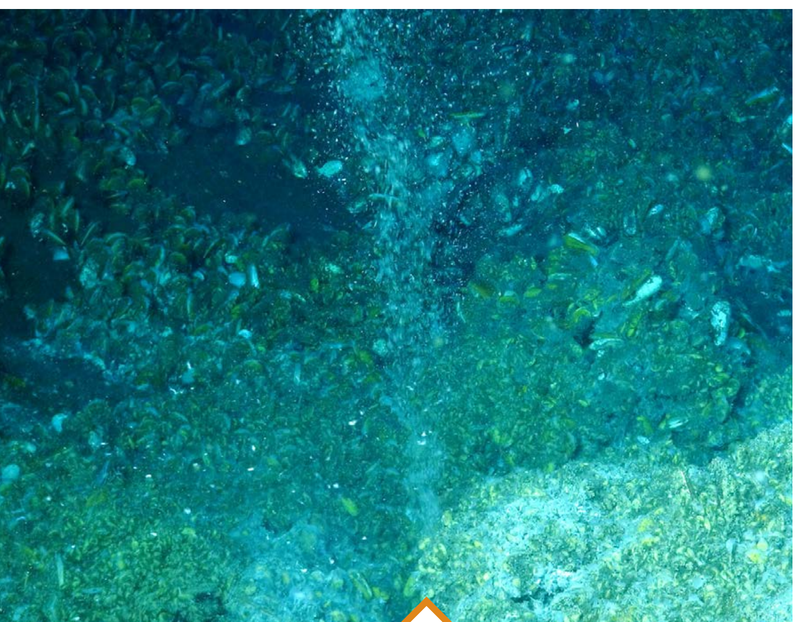


Figure 12. Methane gas bubbles rising from the seafloor. This type of activity was originally detected in multibeam sonar data collected by *Okeanos Explorer* during a 2012 mapping survey. *Image credit: NOAA OER/BOEM/USGS*

REACHING OUT IN NEW WAYS

Since the inception of *Okeanos Explorer* education programming, OER has provided over 230 teacher professional development workshops for over 5,400 educators in the use of the NOAA Ship *Okeanos Explorer* Education Materials Collection (Figure 13). Expedition webinars and online courses enable educators to access new tools so that they can share ocean exploration with their students. Materials have been translated into Spanish, Portuguese, and Bahasa Indonesia, and professional development has been offered in some of the most remote regions of the world to increase access to these materials.

The OceanExplorer.NOAA.gov website as well as OER social media accounts, including Facebook, Twitter, Instagram, and YouTube, have greatly expanded the reach of *Okeanos Explorer* expeditions, inviting members of the public to watch live video of ROV dives and follow expedition discoveries. Online expedition content has caught the eye of traditional media as well, resulting in coverage of *Okeanos Explorer* missions by hundreds of media outlets.

Live interactions between the ship and classrooms, informal science centers, and members of the US Congress, partner organizations, and others have allowed OER to share the excitement of ocean exploration and demonstrate its value. Additionally, OER has hosted public events at ports as well as ship tours for educators, members of the media, and VIPs.

As part of its commitment to train the next generation of ocean explorers, OER has collaborated with the NOAA Educational Partnership Program, University Corporation for Atmospheric Research, and University of New Hampshire to engage hundreds of students in OER's Explorer-in-Training program. These students and early career scientists gain hands-on experience by actively participating in mapping expeditions on *Okeanos Explorer*. Since 2009, OER and partners have hosted over 120 mapping Explorers-in-Training. For many, this first at-sea experience was invaluable to subsequent academic and career pursuits.

Figure 13. Educators learn about why it is important to explore the ocean and how it is done during an OER professional development workshop.

10 Years of Scientific Publication

Top 10 subject areas of OER-supported articles published between 2008 and 2018.

Brittle stars may perch on corals to feed on food particles in the water column.

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Geochemistry/Geophysics – NSF/NOAA, Jason, © WHOI;
Biology – Dann Blackwoood, USGS; all other photos – NOAA OER

PARTNERSHIPS IN EXPLORATION

The full benefits of a national ocean exploration program could not be realized without significant partnerships among federal, state, and local governments; industry; academia; formal and informal educational institutions; and nongovernmental organizations. The "targeted campaign" approach taken with the INDEX-SATAL, ACUMEN, and CAPSTONE expeditions, which engaged multiple ships, associated observing platforms, and other assets, enabled discoveries that would not have been possible using the assets of one ship or one organization, informing important management decisions. Additionally, advancements in telepresence technologies and ROV design and integration through collaborative sharing of assets and capabilities at the University of Rhode Island's Inner Space Center and the Global Foundation for Ocean Exploration opened the door for anyone with Internet access to participate in deep ocean exploration.

Partnerships at all levels have resulted in *Okeanos Explorer* serving as a testbed for acquisition of state-of-the-art data, including multidisciplinary oceanographic, environmental, and acoustic data and geospatially tagged images and video. These data have been complemented by detailed mission plans, mission and dive summaries, and peer-reviewed scientific publications based on expedition results. Through collaborative systems integration and optimization, OER and its partners can deliver data quickly. The data from *Okeanos Explorer* and other NOAA ships are synthesized and made publicly available through the NOAA National Centers for Environmental Information, with a turnaround time as quick as 60 days. These data are critical to our understanding of US submerged resources and are important for resource managers who need accurate baseline information for informed decisions.

THE FUTURE

In 2009, *Okeanos Explorer* was capable of providing integrated telepresence capabilities that connected via Internet2 to shore-based Exploration Command Centers where small interdisciplinary teams of scientists participated in ocean exploration expeditions. Ten years later, anyone, anywhere with a standard Internet connection can participate in *Okeanos Explorer* expeditions—from an ECC, a laboratory, aquarium, or home. This model of telepresence is replicated on ships of exploration belonging to the Ocean Exploration Trust and the Schmidt Ocean Institute. Several vessels of the US academic research fleet (i.e., UNOLS vessels) also utilize telepresence. It is with these exploration partners and other not-for-profit organizations, academic institutions, and private sector entities that we are greatly expanding our knowledge of the deep ocean. That free public access to telepresence-enabled deep ocean exploration has become "routine" is a testament to the wisdom of the 2000 President's Panel for Ocean Exploration and an important measure of the value of the NOAA ocean exploration program. The vision of the 2000 Panel participants for telepresence exploration has been fulfilled.

Looking forward over the next 10 years of ocean exploration, large ships such as *Okeanos Explorer* will remain important, but platforms like autonomous underwater vehicles, drifters, unoccupied surface vehicles, satellites, and moored arrays will be integral to ocean exploration. More capable and less expensive sensors will allow explorers to characterize larger geographic areas of the deep ocean and will support NOAA's effort in the international collaborative project, Seabed 2030, which aims to bring all available bathymetric data to produce the definitive map of the world ocean floor by 2030 and make it available to all. Robust commercial communications networks that are platform (and sensor) independent may permit "bundled services" to be transmitted from the deep ocean to shore, allowing real-time data flows and remote interactions with people and devices at sea. Latency—the time it takes a signal to reach an observer on land from a sensor in the deep ocean—will likely be reduced. The outcome is enhanced, high-quality, publicly accessible scientific data, fit for purpose as we seek to increase understanding of deep ocean areas and phenomena in support of national and international policy for management and sustainable use of our limited, yet dynamic and interconnected, Earth system.

Almost 20 years after the President's Panel reported, there remains an urgent need to continue to explore the unknown and poorly understood deep ocean. Agile strategies that stimulate technological advances will be key to meeting national needs for ocean exploration results over the next decade. An educated and informed public that is aware of ocean issues and of the need to understand deep ocean habitat, ecosystems, and processes is critical. Our nation's economic prosperity and security depends on wise stewardship of the ocean that only will be realized through better cooperation and engagement among the many domestic and international partners and stakeholders with an interest in a healthy, resilient ocean providing services and benefits for all. The progress NOAA has made in responding to the President's Panel report recommendations over the past 10 years, and the major contribution of non-federal ocean explorers such as the Ocean Exploration Trust and Schmidt Ocean Institute and many others positions us well for another decade of similar achievement in understanding our ocean world.

AUGUST 2008: NOAA Ship *Okeanos Explorer* Commissioned

SEPTEMBER 2008: First Multibeam Mapping

Field trials produced the first publicly accessible NOAA multibeam data off the Washington State coast–an area previously restricted by the US Navy.

MAY 2009: Mendocino Gas Plume Discovered

Detection of gas plumes rising from the seafloor, including one rising 1,400 meters off the seafloor at Mendocino Ridge.

MAY 2009: Explorer-in-Training Program Launched

JUNE 2010: INDEX-SATAL Expedition

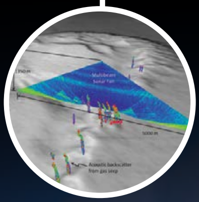
First telepresence expedition and first ever civilian agency expedition in Indonesian waters, revealing that deepwater biodiversity in the Coral Triangle is comparable to that of its shallower waters (up to 50 new species).

OCTOBER 2010: Continuous Plankton Recorder Towed Across 5,100 Nautical Miles of the Pacific from Guam to California, Including the Pacific Garbage Patch to Sample Plankton and Plastics

NOVEMBER 2010: NOAA Ship *Okeanos Explorer* Education Materials Collection Implemented Nationwide

Introduction of new education modules based on *Okeanos Explorer* expeditions, allowing educators to share new discoveries with their classrooms.

2008	2009	2010	2011	2012	201



SEPTEMBER 2011: First Field Trials of EM 302 Multibeam Echosounder to Detect Gas Seeps in Gulf of Mexico

EM 302 water column data testing to validate future uses, for example, origin of natural seafloor seeps or hydrocarbon leaks from man-made structures.

FEBRUARY 2012: ACUMEN Campaign Initiated

NOAA, USGS, BOEM multi-year, multi-partner campaign mapping all or part of every submarine canyon in the EEZ from the US-Canada border to North Carolina.

MARCH 2012: Public Live Streaming Began

Launch of first live stream for easy public access.

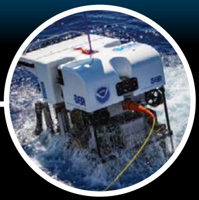
APRIL 2012: Discovery of a Pristine, 19th Century Copper-Sheathed Wreck

The wreck appears to be the best-preserved wooden shipwreck discovered to date in the Gulf of Mexico.

10 YEARS 2008-2018

Ocean Exploration and Research

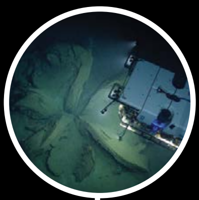
10 Years of Ocean Exploration with NOAA Ship *Okeanos Explorer*



MAY 2013: First Deployment of ROVs *Deep Discoverer* and *Seirios*

AUGUST 2013: Discovery and Mapping of Extensive Methane Seep Province Along Atlantic Margin

EM 302 discovery of hundreds of methane seeps on East Coast.



APRIL 2014: Discovery of Asphalt Volcano Scientists Named "Tar Lily"

In the Gulf of Mexico, what was suspected to be a shipwreck was revealed by cameras on the ROV to be an asphalt volcano supporting marine life.

JULY 2015: CAPSTONE Initiated

A three-year foundational science effort focused on deepwater areas of US marine protected areas in the central and western Pacific, that acquired baseline characterization data in every US territory, marine monument, and monument unit in the Pacific.

AUGUST 2015: Sampling Operations Began

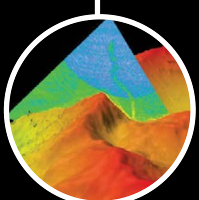
AUGUST 2015: Largest Sponge Known to Date Discovered

A giant 3.5 meter long glass sponge was recorded at a depth of 2,134 meters within Papahānaumokuākea Marine National Monument.

13 | 2014 | 2015 | 2016 | 2017 | 2018

JULY 2016: First Observation of a Living Member of the Family Aphyonidae

Seen at ~2,500 meters in Marianas Trench Marine National Monument, this group of deep-sea fishes display unique life history characteristics.



FEBRUARY 2017: Discovery of Plume of Bubbles and Significant Growth of the Nafanua Cone at Vailulu'u Seamount

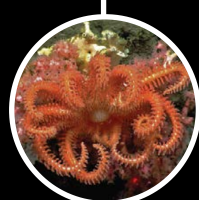
- 1.79 million km^2 of seafloor mapped
- 96 cruises & 1,500+ days at sea
- 425+ ROV dives
- 1,100+ biological & 350+ geological samples collected
- 96,075,798 website visits and ~4,000 hours of ocean exploration video made publicly available

MARCH 2018: First Dedicated Use of *Okeanos Explorer* as Technology Demonstration Platform

In partnership with CIOERT, UNH/CCOM/JHC, and US Navy.

APRIL 2018: Documented Extensive Deep-Sea Coral Communities in the Gulf Of Mexico

Data collected were used by the Gulf of Mexico Fishery Management Council to recommend establishment of new Habitats of Particular Concern (HAPC).



MAY 2018: ASPIRE Campaign Initiated

A major multi-year, multi-national collaborative ocean exploration field program focused on raising collective knowledge and understanding of the North Atlantic Ocean.

JUNE 2018: Discovery of One of the Largest Deep-Sea Coral Habitats Known to Date in US Waters off Southeast US Coast

Ocean Exploration in Support of the Blue Economy

By Amanda N. Netburn and William Mowitt

The United States supports a vast "Blue Economy" that employs millions of Americans and is valued at hundreds of billions (Kildow, 2016) to more than a trillion dollars (Edvardsen, 2016). Ocean industries that contribute to the Blue Economy include fisheries, energy (oil and gas, offshore wind, waves, and tides), minerals mining, recreation and tourism, and marine transportation. Ocean observations are needed to inventory available resources, ensure an efficient permitting process, and monitor impacts of extraction and use. Innovation is required to support these industries for maximum sustainable benefit.

The June 2018 Executive Order, Ocean Policy to Advance the Economic, Security, and Environmental Interests of the United States states: *To advance America's economic, security, and environmental interests, it is critical that we explore, map, and inventory our Nation's waters. By exploring, developing, and conserving the ocean resources of our great Nation, we will augment our economic competitiveness, enhance our national security, and ensure American prosperity.*

NOAA's Office of Ocean Exploration and Research addresses multiple Blue Economy science needs by coordinating exploration efforts, such as mapping and inventorying resources, with NOAA, federal, and non-federal partners (Figure 1). It is impossible to manage for sustainable use of ocean resources without knowledge of what lies below the ocean's surface (Glover et al., 2018).

Below we highlight several key aspects of the Blue Economy that are advanced by ocean exploration activities.

OFFSHORE ENERGY

The Bureau of Ocean Energy Management (BOEM) has proposed opening 90% of the US outer continental shelf to potential oil and gas development, and US companies are rapidly increasing investment in offshore wind farms, with a record-breaking lease sale occurring in December 2018 (Department of Interior 2018; Figure 2). Systematic exploration of the seafloor and waters of the US Exclusive Economic Zone provides critical baseline data to inform siting, permitting, management, and mitigation of environmental impacts of offshore energy installations.

The recent discovery of hundreds of methane seeps off the Atlantic coast (Skarke et al., 2014) is an example of how NOAA's exploration program has revolutionized understanding of the ocean's hydrocarbon potential. Further, work conducted through NOAA-BOEM-US Geological Survey partnerships dating back to 2010 has leveraged resources to provide baseline data on an area of the Atlantic coast seafloor that may soon be open for oil and gas exploration. Public-private partnerships are evolving, and a recent industry-led study used NOAA Ship *Okeanos Explorer* multibeam data to understand areas that likely emit hydrocarbon-rich fluids (Brumley et al., 2018).

CRITICAL MINERALS

Ensuring a domestic supply of critical minerals has both economic and national security strategic importance (Executive Order No. 13817, 2017). Elements such as cobalt, nickel, manganese, copper, and gold are known to occur

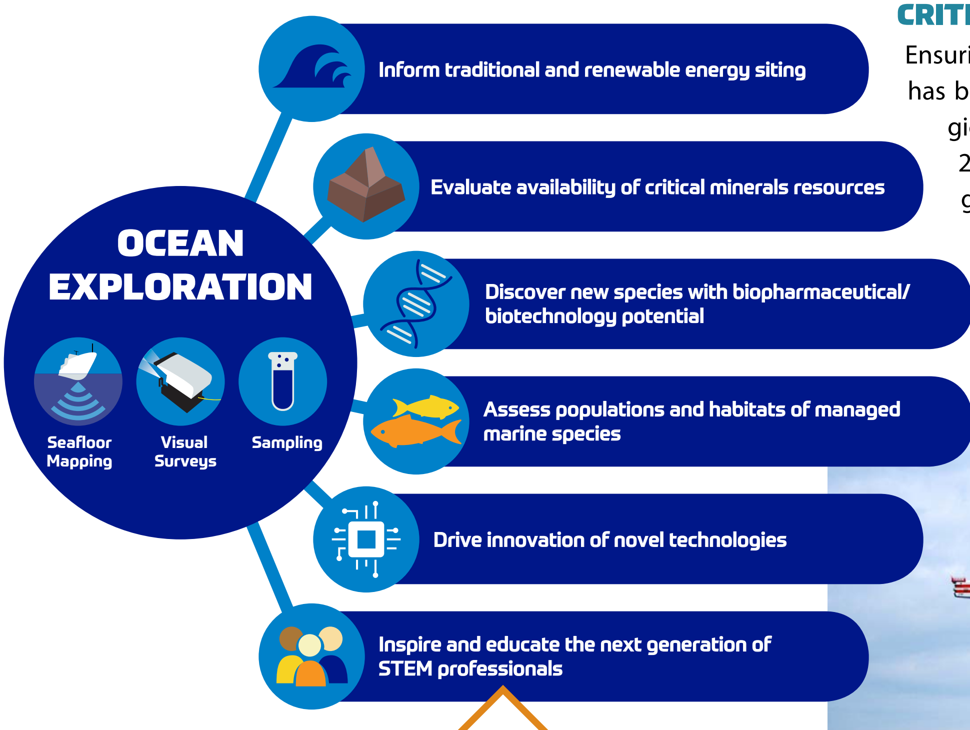


Figure 1. Conceptual diagram of how ocean exploration informs and advances the Blue Economy.

Figure 2. Offshore wind turbine, with oil rigs in the background. *Image credit: BOEM*

Figure 3. Queen snapper (*Etelis oculatus*) is an important fishery species in the Caribbean, though little is known about them or the habitats where they are found. Many queen snappers were observed in Puerto Rican waters during the Océano Profundo 2018 expedition (see pages 90–91], including this individual seen at a record depth of 539 m. The species was previously known only to depths of 450 m.

in significant quantities in the ocean in polymetallic nodules, ferromanganese crusts, and seafloor massive sulfides (Hein et al., 2013). Little is known about the ecosystems that these sensitive habitats support (Ramirez-Llodra et al., 2010), and new organisms are regularly discovered in areas of potential seabed mining (Amon et al., 2016). Many of these mineral resources are within the jurisdiction of the International Seabed Authority, located in international waters where nations such as Russia, China, and Japan hold mining exploration leases and are actively developing the technologies to mine. Areas of potential mining interest in US waters include the remote Pacific US territories and the Escanaba Trough off northern California.

OER and its federal and academic partners recently completed the three-year (2015–2017) Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE). Focused on mapping and exploration in and around US marine protected areas in the Central and Western Pacific, an objective was to collect baseline information in deep waters to support science and management decisions, including those for deep-sea ecosystems that could be affected by future mining activities. Exploration activities included multibeam mapping and ROV dives. The goals of the dives were to collect biological samples and assess biodiversity and community density and to collect rock samples to assess the mineral composition and value of the resources. This past year, an OER-funded expedition explored the Central Pacific Ocean to gather critical ecosystem information on a region with a large area of mining exploration leases (see page 120).

MARINE-DERIVED PHARMACEUTICALS

Many deep-sea organisms are adapted to living in environmental extremes of pressure, temperature, and chemistry. Adaptation often involves the generation of compounds, many of which have been found to have pharmaceutical application. Some marine-derived compounds have the potential to treat cancers such as leukemia, viruses, diabetes, colds, and chronic pain (Blunt et al., 2018). As of 2016, seven approved marine-derived drugs were on the market with 20 more in clinical trials. Approximately 1,000 new compounds are discovered yearly (Lindequist, 2016).

Large numbers of undescribed coral and sponge species exist in the US EEZ (Hourigan et al., 2017). Thus, there is potential for ocean exploration to facilitate significant discovery in this field by providing the tools necessary to collect organisms from remote regions for further study. NOAA partners at the Cooperative Institute for Ocean Exploration, Research & Technology at Harbor Branch Oceanographic Institute have facilitated drug discovery from deepwater sponges and other marine species (see page 119).

FISHERIES

Deep-sea corals and sponges provide critical habitat for commercially and recreationally valuable species. Thus, understanding the extent of these ecosystems is important for managing dependent fish species (Hourigan et al., 2017). Visual assessment of habitat, either through video, photogrammetry, or direct human observation is key to understanding deep coral and sponge ecosystems. By providing access to deep waters, ocean exploration can aid fisheries partners by surveying habitat and communities that support deep fisheries. An example of this is the queen snapper shown in Figure 3 (see also pages 90–91).

INNOVATION AND STEM EDUCATION

Novel sensors and autonomous platforms will facilitate the next great era of ocean exploration. Innovations abound in artificial intelligence for decision-making and include complex data processing capabilities that will expand the spatial, temporal, and disciplinary scope of ocean exploration. This transformation requires a workforce well educated in STEM, which motivates OER's unique educational programming and outreach (see pages 110–116).

OER has supported numerous technology development grants (see page 120), and in 2018 began using *Okeanos Explorer* for dedicated technology demonstration expeditions (see pages 100–103).

Data collected from 10 years of *Okeanos Explorer* expeditions and almost 20 years of grant-funded projects are available to inform the Blue Economy (see pages 106–109). Ongoing and future OER-supported expeditions and projects will continue to advance efforts to support the sustainable development of the vast wealth contained within and beneath US waters.

NOAA Ship *Okeanos Explorer*

By Craig Russell, John McDonough, and Stephen R. Hammond

In 2008, NOAA commissioned NOAA Ship *Okeanos Explorer*, the nation's first vessel dedicated to exploring unknown and little-known areas of the world ocean. Outfitted with sophisticated sonars, a dual-body ROV system, and the latest in broadband communications technology, *Okeanos Explorer* has investigated regions from the far western Pacific to the Atlantic. The expeditions have generated high-resolution maps of the seafloor, recorded high-definition video of previously unknown habitats and species, and collected thousands of samples, spurring research and informing marine resource management. Most importantly, *Okeanos Explorer* pioneered a new collaborative model for ocean exploration and research, using telepresence technology to engage shore-based scientists, natural resource managers, educators, students, and the general public in real time—a model that continues to evolve in partnership with a growing community of explorers.

Okeanos Explorer's exploration assets are operated by NOAA's Office of Ocean Exploration and Research, in partnership with the Global Foundation for Ocean Exploration (GFOE) and Office of Marine and Aviation Operations (Figure 1). Since commissioning, the ship's capabilities have been augmented with new technologies and methods to increase the pace and efficiency of exploration and streamline accessibility to data collections. Here, we provide key milestones that reflect how *Okeanos Explorer*'s mapping, ROV, and telepresence capabilities have evolved.

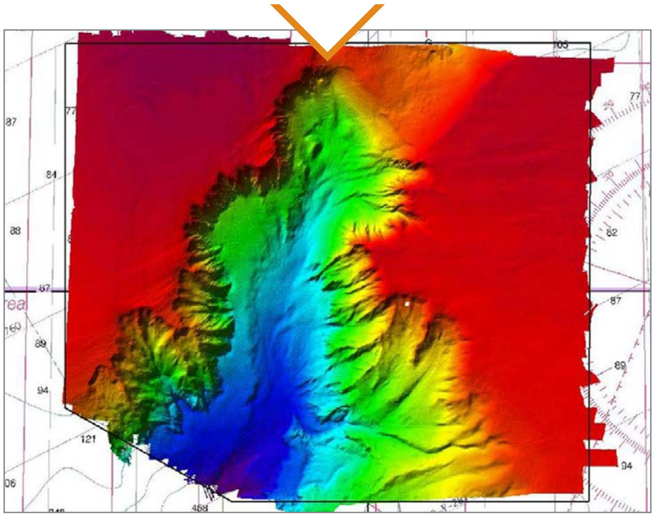
MAPPING

Mapping has always been the foundation of *Okeanos Explorer* operations. Immediately following commissioning, field trials produced the first publicly accessible NOAA multibeam data off the coast of Washington State—an area previously restricted by the US Navy (Figure 2). OER worked closely with partners from NOAA, the University Corporation for Atmospheric Research (UCAR), Bureau of Ocean Energy and Management, and the University of New Hampshire to test the EM 302 multibeam system's capabilities to detect and quantify gases in the water column. In early 2012, we were able to quantify gas seep flux by comparing the *Okeanos Explorer* EM 302 water column backscatter data with fisheries sonar data. Shortly thereafter, while systematically mapping the US Atlantic margin, OER discovered an extensive province of deepwater seeps along the continental margin from Cape Hatteras to the Canadian EEZ border, demonstrating the EM 302 as an invaluable seep-hunting tool and yielding data that are meeting a variety of mission requirements.

Keen to maximize the scientific value of each day at sea, OER's mapping team conceived and operationalized the "Always Exploring" mode of operating: during transits, tracklines are strategically aligned to maximize the

Figure 1. The Global Foundation for Ocean Exploration team preps for the first ROV dive of the mission on NOAA Ship *Okeanos Explorer*. *Image credit: Art Howard, GFOE*

Figure 2. During *Okeanos Explorer*'s initial field trials in 2008, OER and partners collected the first publicly accessible multibeam data off the coast of Washington State in Juan de Fuca Canyon—an area previously restricted by the US Navy.



data yield, sonars operate 24/7 when permitted, and all data are processed into standardized publicly accessible data products available through NOAA's National Centers for Environmental Information. Using this model, new seamounts were discovered and critical information was provided in areas of interest to the US ocean sciences, management, and industry communities.

More recently, several new sonars were incorporated to improve water column characterization, and in 2019 a new EK80 wideband sonar will be installed. OER also implemented a new "telepresence mapping" model, where watch leaders manage mapping operations and data processing from shore with real-time connectivity to shipboard systems. Telepresence mapping also supports *Okeanos Explorer*'s Explorers-in-Training program (see pages 114–115), with UCAR providing hands-on training onshore. Looking ahead, partnerships are being leveraged to evaluate telepresence-enabled autonomous underwater vehicle operations in order to help facilitate a community-wide goal of mapping the entire US EEZ by 2030.

REMOTELY OPERATED VEHICLES

A hallmark of *Okeanos Explorer* expeditions has been providing world-class deepwater video imagery in real time. This effort began with a 4,000 m rated refurbished ROV *Little Hercules* on loan from the Sea Research Foundation, and in 2013 a new 6,000 m two-body ROV system—*Deep Discoverer* and *Seirios* (developed, maintained, and operated by the GFOE)—was completed. Using these ROVs, 425 ROV dives were conducted from 250 m to 6,000 m depths with a 99.5% uptime rate.

In recent years, new sampling capabilities enabled collection of biological and geological voucher specimens to improve habitat characterization. Through valuable partnerships with the Ocean Genome Legacy Center, the Smithsonian Institution's National Museum of Natural History, Oregon State University, and others, scientists now have access to over 1,100 biological specimens and over 350 geological samples in publicly accessible repositories (Figure 3). In 2019, an advanced suction sampler will be implemented to sample soft organisms, and pioneering techniques will be tested that will enable non-invasive sampling. New cameras for improved imaging and methods for automated image analysis will also be selected for testing.

Figure 3. In 2015, *Okeanos Explorer* missions collected limited samples to aid in site characterization. Shown here is a piece of black coral collected from the Northwestern Hawaiian Islands. *Image credit: Art Howard, GFOE*

TELEPRESENCE

OER's telepresence-enabled exploration operating model for *Okeanos Explorer* relies on innovative video, satellite, and network engineers weaving together critical services. In 2008, low-latency, high-definition video with 1.5 second delay was streamed across Internet2 to Exploration Command Centers at NOAA and US universities where dedicated and centralized science teams participated in missions in real time. In 2012, after launching YouTube Live's first ocean exploration video stream in partnership with the University of Rhode Island and making the video streams publicly available on the Internet, a more distributed science model arose with teams and individuals participating from dozens of locations around the world. Most recently, GFOE installed a new VSAT system aboard the ship that is creating a more reliable and more capable network. Our collaborations with Ocean Networks Canada also continue to yield an invaluable tool for real-time distributed scientific video annotations through SeaScribe and SeaTube (see pages 106–109).

There is much to celebrate after 10 years. Yet, the drive to improve never ceases. As we forge new partnerships to begin testing new technologies and develop Telepresence 2.0 concepts, we remain committed to delivering high-quality data and fostering robust partnerships to ensure OER's *Okeanos Explorer* missions are a community success.

ASPIRE: Atlantic Seafloor Partnership for Integrated Research and Exploration Campaign 2016–2020

By Caitlin Adams, William Mowitt, and Katie Wagner

The Atlantic Seafloor Partnership for Integrated Research and Exploration (ASPIRE) is a multiyear, multinational collaborative ocean exploration campaign focused on increasing knowledge and understanding of the North Atlantic Ocean. ASPIRE provides data to inform and support research planning and management decisions in the region. Building on the successful 2012–2013 Atlantic Canyons Undersea Mapping Expeditions (ACUMEN), ASPIRE broadens the geographic focus to include more of the US Atlantic and high seas. It also extends the scope of partnerships to include federal agencies such as the Bureau of Ocean Energy Management and US Geological Survey, as well as international partners from the European Union and Canada. Initial ASPIRE fieldwork was conducted in 2016 and 2017, and NOAA Ship *Okeanos Explorer* began operating in the region in 2018.

WHY THE NORTH ATLANTIC?

The North Atlantic Ocean plays a pivotal role in Earth's habitability, providing biological and geological resources and ecosystem services such as seafood production and climate regulation, and serving as a major route for trade and travel between Europe and the Americas. The countries bordering the North Atlantic have a long history of scientific collaboration in the study of their shared marine resources. With increased globalization, efforts to understand, conserve, manage, and defend the maritime commons have become an essential shared responsibility.

Despite its importance, we have only begun to understand the North Atlantic Ocean's ecosystems, resources, and oceanography. Much about the seabed bathymetry, geology and mineralogy, and transatlantic connectivity of biological communities remains unknown. With the signing of the Galway Statement on Atlantic Ocean Cooperation in 2013 and the deep-sea science and exploration efforts of the Atlantic Ocean Research Alliance, there is significant momentum within the international community to cooperate on integrated exploration and research.

ASPIRE GOALS

The ASPIRE campaign will provide a foundation of publicly accessible baseline data to increase understanding of the North Atlantic Ocean. The effort will also provide critical information relevant to emerging Blue Economy priorities related to sustainable fisheries, offshore energy and marine minerals, coastal and offshore hazards, and marine tourism and recreation. Specific ASPIRE goals are to:

- Improve knowledge of unexplored areas within the US EEZ and in deep-sea areas that have been mapped for the US Extended Continental Shelf Project to inform national security, management needs for sensitive habitats, geological features, maritime heritage sites, and potential resources
- Locate and characterize deep-sea coral, sponge, and chemosynthetic communities
- Characterize water column habitats throughout the Atlantic basin
- Enhance predictive capabilities for vulnerable marine habitats and submarine geohazards
- Extend bathymetric mapping coverage in the US EEZ and international waters in support of Seabed 2030
- Increase understanding of deep-sea ecosystem connectivity across the Atlantic basin
- Improve international collaboration and serve as a major contribution to the Galway Statement on Atlantic Ocean Cooperation and the Atlantic Ocean Research Alliance's deep-sea mapping and exploration efforts
- Leverage international partnerships to conduct coordinated exploration and mapping of priority high seas areas of the North Atlantic

ASPIRE SCIENCE PLANNING WORKSHOP

On November 15–16, 2018, NOAA's Office of Ocean Exploration and Research hosted over 50 participants from the United States, European Union, Iceland, Russia, and Canada at the ASPIRE Science Planning Workshop in Silver Spring, Maryland. Attendees included a mix of early to late career professionals and represented the diverse interests of academia, industry, and government. Over the course of two days, participants heard a number of presentations on existing NOAA and international activities centered around the Galway Statement. During three breakout sessions, participants identified and refined areas and features for ocean exploration within discrete zones across the North Atlantic Ocean basin and discussed assets, data availability, partners, challenges, and potential expedition plans. These discussions incorporated and built upon scientific rationales for exploration submitted by the broader oceanographic community during a pre-workshop call for white papers. During the final breakout session, each regionally focused group identified the highest priority areas for future expeditions (Figure 1), which included the New England Seamounts, the Laurentian Fan, Blake Plateau, and large sections of the Mid-Atlantic Ridge. This input will form the foundation of a forthcoming ASPIRE workshop report and will shape the priorities of the ongoing ASPIRE campaign, including the 2019 and 2020 NOAA Ship *Okeanos Explorer* expeditions.

Figure 1. Map showing feedback received at the 2018 ASPIRE Science Planning Workshop.

CAMPAIGN FIELD ACTIVITIES TO DATE

ASPIRE expeditions began in 2016 and will continue in the region through calendar year 2020. These past, present, and future expeditions (Figure 2) contribute globally to a more robust understanding of ocean dynamics, seafloor features, and habitats that will shape ocean science, innovation, and research. Significant fieldwork will continue to be accomplished on *Okeanos Explorer*, and additional vessels have been identified that will contribute to the campaign as well. The following is a list of expeditions that have or are expected to contribute to the ASPIRE campaign:

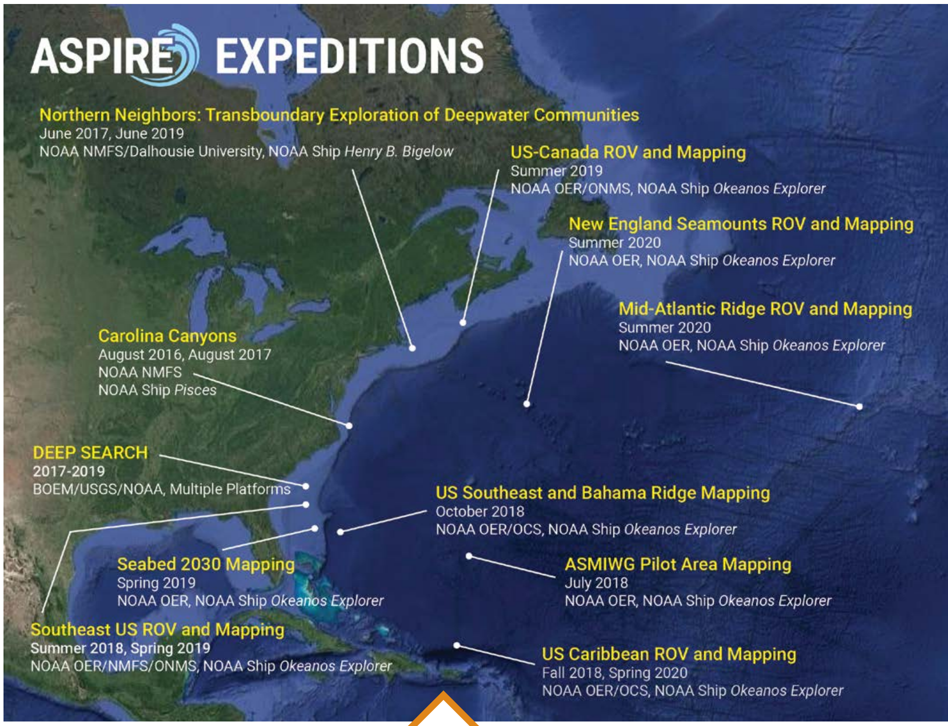


Figure 2. Map of currently identified ASPIRE expeditions (2016–2020).

- August–September 2016: One cruise on NOAA Ship *Pisces* used AUV *Sentry* to explore deep-sea coral habitats associated with deepwater canyons off the coast of North Carolina.
- June–September 2017: One cruise on NOAA Ship *Henry B. Bigelow* used the Canadian Scientific Submersible Facility's ROV *ROPOS* to explore submarine canyons along the Canada-US boundary. Two cruises on *Pisces*, including the National Oceanographic Partnership Program-sponsored interagency DEEP SEARCH mission (see pages 104–105), used AUV *Sentry* to explore coral, canyon, and methane seep habitats offshore of the Carolinas.
- May–December 2018: *Okeanos Explorer* mapped and characterized deepwater areas off the southeastern United States, international waters south of Bermuda, and the US Caribbean. The DEEP SEARCH team used R/V *Atlantis* and human-occupied vehicle (HOV) *Alvin* to further explore off the Mid- and South Atlantic US coastline.
- April–September 2019: In 2019, *Okeanos Explorer* will continue to focus on mapping and characterizing the North Atlantic and will expand its work with international partners in Canada and the European Union. Other work in support of ASPIRE will include a DEEP SEARCH expedition on NOAA Ship *Ronald H. Brown*.
- 2020: Field activities are anticipated to continue in both US and international waters, with a continued focus on the Mid-Atlantic Ridge and the potential for expanded collaboration with international partners.

2018 Expeditions with NOAA Ship *Okeanos Explorer*

By Kelley Elliott and Craig Russell

219 days at sea

298,800+ km^2 of seafloor mapped

68 ROV dives

30 CTD casts

424 biological & 61 geological samples collected

225 participating scientists

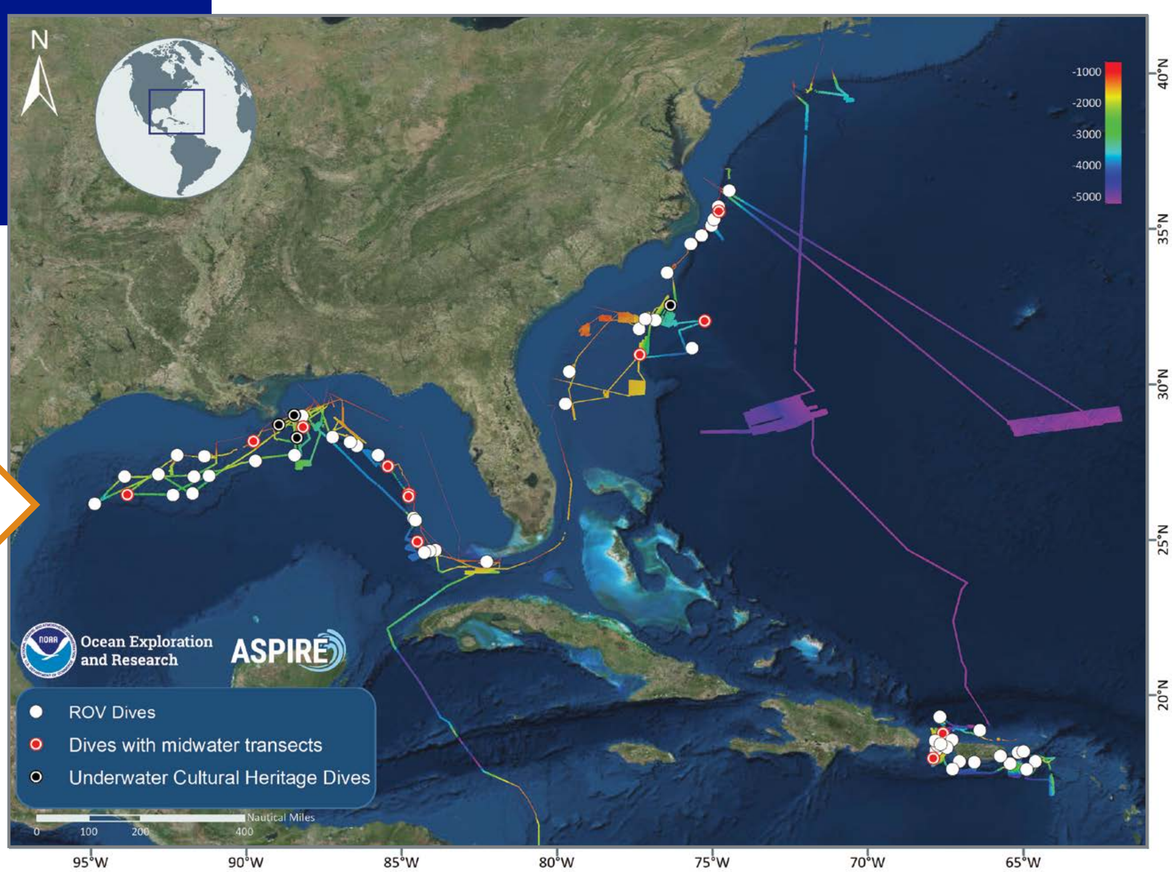
~993,300 live video views

The 2018 NOAA Ship *Okeanos Explorer* expeditions began with seafloor mapping during a transit across the Pacific and a return to the North Atlantic where the ship acquired critical information supporting the interests of stakeholders at home and abroad.

GULF OF MEXICO

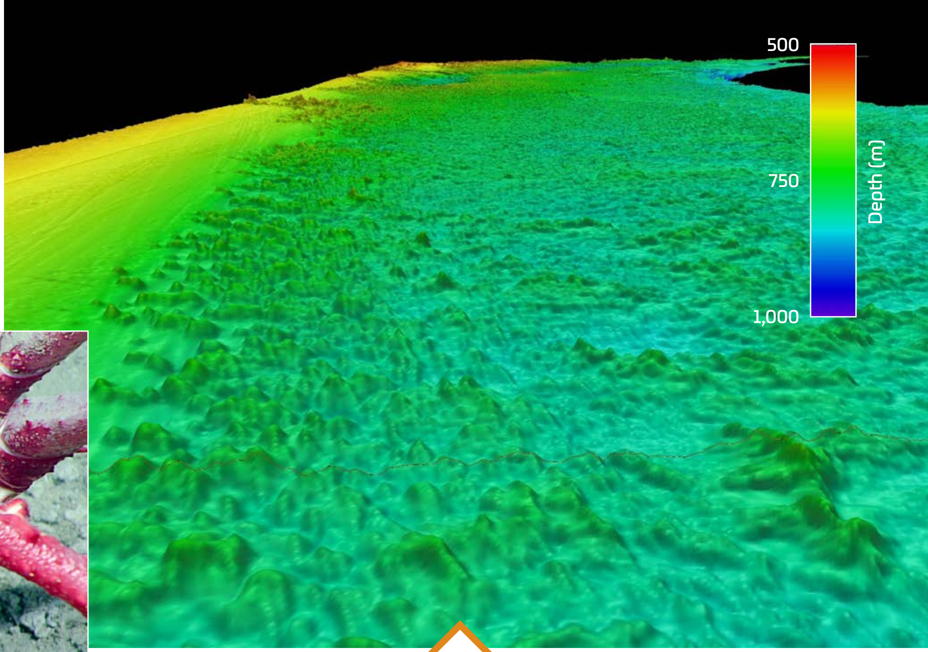
The US Gulf of Mexico expeditions collected baseline information about unknown and poorly understood deepwater areas, focusing on the priorities of regional and federal managers (see pages 78–81). Areas lacking high-resolution multibeam data were mapped, and ROV dives surveyed proposed marine protected areas and shipwrecks of interest to managers. The dives also led to the discovery of new vulnerable marine habitats. Following a winter repair period, a shakedown cruise tested and calibrated systems to ensure quality data collection for the field season.

In May, NOAA scientists deployed optical sensors for validation of Visible Infrared Imaging Radiometer Suite (VIIRS) satellite data offshore the southern US Atlantic coastline, and acquired opportunistic mapping and CTD rosette data. The VIIRS expedition brought the ship into the North Atlantic to join NOAA's ASPIRE campaign (see pages 74–75).



Map showing bathymetric data and ROV dive sites from 12 NOAA Ship *Okeanos Explorer* cruises conducted during the 2018 field season. One cruise from Hawai'i to Panama is not shown.

Windows to the Deep 2018 documented several instances of rarely observed predation that contribute to our understanding of the deep sea and the organisms that live there. This lithodid crab was observed eating a brittle star, a previously unknown predator-prey interaction.



Bathymetric data acquired by *Okeanos Explorer* in 2014 revealed the "Million Mounds" region offshore of the southeast US continental margin. ROV dives in 2018 confirmed that these mounds are biogenic and host a high density of corals, revealing one of the largest areas of deep-sea coral reef habitat discovered in US waters.

SOUTHEASTERN US CONTINENTAL MARGIN

Two cruises of the 2018 Windows to the Deep Expedition investigated the southeastern US continental margin—the most unexplored waters off the US mainland see pages 82–85). These *Okeanos Explorer* expeditions were the first in support of ASPIRE and filled major mapping gaps to support the Seabed 2030 initiative. Bathymetric data and ROV dives revealed one of the largest areas of deep-sea coral reef habitat discovered in US waters.

NATIONAL AND INTERNATIONAL PRIORITIES

In July and August 2018, OER and international partners conducted the first US-led mapping effort in support of the Galway Statement on Atlantic Ocean Cooperation to map an area southeast of Bermuda identified as priority by the Atlantic Seabed Mapping International Working Group (see pages 88–89). An October cruise mapped areas around the Blake-Bahama Ridge to provide critical data for the US Extended Continental Shelf Project and inform boundary negotiations with the Commonwealth of The Bahamas (see pages 98–99).

US CARIBBEAN

The 2018 Océano Profundo expedition explored deep waters surrounding Puerto Rico and the US Virgin Islands—the least explored waters in the US Atlantic Exclusive Economic Zone (see pages 90–91). Local engagement efforts were strengthened with establishment of a new Exploration Command Center in Puerto Rico, sponsored by the Tennenbaum Exploration Initiative and the Soul of Bahia Foundation, and inclusion of bilingual expedition components.

TECHNOLOGY ADVANCES AND DEMONSTRATIONS

This year, OER conducted the first expeditions dedicated to testing emerging technologies, taking *Okeanos Explorer*'s mission to serve as a dedicated platform for technology testing to the next level (see pages 102–103). Ship-to-shore connectivity was also improved by overhauling the shipboard mission network, which is now managed by partners at the Global Foundation for Ocean Exploration. Remote science participation capabilities were augmented with launch of SeaTube Version 2 in partnership with Ocean Networks Canada, and *Okeanos Explorer*'s in-hull multibeam receive and transmit array was refreshed during the summer dry dock.

LOOKING TO THE FUTURE

In December 2018, scientists and managers from the United States, Canada, Iceland, European Union, and United Kingdom participated in the ASPIRE planning workshop to identify priorities and plan future expeditions. In 2019, *Okeanos Explorer* expects to investigate unknown and poorly known deepwater areas of the Atlantic margin off the US and Canadian east coasts.

Deep-Sea Exploration of the US Gulf of Mexico with NOAA Ship *Okeanos Explorer*

By Scott C. France, Diva J. Amon, Charles Messing, Adam Skarke, Daniel Wagner, Michael P. White, Brian R.C. Kennedy, and Nick Pawlenko

INTRODUCTION

The Gulf of Mexico is an important driver of the US Blue Economy. Industries such as tourism, commercial fishing, oil and gas extraction, and shipping generate trillions of dollars in revenue annually and provide millions of jobs. Many of these industries rely on a healthy Gulf of Mexico ecosystem, but much of it remains poorly known, particularly deepwater habitats. Thus, decision-makers often work with limited information when making important resource management decisions.

From November 2017 to December 2018, NOAA's Office of Ocean Exploration and Research, as part of the Southeast Deep Coral Initiative (SEDCI), worked with regional partners and the scientific community to conduct three expeditions in the Gulf of Mexico, one of which focused on testing emerging technologies. To address knowledge gaps and inform resource managers, NOAA Ship *Okeanos Explorer*'s suite of deepwater mapping systems and the capabilities of ROV *Deep Discoverer* were used to explore deepwater ecosystems of the US EEZ in the Gulf of Mexico.

The expeditions built on previous *Okeanos Explorer* exploration in the Gulf of Mexico in 2011, 2012, and 2014, as well as OER-sponsored projects such as Lophelia II and Pulley Ridge. Drawing on the community of partners OER has developed over the years, as well new ones, over 100 managers and scientists from more than 40 institutions participated in cruise planning via OER's suite of telepresence-enabled collaboration tools. This collaborative approach to ocean exploration continues to be useful and ensures that OER's work is relevant to the broader science and management communities. ROV dive sites were chosen based on numerous criteria, with a particular focus on areas that were likely to contain deep coral and sponge communities, bottomfish habitats, shipwrecks, and a variety of chemosynthetic habitats, including cold seeps, mud volcanoes, and brine pools. In addition to these particular types of locations, dives were preferentially conducted in areas that were under consideration for management actions to ensure bodies such as the Gulf of Mexico Fishery Management Council have the best possible data.

During the 2017 and 2018 Gulf of Mexico expeditions, the at-sea team successfully conducted 32 ROV dives with ROV *Deep Discoverer*, which is operated and maintained by the Global Foundation for Ocean Exploration, and mapped 53,300 km^2 within the US EEZ (Figure 1). ROV dives during this expedition explored the seafloor between 300 m and 3,010 m depth and four dives explored the water column at depths ranging from 300 m to 2,100 m. During the expeditions, 172 biological samples were collected because they were thought to be undescribed species, they represented significant range extensions of known species, or they represented the dominant morphotype of an area. Additionally, 20 rock samples were collected to help characterize the petrology of the Gulf. All samples collected during the expedition will be archived in publicly accessible repositories so they can be used by the marine science community. In addition to exploring the Gulf's geological and biological resources, the expeditions surveyed submerged cultural heritage sites.

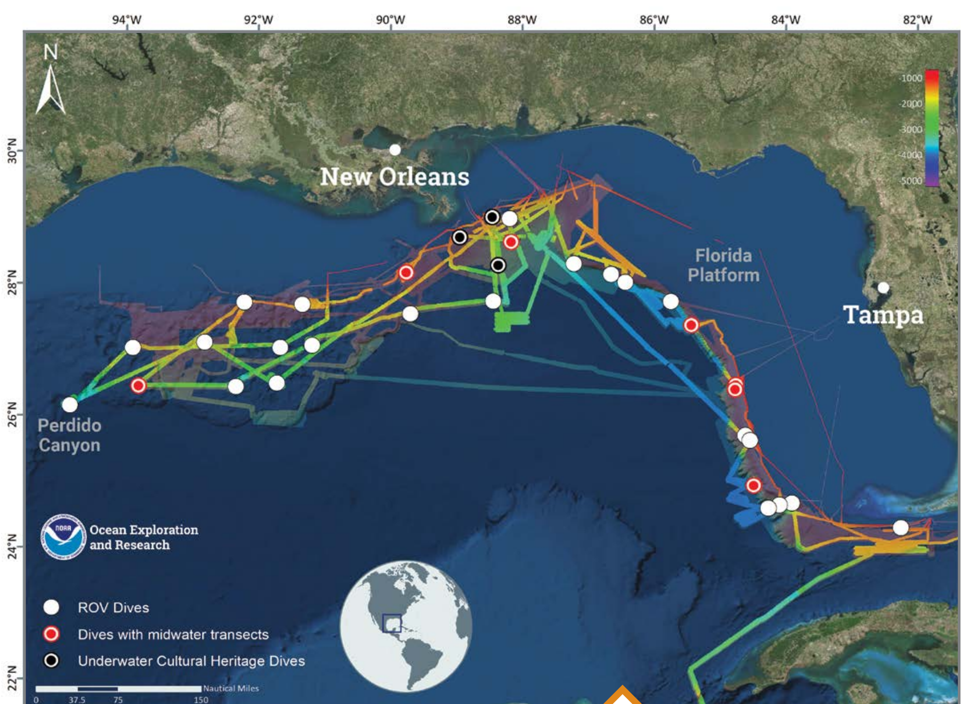


Figure 1. Map of the Gulf of Mexico showing cumulative color-coded multibeam sonar bathymetry collected during all NOAA Ship *Okeanos Explorer* expeditions, including the three most recent expeditions.

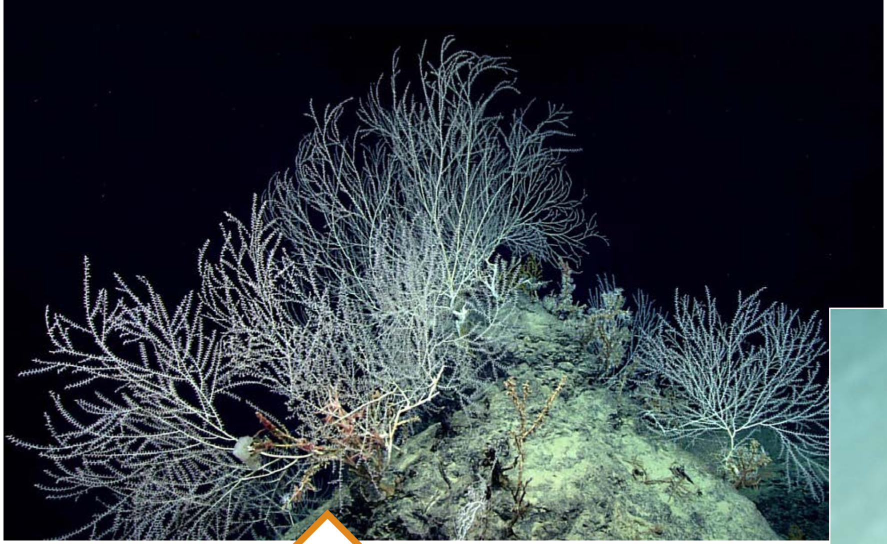
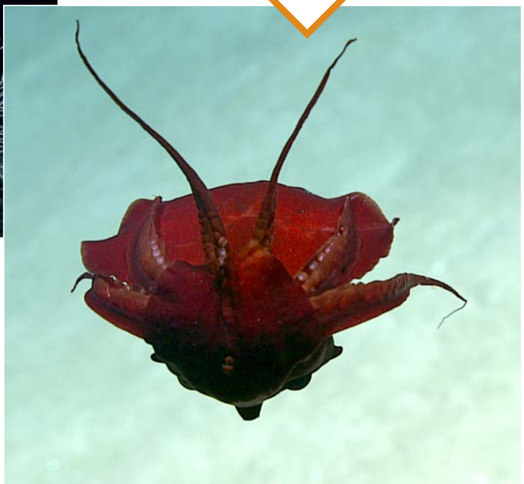


Figure 2. While diving on Escarpment Canyon Ridge at the southwest edge of the Florida Escarpment, a very high density of bamboo corals and glass sponges were observed at approximately 2,300 m depth. To date, these high-density communities are among the deepest recorded in the Gulf of Mexico.

Figure 3. This unidentified squid (possibly *Discoteuthis discus* in the family Cycloteuthidae) exhibited behavior seen in this picture that was described as "probably the most bizarre squid I've ever seen" by cephalopod expert Michael Vecchione from NOAA's National Marine Fisheries Service.



BIOLOGICAL HIGHLIGHTS

During the two ROV expeditions, the team documented a rich diversity of habitats and organisms. *Deep Discoverer* documented at least 22 previously unknown chemosynthetic communities across the northern Gulf. These communities thrive on chemical energy and hydrocarbons that naturally seep into the water. These natural cold seeps are also an important source of exposed rock that can provide habitats for coral and sponge communities. Additionally, at least 14 high-density and high-diversity coral (Figure 2) and sponge communities were located, including one at approximately 2,600 m depth, the deepest known in the Gulf of Mexico.

Initial study of the physical specimens collected has yielded potentially dozens of substantial species range expansions and several likely new species. Previously unobserved behaviors in known species (e.g., squid defensive posture [Figure 3], octopus aggressive behavior, several sea stars feeding on sponges) were documented. Highlights also include the first record of the crinoid family Hyocrinidae (a probable new species) in the tropical western Atlantic and a likely new and locally abundant species in the crinoid family Thalassometridae, the first-ever in situ observation of the rare sea star *Remaster palmatus* (family Korethrasteridae), and the first documentation of several species of sea stars feeding, including one on a black coral.

GEOLOGICAL HIGHLIGHTS

These expeditions explored a wide variety of deep-sea geological settings, including carbonate shelves, escarpments, cold seeps (Figure 4), mud volcanoes, asphalt seeps, brine pools, and sedimented plains and slopes. ROV *Deep Discoverer* was used to explore the seafloor from the remote Perdido Canyon, which is on the border of the US EEZ and just over 200 nm from the southernmost tip of Texas, to Pourtales Terrace, which is just 50 nm southwest of Key West, Florida (Figure 1).

During the 15 dives over salt domes in the western Gulf, we observed methane seeps (some with visible methane hydrate), asphalt seeps, and brine rivers, with most locations supporting well-developed chemosynthetic communities, including bacterial mats. Many of these chemosynthetic

Figure 4. High-viscosity oil (black tubules) seeping from the seafloor among white bacterial mats forms asphalt when the extrusions solidify. The long tubules are bent to the left due to the current.

sites were surrounded or interspersed with asphaltic or authigenic carbonate outcrops that hosted coral and sponge-based communities. These exposures and their communities are like oases in broad expanses of sediment.

The rocks and sediments collected will be analyzed for chemical composition and age to increase understanding of how these features formed. The rock samples were primarily collected from exposed siliciclastic and carbonate rock outcrops, but also included authigenic carbonate rock, asphalt, a fossilized coral, and a fossilized burrow cast or bone.

Twelve dives were conducted on the West Florida Escarpment, the steep western slope of the Florida Platform, to better understand its geological composition and origins. Some of the dive sites featured exposed carbonate formations with amphitheater-like features and steep cliff faces often encrusted with ferromanganese deposits. Carbonate deposits were usually exposed only on very steep slopes. Gentler slopes were either completely covered by sediment or had only very small exposed surfaces. The expeditions also explored previously unmapped and unexplored sinkholes on the Pourtales Terrace, the deep shelf south of the Florida Keys.

ARCHAEOLOGY HIGHLIGHTS

ROVs were used to explore five suspected cultural heritage sites in the Gulf. Bureau of Ocean Energy Management archaeologists identified one of the wrecks as an early nineteenth-century copper-clad merchant vessel. Visible artifacts included glass bottles, ceramic and porcelain vessels, remnants of a suction bilge pump with cast-iron flywheels, an anchor, and a cast iron stove. Draft marks on the bow indicated that at least four vertical meters of hull were buried in the seafloor, so the full nature and extent of the cargo could not be determined. Working with BOEM archaeologists, *Deep Discoverer* ran a series of video transects along and across the wreck's forepart to supply the imagery required for making a three-dimensional digital reconstruction.

Expedition archaeologists and scientists also conducted the first exploration of the sunken tug boat *New Hope* (Figure 5). In 1965, the US Coast Guard performed a daring helicopter rescue to save the vessel's crew during Tropical Storm Debbie. All lives were saved. Information collected during the dive confirmed the identity of the wreck, and could help support an application for the *New Hope* shipwreck to be added to the National Register of Historic Places.

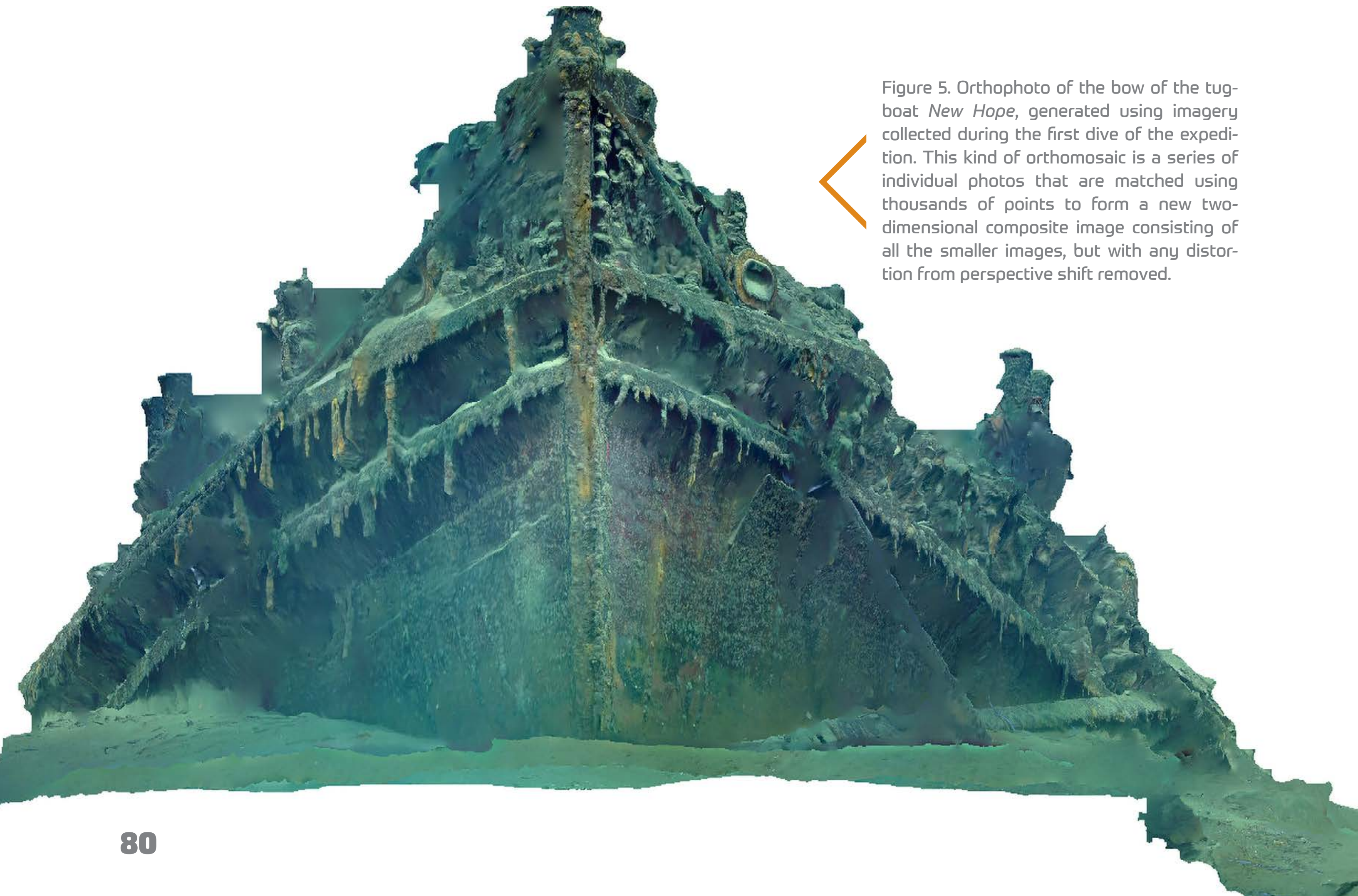


Figure 5. Orthophoto of the bow of the tugboat *New Hope*, generated using imagery collected during the first dive of the expedition. This kind of orthomosaic is a series of individual photos that are matched using thousands of points to form a new two-dimensional composite image consisting of all the smaller images, but with any distortion from perspective shift removed.

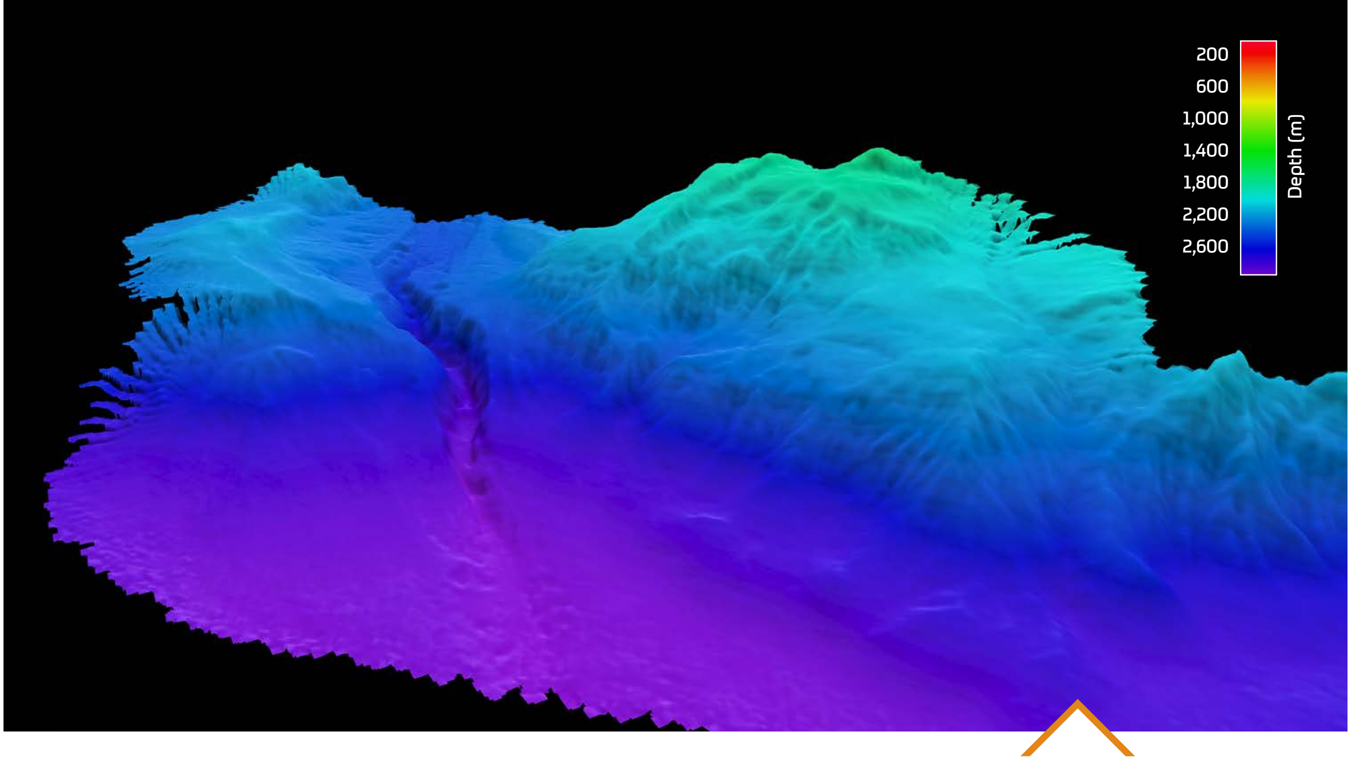


Figure 6. Perdido Canyon was identified as a high priority by the scientific community as an unexplored area of the Gulf of Mexico. The onboard team was able to map this canyon and provide publicly available high-resolution multibeam bathymetry for the first time.

MAPPING HIGHLIGHTS

During the three expeditions, areas where high-resolution mapping data are not available publicly were targeted, such as portions of Perdido Canyon in the far western Gulf (Figure 6), Pourtales Terrace, and the West Florida Escarpment. Multibeam mapping operations also revealed sonar anomalies likely to be gas seeps, one at Whiting Dome and another at Walker Ridge 488, both offshore of the mouth of the Mississippi River. Nighttime operations acquired high-resolution mapping data over potential ROV dive sites chosen to support dive planning.

The science team used seafloor backscatter data to target areas likely to be hard ground during subsequent ROV dives. In addition to identifying potential gas seeps, water column mapping data were used to image part of an oil platform. By identifying the exact location of the cables in the water column, the team was able to successfully plan and execute an ROV archaeology dive within close proximity to the oil platform.

SUPPORTING MANAGEMENT

One of the primary goals of the expeditions was to explore areas that are a priority for resource managers. To that end, seven proposed Habitat Areas of Particular Concern (HAPCs) that are under consideration by the Gulf of Mexico Fishery Management Council were surveyed. Four of the sites host high-density coral and sponge communities and one has extensive chemosynthetic communities. In addition to informing Council resource managers, the expeditions explored eight sites that are included in some of the Flower Garden Banks National Marine Sanctuary proposed expansion zones. High-diversity and high-density coral and sponge communities were discovered at two areas, including a spectacular *Madrepora oculata* coral garden. Chemosynthetic communities located at sites of brine rivers and asphalt seeps were observed in five of the areas under consideration for inclusion into the Sanctuary.

SUMMARY

Because of its proximity to the US mainland and its extensive exploitation by industry, the Gulf of Mexico is often regarded as well explored. However, the many new findings of the 2017–2018 *Okeanos Explorer* Gulf of Mexico expeditions highlight that there is still much to be discovered and learned about this important body of water. Over half of the ROV dives documented species potentially new to science or behaviors that had never been previously observed. In addition to exploratory information gathering, these expeditions acquired data in priority areas identified by the resource management and scientific communities. Specifically, the expeditions explored the habitats of deep-sea corals and sponges, as well as those of midwater and chemosynthetic communities—several of which are in areas that have been proposed as new marine managed areas. Marine cultural heritage sites were also explored. Information obtained during these expeditions will help inform management about the diverse and rich communities living in the deep waters of the Gulf of Mexico that help support the region's Blue Economy.

Windows to the Deep 2018: Exploration of the Southeast US Continental Margin

By Leslie R. Sautter, Cheryl L. Morrison, Kasey Cantwell, Derek Sowers, and Elizabeth Lobecker

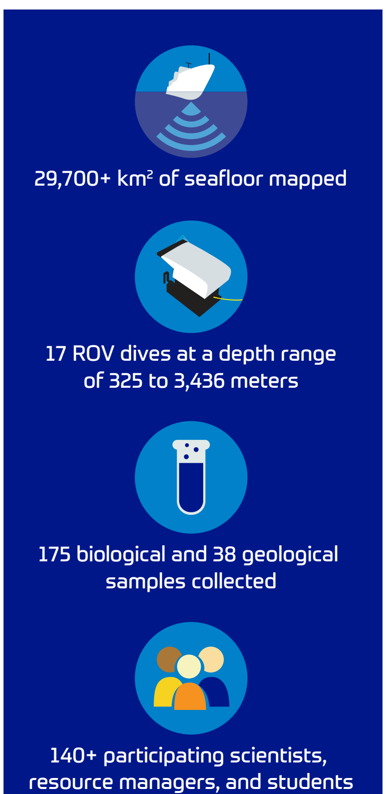
INTRODUCTION

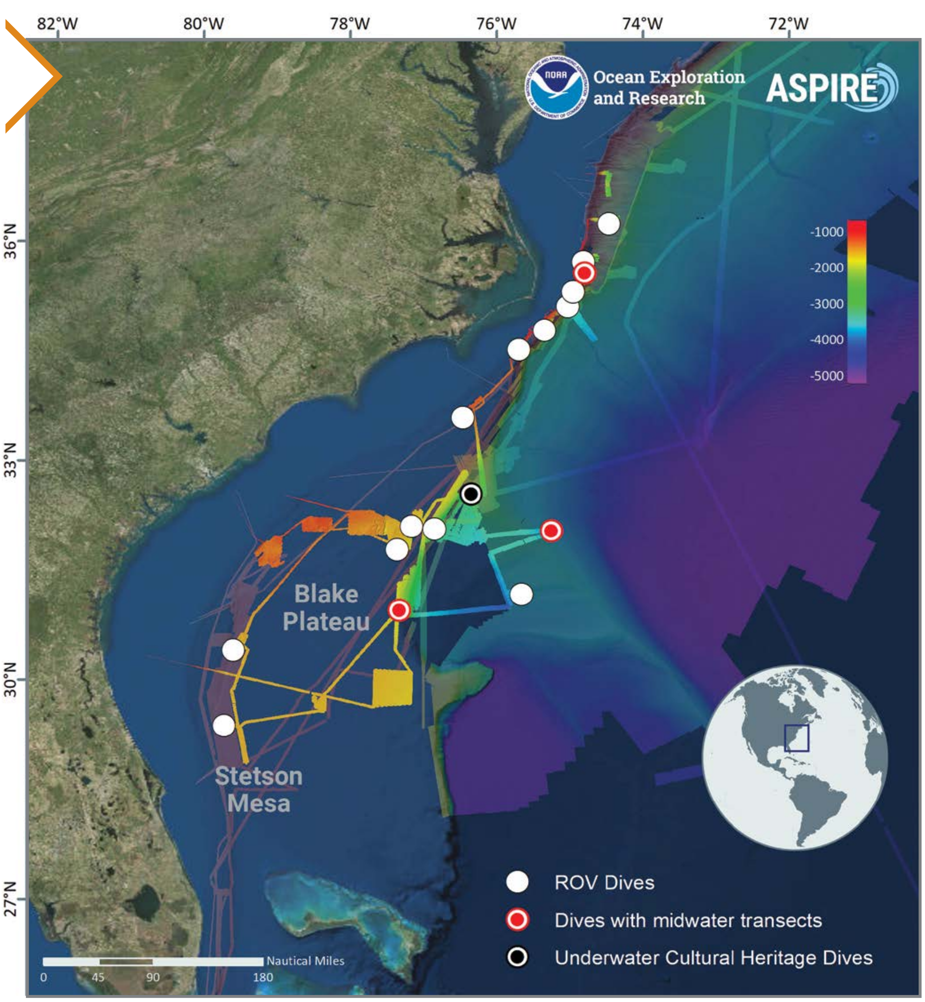
Windows to the Deep 2018: Exploration of the Southeast US Continental Margin was a 36-day expedition aboard NOAA Ship *Okeanos Explorer* to acquire data on priority exploration areas identified by the ocean management and scientific communities. This expedition involved high-resolution multibeam sonar mapping and ROV dives, ranging from 340 m to 3,400 m depth, across the southeast US continental margin (Figure 1). Operations primarily targeted areas with potential to host deep-sea coral and sponge communities, including mounds, ridges, and terraced features on the continental slope. Dive sites also included maritime heritage sites, a submarine landslide feature, and several submarine canyon slopes, some of which exhibited evidence of active cold seeps. High biological abundance was noted at six of 17 dive sites, three of which also had high biological diversity. Additionally, deep-sea corals or sponges were observed on every dive except one, which was dedicated to gas seep exploration.

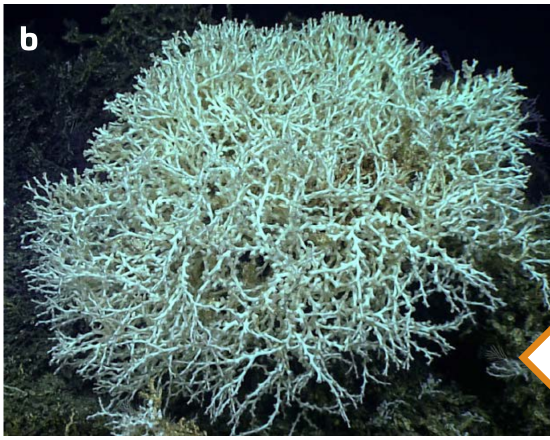
MAPPING HIGHLIGHTS

Mapping data collected during this expedition filled data gaps in the region and contributed to Seabed 2030 goals to map unexplored regions of Earth's ocean. More than 29,700 km^2 of seafloor (an area larger than the State of Maryland) were mapped at high resolution, providing new insights into this region. Although not all areas were explored using the ROV, newly mapped areas revealed interesting features on Blake Plateau, including intraslope terraces along the plateau's eastern edge, karstic features and scarps, and numerous likely biogenic ridges and mounds on the plateau's western edge in areas significantly influenced by the Gulf Stream. Due to their sizes, these biogenic features cannot be resolved from satellite data and were only revealed in detail using the ship-mounted multibeam sonar. Finding numerous and previously unknown features has implications for habitat modeling, given that similar features may occur elsewhere in the region.

Figure 1. Summary map of the Windows to the Deep 2018 expedition.







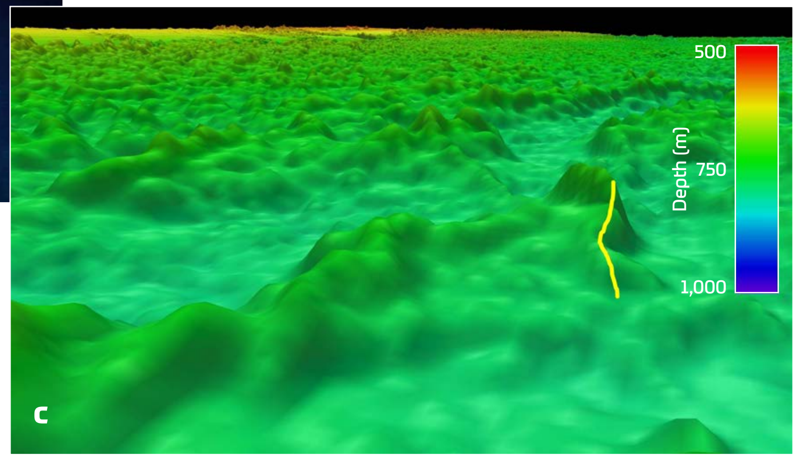


Figure 2. A dive at "Stetson Mesa South" explored a few of the thousands of similar features that have given the region the name "Million Mounds." (a) View of crest of *Lophelia* coral mounds observed during the dive. (b) Large *Lophelia* colony encountered during the dive. (c) Oblique three-dimensional view of seafloor bathymetry, with the approximate ROV transect path shown in yellow (vertical exaggeration 6x).

DEEP CORAL MOUNDS

Through both mapping and visual surveys, this expedition added substantial evidence that the numerous mounds on Stetson Mesa offshore of Florida and Georgia are comprised of thick accumulations of dead coral rubble, the remaining skeletal framework of old colonies of the stony coral *Lophelia pertusa* (Figure 2). Documenting the biogenic nature of the coral mounds along Stetson Mesa (600–780 m depth) and at Richardson Ridge (660–870 m depth) was a highlight of the expedition. Though the expedition only explored three Blake Plateau mounds, all were rich with live coral stands at their crests. The Stetson Mesa mounds are representative of thousands of similar features mapped during previous *Okeanos Explorer* expeditions, revealing one of the largest areas of potential deep-sea coral reef habitat discovered to date in US waters. These mounds range in size from 10 m to 75 m of vertical relief, with crests at depths between 600 m and 700 m, and exhibit gradual to steep slopes ranging from 15° to 30°. Skeletal framework provided the complex, hard substrate that is ideal habitat for a high diversity of organisms such as sponges, echinoderms, solitary corals, crabs, and octocorals that live both attached to the framework and within cave-like areas beneath. At the shallowest points of the Blake Plateau mounds, in areas with the strongest current velocities, thriving communities of *L. pertusa* were encountered. However, on the mound flanks and swales between crests, few living colonies were observed, and only moderate currents were encountered. The new data collected on the expedition highlights the vastness of potential deep-sea coral habitat in this region.

The Gulf Stream strongly influences all coral mounds explored. Even Richardson Ridge, located well east of the current's usual path, is affected by significant flow due to the eastward bending of the stream axis. Differences in mound distribution were noted between the Stetson Mesa and Richardson Ridge areas. While the coral mounds in the Stetson Mesa region are rounded and fairly evenly distributed, Richardson Ridge is composed of a series of mounds in a chain-like arrangement, shaped by significant erosion from slumping, resulting in steep (>30°) walls and a narrow ridge crest. The northernmost coral mound visited, within the Cape Fear Lophelia Banks Deepwater Coral Habitat Area of Particular Concern, is significantly shallower than the other mounds and resembles the Stetson Mesa mounds, although live coral coverage is lower.

INTRASLOPE TERRACES

Several ROV dives along the Blake Escarpment revealed a high diversity of deep-sea corals and sponges on low relief, intraslope terraces (Figure 3). Dives were conducted along the outer reaches of Blake Plateau, where the relatively flat-lying rock-layers (strata) are exposed as depths increase toward the Blake Escarpment. The edges of these strata form step-like areas, often resulting in rock surfaces where invertebrates settled. Dives at Blake Escarpment North (1,675–1,740 m depth), Blake Escarpment South (1,246–1,310 m), and Richardson Scarp (868–1,006 m) each began at the foot of a terraced feature identified in the high-resolution multibeam maps. Backscatter imagery for these dive sites showed high-intensity returns, indicating

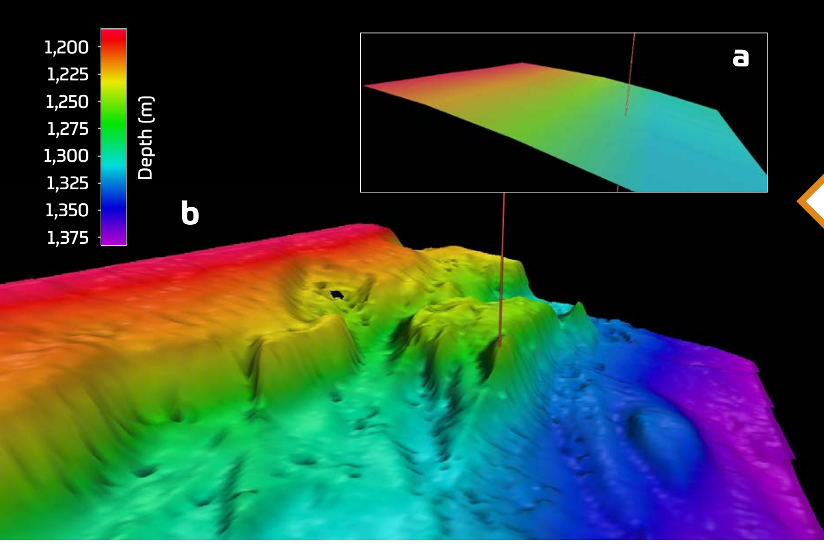
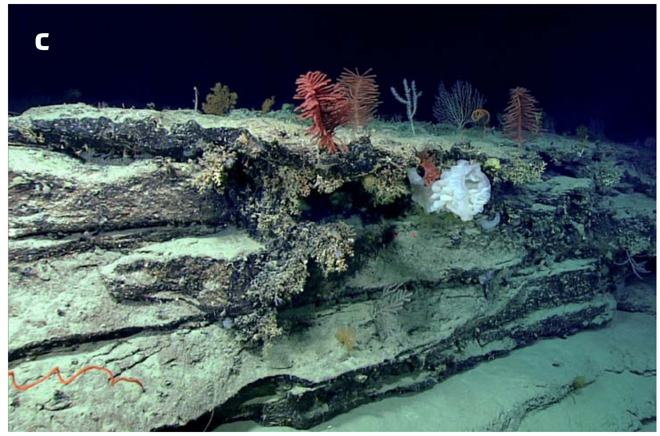


Figure 3. Prior to the Windows to the Deep 2018 expedition, based on satellite altimetry (V18.1 of Smith and Sandwell, 1997), this section of the Blake Escarpment appeared to exhibit a low slope with no distinct features. (a) Satellite altimetry at the Blake Escarpment South location (red vertical line in b). (b) During the mapping leg of this expedition, multibeam data revealed a series of terraced features. (c) ROV exploration documented highly diverse, dense communities of deep-sea corals and sponges throughout the dive.



relatively hard substrate, and potentially suitable habitat for deep-sea corals and sponges. The seafloor at the base of these features was very low-sloped pelagic mud seafloor, with intermittent rock slab outcrops at the terrace steps. Generally, echinoderms such as brittle stars, sea stars, and pancake urchins, along with sea pens and cerianthid tube anemones, were observed in the mud habitat, though bamboo corals and sea pens were present at Blake Escarpment North as well.

Exposed rocks were sometimes observed on steep slopes at the edges of the terraces, most commonly composed of interbedded indurated/semi-lithified pelagic muds, likely of biogenic origin. Many surfaces were coated with what appears to be ferromanganese crust. In nearly all areas, rock slabs served as excellent substrate for numerous species of corals, sponges, and many mobile organisms. The highest diversity of black corals and octocorals occurred at the southern portion of the Blake Escarpment, making this dive a highlight of the expedition.

DEEP TERRACE, SEDIMENT PLAINS, AND GIANT BEDFORMS

Three ROV dives were completed over mostly sedimented benthic environments in deeper waters (> 2,500 m). These sites each exhibited unique geomorphology. The Blake Ridge site (3,360–3,420 m) had the highest coverage of hard substrate, consisting of tabular mudstones and gravel that was colonized by demosponges (e.g., *Phakellia* and *Geodia*) and glass sponges, as well as several unbranched octocorals (*Convexella* spp.) and a stalked tunicate. High-resolution bathymetry indicated a gently sloped landscape with minimal terracing. Although backscatter surfaces showed this dive was positioned within a large area of high-intensity backscatter, much of the site was covered with mud that often included large areas of gravel that appeared to have a ferromanganese crust. Occasional outcrops of tabular mudstones that tilted beneath the muds supported numerous large sponges throughout these sites. It is likely that the seabed mud was underlain by this hard substrate and the sonar penetrated the mud sediment veneer, generating the observed high-intensity return. Gravel was often concentrated in the lee of large sponges, indicating episodes of significantly high current velocities.

The third dive of the expedition (3,330–3,350 m) explored an area of Blake Ridge characterized by enormous undulating dune-like bedforms where crest-to-crest lengths exceed 800 m. Sediments collected were stiff and cohesive and were dominated by clay-sized particles (likely calcium carbonate nannofossils). Planktonic foraminifera were the primary component of the silt-size fraction. One portion of a bedform sloped at least 70° and exhibited ripples from horizontal currents moving along the wall. No rock outcrops were present. A few of the sessile organisms documented during the dive were entwined with *Sargassum*, likely a result of the macroalgae drifting in the current after sinking from the surface.

SUBMARINE CANYON SLOPES

Five dives were located on steep slopes within and between submarine canyons along the North Carolina continental slope, with dives ranging from 340 m to 1,700 m depth. Substrate throughout these dives was consistently clay/silt particles (mud), comprised mostly of calcareous microfossils and an increasing fraction of terrigenous material in shallower areas. No rock or hard substrate was encountered. However, some areas showed significant mud compaction that facilitated the formation of the steeply sloped seabed. Bacterial mats indicative of methane gas seeps were seen at Hatteras Canyon (310–520 m depth), Keller Canyon

(510–720 m), and Pea Island (340–520 m). Active methane seep bubbling was observed at both Hatteras Canyon and Pea Island, although gases were not venting vigorously. Pea Island appeared to be the most active of the sites visited, as evidenced by the high density of white bacterial mats, with underlying black, anoxic sediments. No evidence of methane seepage was seen during the other canyon dives.

The biota observed at these five submarine canyon slope areas were typical of sedimented habitats, including anemones, gastropods, and echinoderms. Squid and octopus were commonly observed, along with eelpouts and rattail fishes. Although some taxa were common across the canyon slope sites, each site also had unique benthic biota. For example, brittle stars dominated at the South of Pamlico site, whereas high abundances of mud stars (*Plutonaster* sp.) were observed on the seafloor at Intercanyon Ridge and Hatteras Canyon, and quill worms were common at the Pea Island site. Numerous pycnogonids (sea spiders) were seen on the compacted mud walls of Keller Canyon. Exploration at Pea Island revealed an active water column, with instances of bentho-pelagic coupling, where benthic organisms were observed preying upon midwater organisms.

SHELF-EDGE ROCKY LEDGES

Initially, a dive was planned to explore and identify a potential World War II wreck off the North Carolina coast. Previously mapped high backscatter returns were coincident with a large, high-relief structure at the edge of the continental shelf (Figure 4). Additional multibeam tracklines verified the presence of a structure and enhanced bathymetry available for this site. Anomalous sonar returns were also observed in the water column immediately above the site. However, no wreck was discovered. Instead, the ROV encountered a steep scarp with slopes ranging from 20° to 50°, exhibiting many layers of outcropping sedimentary rocks. This rock feature—subsequently named Wreckless Scarp—provides habitat for a rich diversity of fishes and invertebrates. The close proximity to the Gulf Stream undoubtedly helps this community thrive on the hardbottom substrate.

MUD CLIFFS

The final dive (1,760–1,880 m depth) of the expedition explored the lower portion of the Currituck Landslide feature (1,760–1,880 m depth). A large 100 m vertical wall of cohesive mud was explored. Meter-high mud blocks were strewn at the wall's base, having detached from the sheer cliff. Despite the lack of hard rock substrate, the mud cliffs and consolidated mud blocks created habitat for corals, sponges, and numerous echinoderms. The most conspicuous echinoderm was the brisingid sea star that inhabited many surfaces, including the sheer cliff face. Corals encountered included the stony solitary coral *Desmophyllum dianthus*, plus *Chrysogorgia*, *Anthomastus*, and *Paramuricea*, as well as bamboo corals *Acanella* and *Keratoisis*. The only black coral observed was *Bathypathes*, which grew on the sheer wall. Fishes included halosaurs, *Bathysaurus*, synaphobranchid eels, and the flatnose codling (*Antimora rostrata*).

LEGACY OF DATA

During the Windows to the Deep 2018 Expedition, we were able to observe a variety of seafloor features identified by both the expedition's mapping efforts and previous expeditions conducted by NOAA and the US Geological Survey. High-resolution bathymetry is sparse across this region, and important discoveries are made with each new survey. Many exciting biological observations were made, including high-density and high-diversity coral and sponge communities, commercially important species in areas where they have not been previously observed (e.g., *Chaceon fenneri* documented in newly explored areas of the Blake Plateau), dramatic predation events, mating, juveniles utilizing habitat, species at deeper depths or wider geographic distributions than previously known, associations between corals and/or sponges with other species, sightings of rare species, and marine debris at most dive sites. Expedition data are now publicly available and have already been used to guide additional discoveries (pages 104–105).

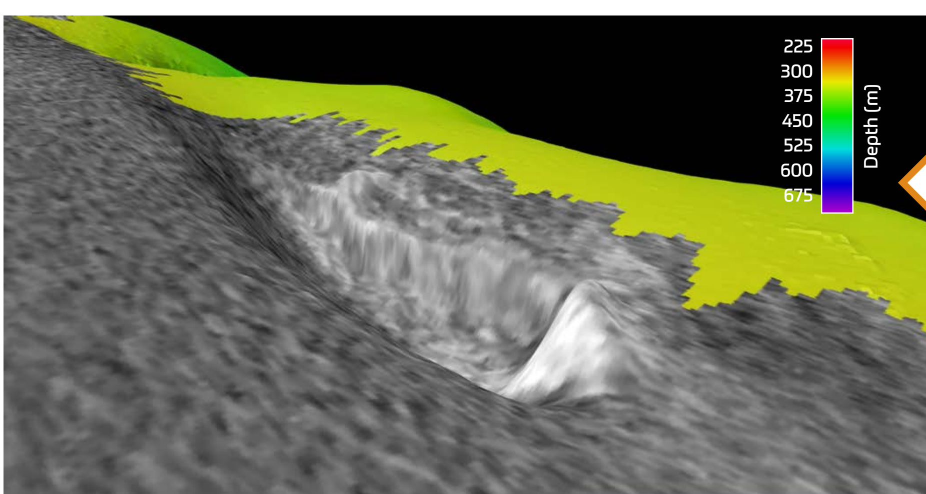


Figure 4. Three-dimensional view of the Wreckless Scarp sonar anomaly, with multibeam sonar backscatter intensity draped on bathymetry (3x vertical exaggeration). Brighter areas are stronger return echo intensities, which turned out to be rocky reef habitat and not a shipwreck.

The Blake Ridge Wreck

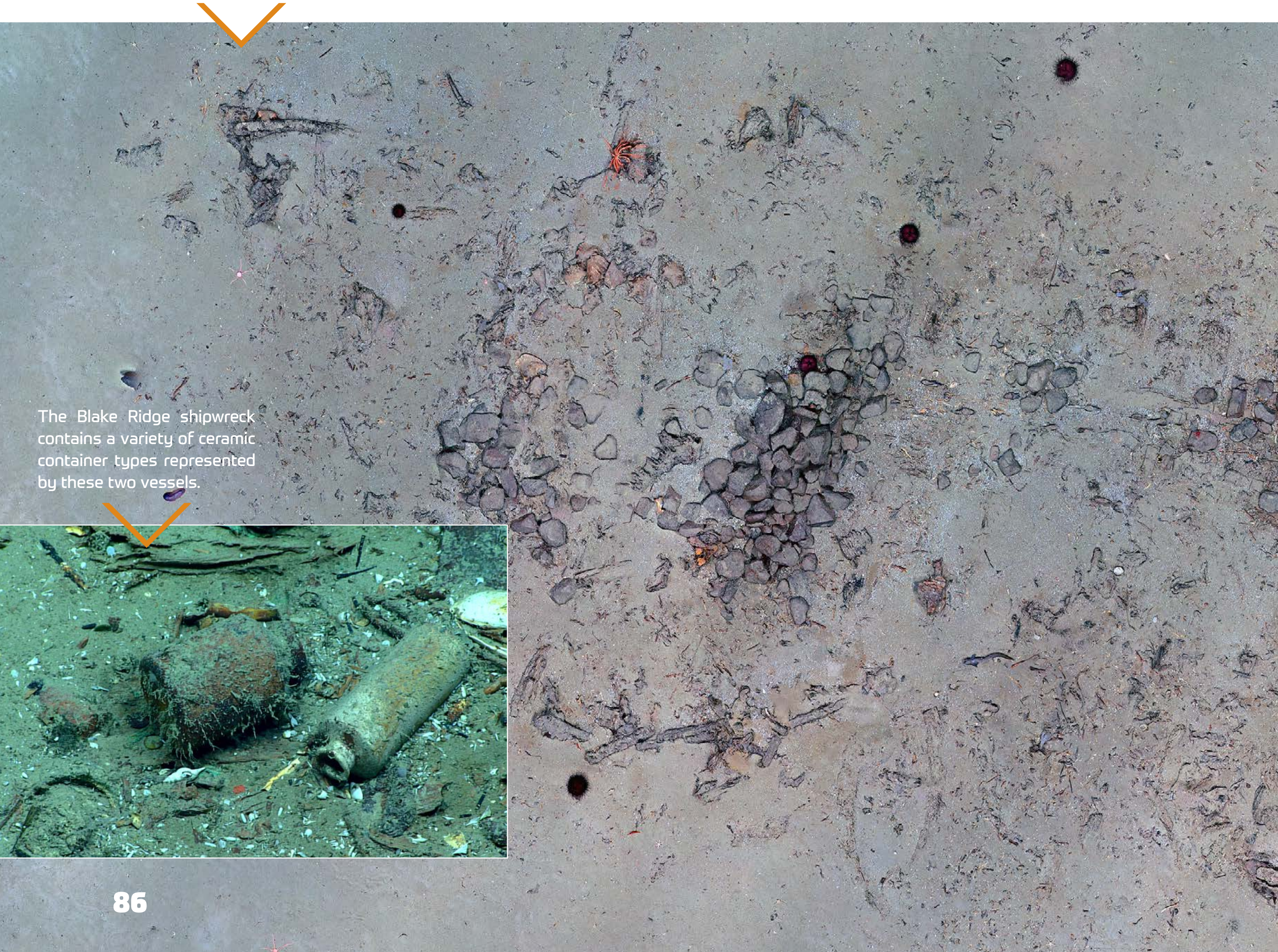
By James P. Delgado, Frank Cantelas, and Scott Sorset

During Windows to the Deep 2018: Exploration of the Southeast US Continental Margin, *Okeanos Explorer* deployed to a site identified in 2015 by scientists from Duke University and Woods Hole Oceanographic Institution. While searching for a missing instrument package, the team in HOV *Alvin* came upon the faint "ghost" of a wooden shipwreck more than 160 km off the coast of North Carolina in about 1,000 m of water. Resting on Blake Ridge, the wreck was briefly inspected, with the team in *Alvin* discovering scattered bottles, a ship's navigational octant, ceramics, and a pile of bricks.

We returned to the Blake Ridge wreck with *Okeanos Explorer* to learn more about the site and document it using three-dimensional imaging techniques. Colleagues from BOEM, other agencies, universities, the private sector, and the interested public participated in this exploration via telepresence. The slow pace of mapping gave us time to assess the wreck. Our approach, not unlike sonar surveys in which we "mow the lawn," provided both 100% coverage of the site, as well as a high-resolution virtual "copy" of the exposed portions of the wreck. This methodology of patient adherence to comprehensive documentation was challenging at times, for example, when an interesting cultural or biological feature appeared, but we stayed on course.

As we have "re-dived" the site, a number of features are now apparent. The wooden hull, while consumed by marine organisms down to what appears to be the lower hold, retains the form of a small, ~12 m long vessel that was likely rigged as a two-masted schooner. It was fastened with iron, and the basic outline and the style of the chain plates that supported the rigging on the masts suggest it was built around 1825–1840, and likely lost before 1850. It

The Blake Ridge site, as processed by author Scott Sorset at BOEM.



The Blake Ridge shipwreck contains a variety of ceramic container types represented by these two vessels.

probably carried a small crew of three to five people.

The pile of red bricks marks the location of the ship's galley where meals were prepared. Lying close by, in an area where the ship's cabin would have been, a pile of conch shells suggests a stop in the Bahamas or Florida, where these shells would have been harvested or bought as food for the crew. There were artifacts that spoke to the people on board—bottles of wine, ceramic jugs, containers for food and other liquids, a small sewing kit with a pile of brass buttons, a slate, a tobacco pipe, and a comb, as well as the octant. The presence of these artifacts on the wreck, which would have been taken if the crew had abandoned ship, suggests no one survived this wreck.

The wreck lies well offshore and off the edges of the Gulf Stream, which has been a highway for oceanic traffic for centuries. The ship appears to be a humble, working-class vessel. In that, and given its location, this vessel probably was one of many small ships using that ocean highway to connect to various ports, carrying out trade and serving commerce much as long-haul semis do on the highways and freeways of our time.

Personal items like this clay smoking pipe provide glimpse into the lives of the sailors who worked on this vessel.

The octant was used for navigating the ship, while the ceramic jug was used to store liquids.

Mapping Deepwater Areas Southeast of Bermuda

in Support of the Galway Statement on Atlantic Ocean Cooperation

By Tatum Miko Herrero, Michael P. White, and Caitlin Adams

EXPEDITION OVERVIEW

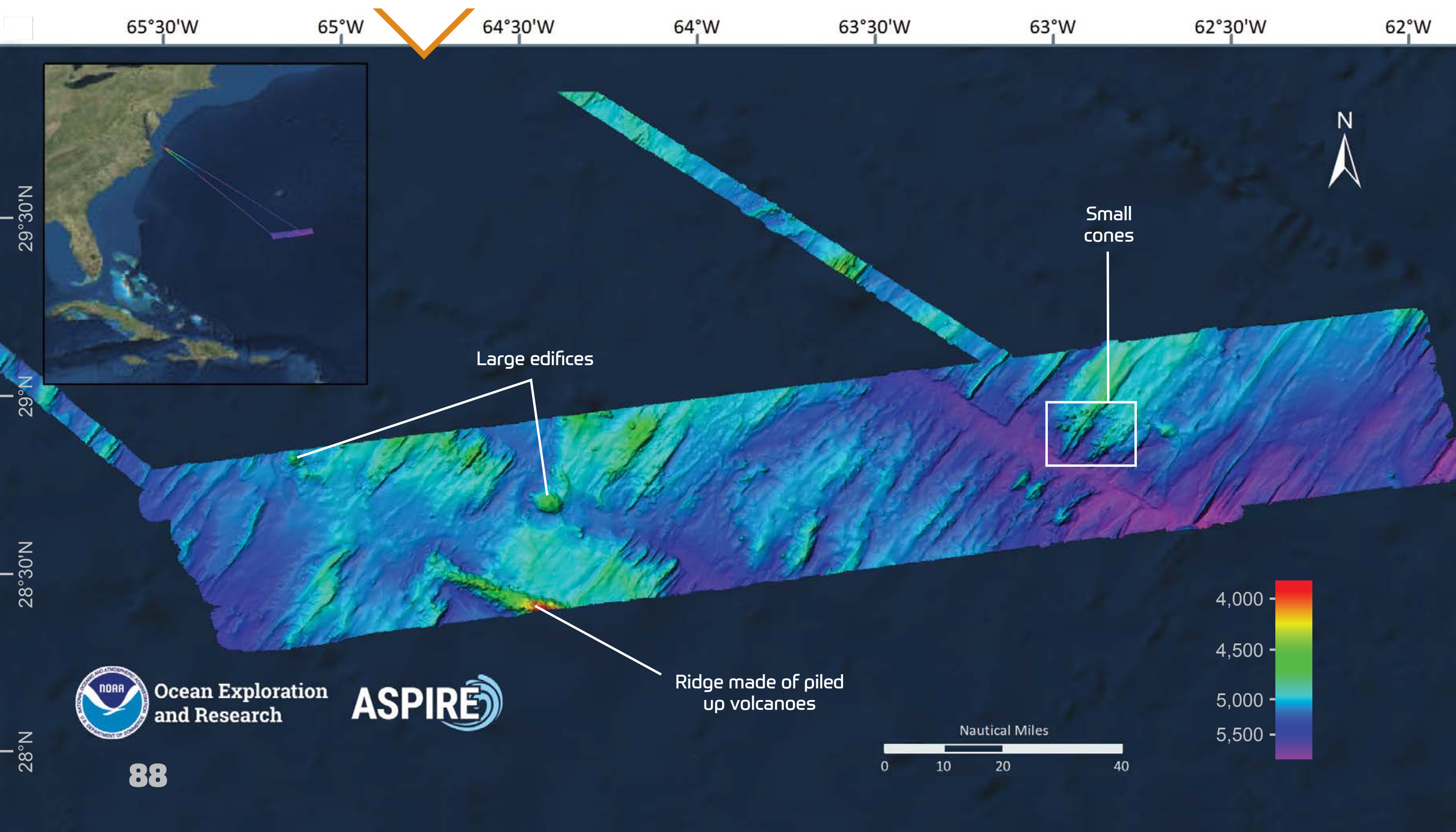
The 2018 Mapping Deepwater Areas Southeast of Bermuda in Support of the Galway Statement on Atlantic Ocean Cooperation expedition collected baseline mapping information in an area of international interest southeast of Bermuda. The expedition was the first dedicated government-sponsored non-transect survey in support of the Galway Statement on Atlantic Ocean Cooperation. Through the Galway Statement and its coordinating body, the Atlantic Ocean Research Alliance (AORA), the Atlantic Seabed Mapping International Working Group (ASMIWG) designed a suitability model to identify priority mapping areas in the Atlantic Ocean, factoring in areas of public interest, sensitive marine areas, and areas with marine resource potential. NOAA Ship *Okeanos Explorer* contributed to this international mapping effort with a 20-day cruise in international waters south of Bermuda. *Okeanos Explorer*'s sonar acquisition screens were broadcast to shore where they were monitored by the ASMIWG and other scientific community members who then communicated adjustments to the ship during the survey.

Mapping operations during the expedition extended bathymetric coverage in the US Exclusive Economic Zone and international waters in support of Galway and Seabed 2030. Over 52,000 km^2 were mapped, an area almost three times the size of New Jersey. The expedition mapped over 20,500 km^2 within the ASMIWG priority area (Figure 1).

GALWAY STATEMENT

The Galway Statement on Atlantic Ocean Cooperation launched the European Union, Canada, and United States AORA. Through AORA, members recognize the importance of the Atlantic Ocean as a shared resource whose health and stewardship is intimately linked to the success of current and future generations. Successful management of the Atlantic Ocean would enable conservation of its rich biodiversity, promote sustainable management of resources, and support social and economic priorities. Formal AORA trilateral

Figure 1. During this expedition, *Okeanos Explorer* mapped over 20,500 km^2 within the ASMIWG priority area. Bathymetric mapping revealed a complex seafloor structure, including conical features, a seamount, and southwest-northeast trending linear ridges.



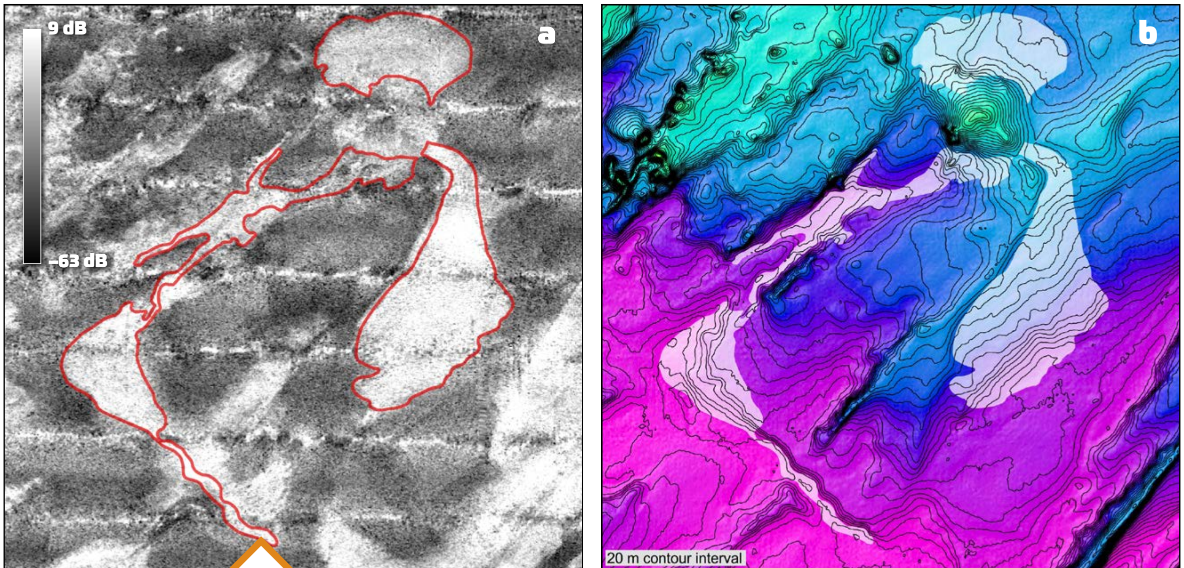


Figure 2. (a) Field-processed backscatter from the expedition. The higher intensity areas outlined in red may be evidence of more recent volcanic eruptions that are forming new seafloor. (b) The same area as (a), overlain on multibeam bathymetry. The potential volcanic flows are contained within valleys and depressions, emanating from a single cone. Black contour lines are at 20 m intervals.

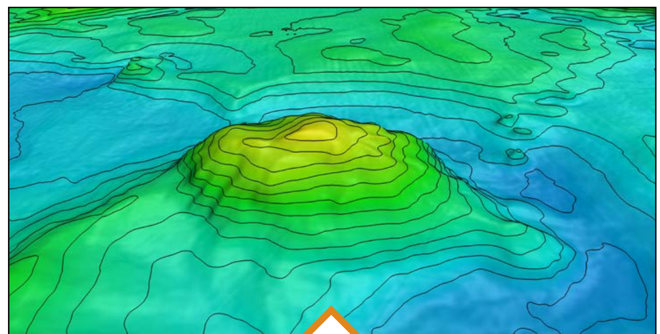


Figure 3. Almost twice the height of the Empire State Building, this not-quite-a-seamount stands 800 m above the seafloor. Technically defined as a knoll, this distinct mound was a relatively unique feature because it was not associated with the southwest-northeast trending linear ridges crossing the survey area. It is 11 km from flank to flank and likely volcanic in origin. Black contour lines are 50 m.

working groups have been established to develop scientific plans for the following priority areas: Atlantic seabed mapping and cooperation, aquaculture, ocean literacy, ocean health and stressors, and ocean observation and prediction.

The ASMIWG was formed to address objectives concentrated around ocean mapping. These objectives include identifying the needs and priorities that would allow preparation of a complete seabed map of the shared Atlantic, guaranteeing data availability and sharing among members, and developing a process to identify high-priority polygons for seabed mapping projects. During summer 2018, *Okeanos Explorer* mapped part of one of these priority polygons.

VOLCANIC FEATURES

The expedition mapped seafloor that was 100–115 million years old and exhibited small cones (100 m in height and 1 km in diameter, on average), large edifices (up to 600 m in height and 8 km in diameter), and a ridge consisting of piled up volcanoes (1.4 km in height at the highest elevation) (Figures 2–3). The larger edifices and the ridge were unexpected finds because large volume eruptions are usually related to underlying hotspots, which the mapping area had not been identified to have. Backscatter data revealed highly reflective surfaces, providing evidence of eruptions much younger than surrounding seafloor. Figure 2a shows that mostly highly reflective surfaces define three lobes that are contained within valleys and depressions.

EDUCATION AND ENGAGEMENT

As part of the international collaboration under AORA, the onboard team included a scientist from Canada and another from Germany. Collaboration with onboard international scientists involved initial interpretation of deep-sea mapping data and detailed bathymetric data processing. Four NOAA Explorer-in-Training students, including one from NOAA's Educational Partnership Program, were trained in the acquisition and processing of sonar data. The Explorer-in-Training team consisted of an ex-Marine studying archaeology, a student now pursuing her PhD in deep-sea biology, and a maritime academy student. For the first time in several years, OER also hosted a NOAA Teacher at Sea from the Peddie School in Hightstown, New Jersey, who blogged about the variety of career opportunities on the ship. The team hosted five live interactions with over 85 individuals from the NOAA Seattle Science MiniROV Camp, the Engineeristas Technology Camp, and other groups visiting the University of New Hampshire.

Océano Profundo 2018: Exploration of Deep-Sea Habitats of Puerto Rico and the US Virgin Islands

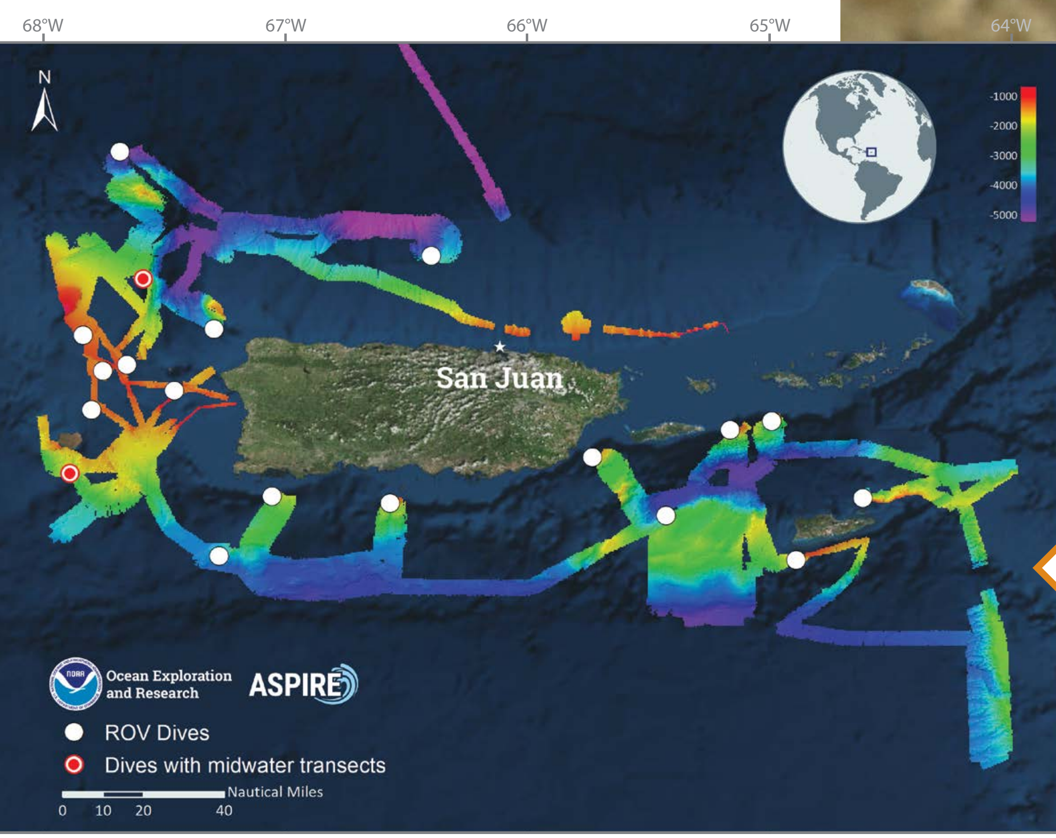
By Stacey M. Williams, Steve Auscavitch, Scott C. France, Daniel Wagner, and Derek Sowers

Between October 30 and November 20, 2018, NOAA and partners conducted a 22-day expedition aboard NOAA Ship *Okeanos Explorer* to collect critical baseline information about poorly studied deepwater areas surrounding Puerto Rico and the US Virgin Islands. The expedition used ROV dives in combination with mapping operations to increase our understanding of deep-sea ecosystems of this region, as well as to provide publicly accessible data to spur further exploration, research, and management activities.

The expedition completed 19 ROV dives ranging in depth from 250 m to 5,000 m to explore midwater, deep-sea fish, and coral habitats, submarine canyons, landslides, and more. Two dives at depths ranging from 300 m to 900 m explored the largely unknown pelagic fauna of the region. Hundreds of different species were observed, including several potentially undescribed species and range extensions. Eighty-one biological samples were collected, 19 of which represent either range expansions or potential new species. These samples will support studies of connectivity and biogeographic patterns across the Atlantic Ocean.

Six high-density communities of deep-sea corals and sponges were documented during the expedition. Commercially important deepwater fishes were observed on six dives, including a sighting of the queen snapper *Etelis oculatus* at a record depth of 539 m. Other noteworthy ROV observations included a translucent egg case with a catshark embryo actively swimming inside, first-time doc-

Catshark embryo actively swimming inside an egg case attached to a deep-sea coral at 250 m.



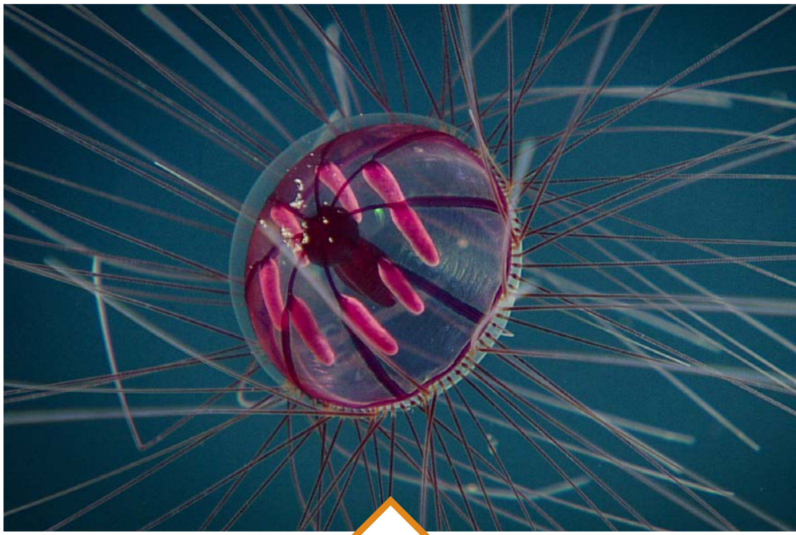
The locations of ROV and mapping operations completed during the Océano Profundo 2018 expedition.

Geological bedforms were observed over steep rocky slopes during Océano Profundo expeditions. These formations were often cracked and full of loose debris.

umentation of several species of deep-sea urchins feeding, and documentation of three species of sea stars that are likely new to science.

The expedition also investigated diverse geological features, including two submarine landslides, one of which is believed to have caused the major tsunami of 1918. Eight rock samples were collected for geochemical analyses and age dating to increase our understanding of the geological context of this region. The expedition mapped over 14,959 km^2 of seafloor, including areas around Mona Island, Saba Valley, and Engaño Canyon that had never before been mapped using high-resolution sonars.

All 14.2 TB of expedition data collected, including video and environmental data from every ROV dive, as well as mapping, oceanographic, and meteorological data, will be made publicly available through national archives. A total of 63 scientists, managers, and students from 37 institutions in seven countries participated in the expedition as members of the science team through telepresence technology. In addition to science activities, the expedition included numerous outreach and education efforts, such as bilingual coverage on the expedition website, narration of the live video feeds, ship tours, school group presentations, media articles, and live interactions. Over the course of the expedition, these avenues reached more than 7,700 people, with another 1.1 million reached by disseminating expedition content online.



The jellyfish *Crossota millsae* at 1,015 m depth, photographed during a midwater transect that explored the largely unknown pelagic fauna of the region.

With its robotic arm, ROV *Deep Discoverer* can pick up rocks from the ocean floor. *Image credit: Art Howard, GFOE*

NOAA Ship *Okeanos Explorer* 2018 Ocean Mapping Achievements

By Derek Sowers, Michael P. White, Mashkoor Malik, Elizabeth Lobecker, Shannon Hoy, and Charles Wilkins

After three contiguous field seasons of remote expeditions in the Pacific Ocean, NOAA Ship *Okeanos Explorer* transited the Panama Canal in fall of 2017 to commence new exploration efforts in the Gulf of Mexico and the Atlantic Ocean. In 2017–2018, the ship boldly continued its tenth year of ocean mapping field operations in support of exploring and characterizing the US Exclusive Economic Zone and the world ocean, mapping almost 300,000 km^2 of seafloor (an area larger than the state of Arizona), while transiting a linear ship track distance of 53,374 km. That distance represents the equivalent of circumnavigating Earth at the equator 1.3 times. Six of the 12 expeditions summarized in this supplement to *Oceanography* were fully dedicated to 24-hour per day mapping exploration. For the remaining six combined ROV/mapping cruises, mapping operations typically comprised over 50% of the at-sea mission time.

IMPROVEMENTS IN OCEAN MAPPING

Each field season of exploratory ocean mapping work brings new opportunities to upgrade equipment, software, procedures, and collaborations to improve methodologies aboard *Okeanos Explorer*. Over the past year, the mapping team implemented Sound Speed Manager, an open-source, user-friendly application for importing, editing, and exporting sound speed profile data, a fundamental requirement for obtaining high-quality multibeam sonar data (Masetti et al., 2017a; Figure 1). This application enables mappers to utilize historical salinity and temperature data from the World Ocean Atlas to improve ship-collected sound speed profiles and generate synthetic profiles when physical sampling is not possible. The software also provides an easy interface for editing and comparing oceanographic profiles of the water column and exporting GIS files or tables of all casts completed during a cruise—all of which streamlines record keeping. The application is often used in combination with SmartMap, a web GIS that helps

TEN YEARS OF OCEAN EXPLORATION MAPPING ACHIEVEMENTS

From 2008 to 2018, NOAA's Office of Ocean Exploration and Research—utilizing "America's Ship for Ocean Exploration," *Okeanos Explorer*—has mapped a cumulative 1.79 million km^2 of seafloor with the ship's multibeam sonar. If projected over the contiguous United States, this area would cover about 23% of the land area of the country (blue area in figure). A majority of this work has been completed within the US Exclusive Economic Zone—host to America's hidden and still largely uncharacterized deep-sea habitats.

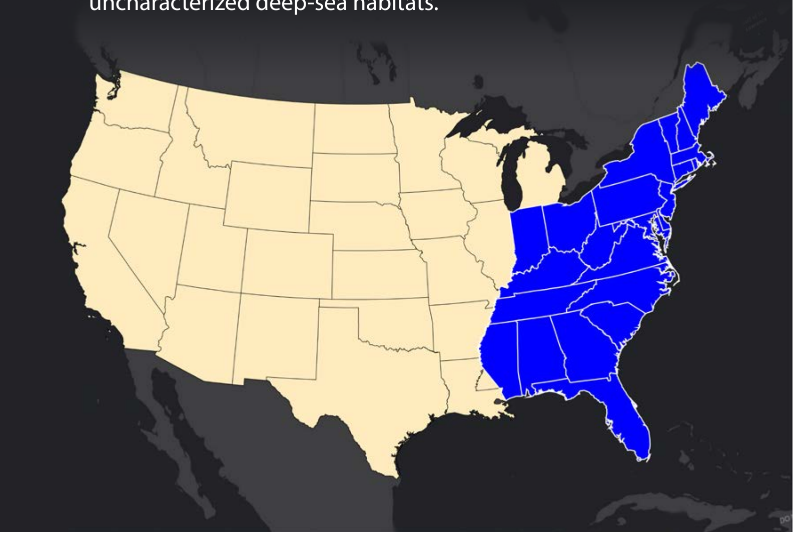


Figure 1. Sound Speed Manager enables the user to generate quick and easy plots for comparing water column sound speed profiles during a cruise. (a) An example of three expendable bathythermograph profiles plotted for day 15 of the November 2018 cruise offshore Puerto Rico, with depth on the y-axis and sound speed on the x-axis. (b) A quick Google Earth export from Sound Speed Manager of all sound speed casts completed during the cruise.

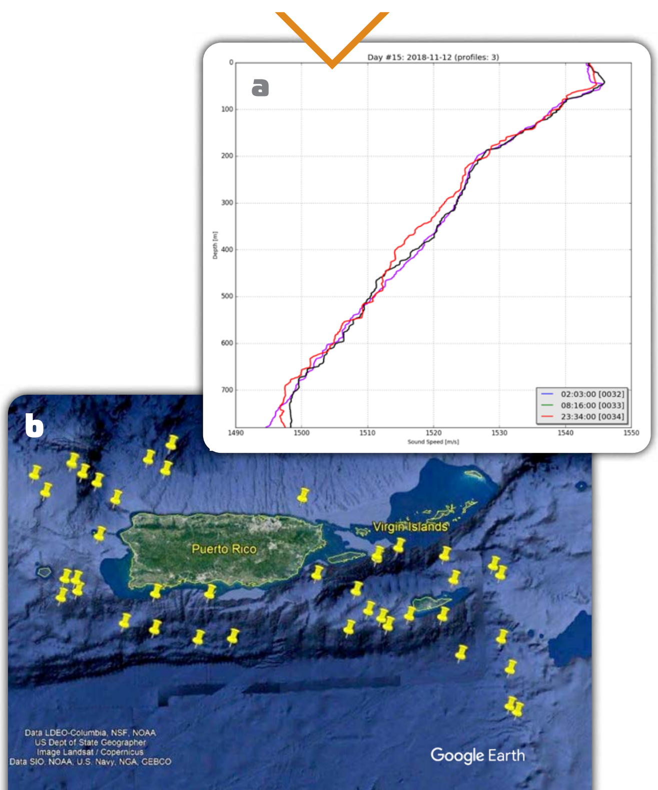
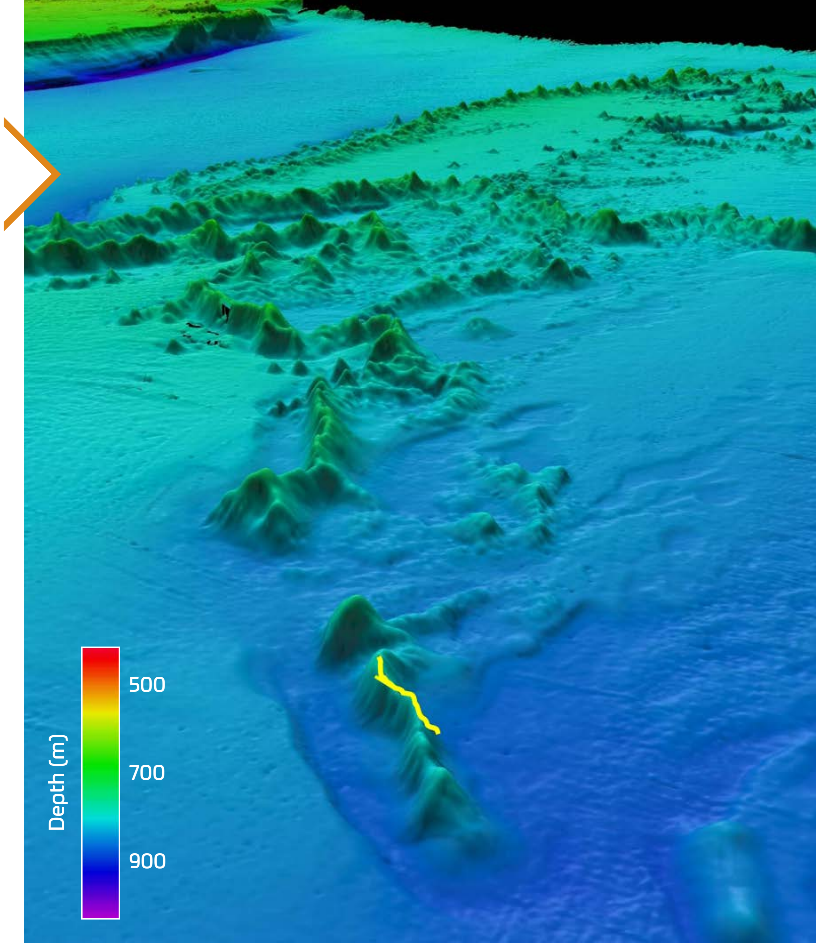


Figure 2. Linear ridge features discovered offshore due east of Savannah, Georgia, at about 800 m depth. During the 2018 Windows to the Deep expedition, ROVs explored one of these features (dubbed "Richardson Ridge") that was found to be densely covered in *Lophelia pertusa* deep-sea corals. The dive track on the ridge feature is shown in yellow (4x vertical exaggeration).



surveyors evaluate the impact of oceanographic temporal and spatial variability on hydrographic surveys (Masetti et al., 2017b). Sound Speed Manager and SmartMap are two of several free applications found within the HydrOffice framework (https://www.hydroffice.org) created through a collaborative effort of the University of New Hampshire's Joint Hydrographic Center and NOAA.

Another significant improvement to both mapping equipment and procedures involved the adoption of automated EK60 sonar calibration methods on *Okeanos Explorer*. Calibration of EK60 split-beam fisheries sonars involves suspending a metal sphere beneath the ship and moving it around within the sonar's beam to collect measurements of the strength of the echoes from the sphere. This arduous task must be done several times per year on five different transducers in order to ensure high data quality. NOAA fisheries vessel scientists developed customized equipment and software to remotely control fishing pole downriggers that move the sphere within the sonar beam. *Okeanos Explorer* has adopted this technology and was able to successfully fabricate auto calibration gear in-house and calibrate the ship's EK60 sonars with it during a shakedown cruise in the spring of 2018. This improvement is expected to decrease the amount of time and effort needed to complete the calibration.

Several improvements to ocean mapping systems aboard *Okeanos Explorer* are planned for 2019. Two Simrad EK80 wideband transceivers (38 and 70 kHz) are scheduled for installation. Wideband sonars use a frequency-modulated (chirp) signal to both send and receive a broader range of frequencies than narrowband sonars. The new wideband transceivers will enable OER to serve as a data gathering testbed for this new advancement in split-beam sonar technology and to explore the advantages of wideband EK80 data over narrowband EK60 data that the ship has been collecting since 2008. Wideband transceivers will provide improved range resolution of targets in the water column (Demer et al., 2017), may be useful in discriminating "acoustic signatures" of various water column targets (because acoustic response for many targets exhibits frequency dependence), and have proven useful in identifying prominent thermohaline layers in the water column where these features exist (Stranne et al., 2017). The ship will also benefit from an equipment upgrade to enable improved syncing of multiple sonars to avoid interference while maximizing data resolution.

MAPPING PARTNERSHIPS IN ACTION

Mapping priorities for the year were driven strongly by OER's commitment to strategic marine mapping and research collaborations with a diversity of national and international partners. For each of these initiatives, maps of the unknown ocean serve as baselines upon which further characterization work can be done. In addition to the primary driver of the ASPIRE campaign (see pages 74–75), mapping work completed during the last field season directly supported the following efforts.

Southeast Deep Coral Initiative

OER continues to be a key collaborator on the Southeast Deep Coral Initiative (https://oceanexplorer.noaa.gov/explorations/17sedci/background/sedci/sedci.html) led by NOAA's National Centers for Coastal Ocean Science. This effort is collecting new scientific information about the distribution, abundance, and diversity of deep-sea coral ecosystems within the Caribbean, Gulf of Mexico, and South Atlantic Bight. Mapping work and ROV exploration completed by *Okeanos Explorer* in this region has been fundamental to providing baseline information on the location of corals and the environmental conditions that support coral habitats (Figure 2). This information is being directly used to improve habitat prediction models for deep-sea corals and inform ocean management decisions.

DEEP SEARCH

OER is providing both financial support for, and allocation of *Okeanos Explorer* sea days to, the DEEP SEARCH project (see pages 104–105). Two *Okeanos Explorer* cruises were dedicated to mapping and ROV exploration within DEEP SEARCH priority areas off the southeast US coast.

Atlantic Seabed Mapping International Working Group

The Atlantic Seabed Mapping International Working Group (ASMIWG) emerged as an implementation group for the Atlantic Ocean Research Alliance formed between Canada, the European Union, and the United States, which resulted from the Galway Statement on Atlantic Ocean Cooperation signed in May 2013. ASMIWG is leveraging resources to collaboratively map the North Atlantic Ocean and has identified high-priority areas to pursue ship-based mapping surveys. *Okeanos Explorer* completed the first focused survey of one of these priority areas (see pages 88–89), and OER is planning extensive exploration work in the North Atlantic for 2019.

Seabed 2030

Seabed 2030 is an initiative led by the Nippon Foundation and the General Bathymetric Chart of the Oceans (GEBCO), with the goal of producing a publicly accessible definitive map of the world ocean by 2030 (https://seabed2030.gebco.net/). With the vast majority of the world's deep ocean remaining unmapped by modern surveying methods, all *Okeanos Explorer* mapping data are substantially contributing to this global effort.

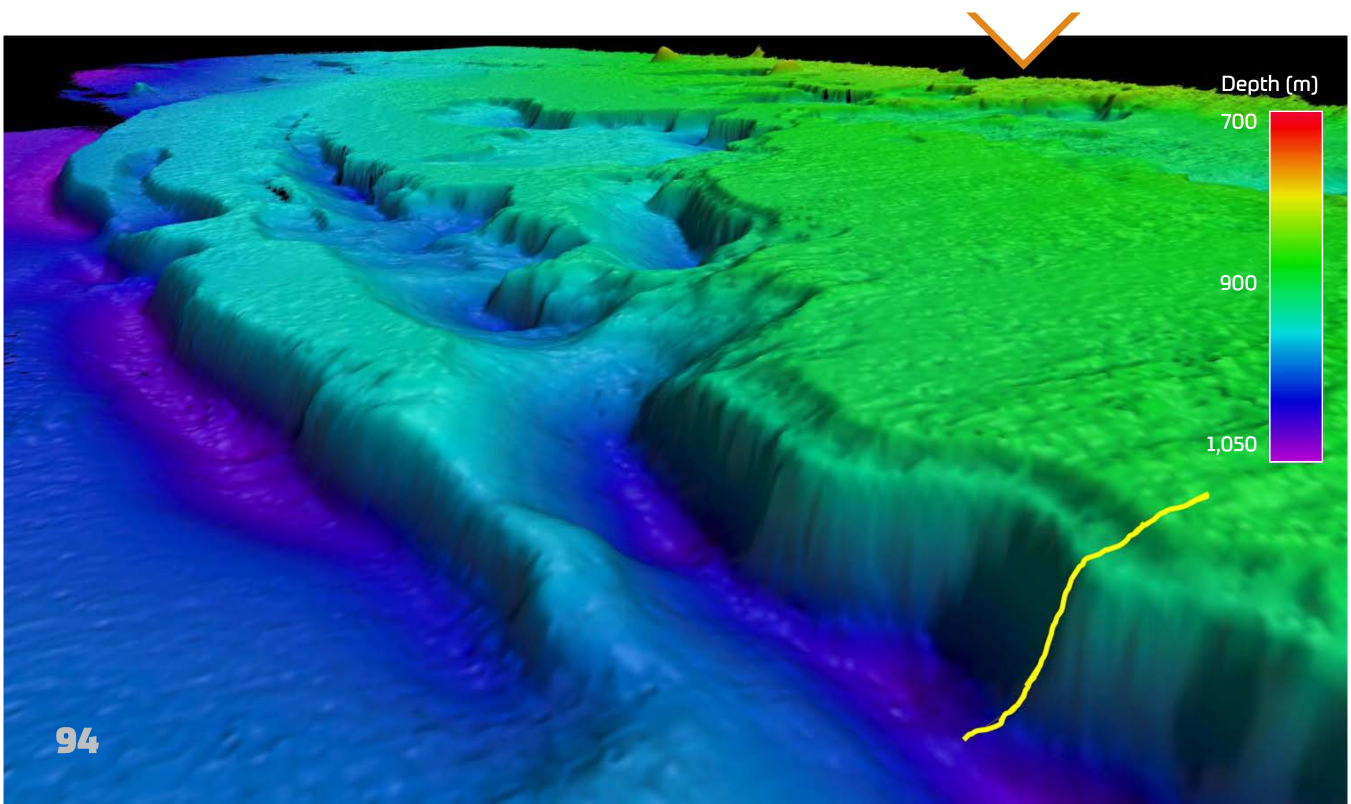
NASA's Visible Infrared Imaging Radiometer Suite

In 2018, *Okeanos Explorer* provided a platform for collecting essential ship-based measurements needed to calibrate the Visible Infrared Radiometer Suite (VIIRS) satellite ocean color measurements (https://jointmission.gsfc.nasa.gov/viirs.html). VIIRS provides remote-sensing data that are critical for assessing broadscale sea surface temperatures, harmful algae blooms, risk to coral habitats, ocean productivity, and weather forecasts.

CRITICAL MAPPING SUPPORT OF SUCCESSFUL ROV DIVE OPERATIONS

With half of the expeditions last year spent as joint ROV/mapping cruises, mapping data played a critical role in ensuring safe and effective ROV dive operations. Interesting features (e.g., seamounts, mounds, canyons, potential shipwrecks) identified through mapping efforts typically serve as the primary basis for selecting ROV dive targets (Figure 3). Mapping team support is particularly important when the need arises to change a dive site at the last minute due to unfavorable wind, weather, or current conditions. This happened with some regularity for ROV dives in the vicinity of the strong Loop Current in the Gulf of Mexico and in the Gulf Stream current offshore of the southeast US

Figure 3. ROV planning scene for Dive 8 (Richardson Scarp) of the 2018 Windows to the Deep expedition offshore of the southeast US coast. This dive track (yellow line) was mapped the night before the dive was conducted, with the science team selecting the biggest and steepest slope in the area to examine the geology and maximize chances to observe attached fauna on hard substrates.



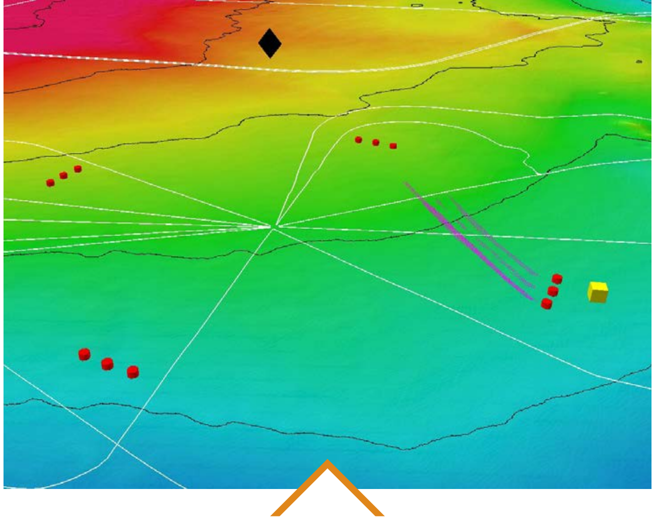
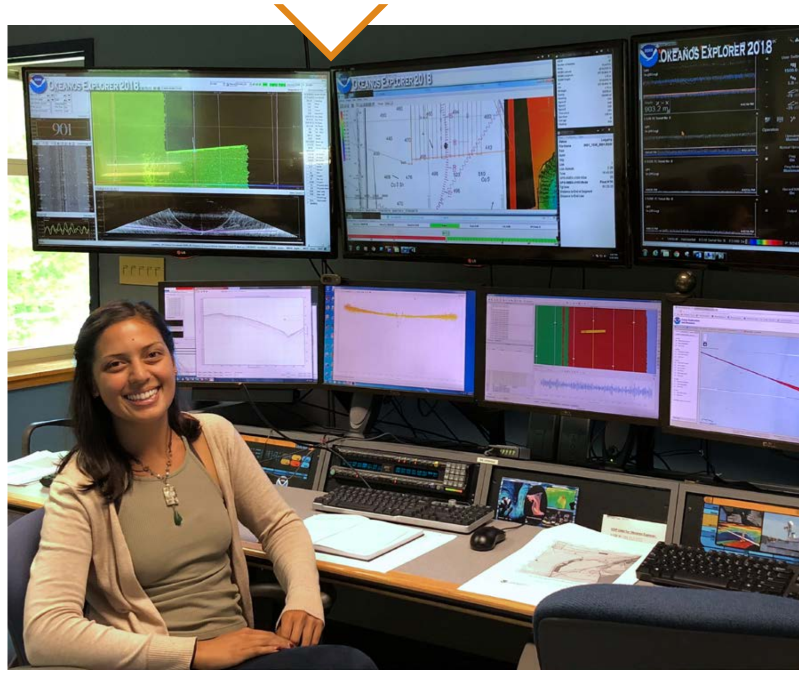


Figure 4. Three-dimensional ROV planning scene for an archaeology dive in the Gulf of Mexico in 2018. The yellow square represents the archaeological dive target in close proximity to mooring anchor points (red circles) and anchor chains (shown in pink, as picked from multibeam water column backscatter data) for a floating oil rig (black diamond). Oil pipeline routes are shown as white lines, with 250 m bathymetric contours shown as black lines. This visualization was built using QPS Fledermaus marine GIS software.

Figure 5. Explorer-in-Training Mikia Weidenbach stands watch, ready to process multibeam sonar data on shore during the mapping leg of the 2018 Windows to the Deep expedition.



coast. Mapping data are quickly utilized to generate a new dive location plan to meet the desired scientific objectives while optimizing ship and ROV orientations relative to wind and current.

Careful use of mapping data is particularly important when planning an ROV dive in the vicinity of morphological features or anthropogenic structures with the potential to entangle or damage the ROVs. Dives are planned to avoid known (charted) subsea cable routes and other man-made obstructions (Figure 4), as well as confined canyons that could be hazardous in the event of equipment or power failures.

ADVANCING THE TELEPRESENCE MAPPING PARADIGM

OER continued to explore the benefits of telepresence-enabled mapping ("telemapping") cruises on *Okeanos Explorer*. A robust computer network and a high-bandwidth ship-to-shore satellite connection enables the OER mapping team to lead mapping cruises from shore. Data collection is overseen at sea by a small team of experienced survey contractors, while high-level planning and decision-making can be handled by the onshore expedition coordinator. Using computer networks and specialized software at the Exploration Command Center at the University of New Hampshire, multibeam data sets are downloaded from the ship for onshore data cleaning and processing that has historically been done at sea. Onshore students (see Explorer-in-Training program information on pages 114–115) stand watch to monitor the ship's sonar performance in real time (Figure 5), as well as to post-process multibeam, subbottom, and water column sonar data to generate value-added mapping products that can be shared rapidly with the broader scientific community. Successful telemapping surveys were conducted in this manner for the ship's long transit from Hawai'i to Panama, and for a mapping cruise off the southeast US coastline in support of DEEP SEARCH project priority areas.

Given the success of these efforts, telemapping operations have been prototyped and can now be replicated on other offshore or shore-based scientific platforms with comparable satellite bandwidth and data sharing capabilities. Live streaming of sonar acquisition screens provides real-time monitoring of survey operations, while processed sonar files (and derivative products such as cleaned bathymetric grids) are produced on shore and made publicly available within 24 to 48 hours of data collection. This paradigm has great potential to expand the number of shoreside participants in a mapping survey by providing exceptional educational opportunities for marine scientists, ocean mappers, and interested citizen scientists. While ocean mapping is often somewhat of a "behind the scenes" aspect of ocean exploration, telemapping could provide a mechanism for engaging more people and delivering mapping products to scientists more quickly and directly than has been conventionally possible.

Mapping and Exploration in Support of the US Extended Continental Shelf Project

By Margot Bohan and US ECS Project Partners

The US extended continental shelf (ECS; Figure 1) is considered a significant maritime zone, comprised of valuable petroleum, mineral, and "sedentary living marine resources." Determining the actual US shelf limits requires collection and analysis of data that describe the depth, shape, and geophysical characteristics of the seabed and subseafloor. While the demand to harvest deep ocean resources is still relatively low, a window of opportunity exists to have these ECS data serve as a foundation for collecting additional physical, biological, and chemical measurements that, in turn, will improve our insights about the extent and value of the marine resources in these frontier ocean regions.

The US ECS Project (https://www.state.gov/e/oes/ocns/opa/ecs/) is thought to be among the largest and most significant cross-agency marine mapping efforts ever undertaken by the United States. Since 2007, NOAA and a consortium of 13 other US agencies have been formally collaborating to gather and analyze ECS survey data, legal data, and seafloor samples to determine the outer limits of the US continental shelf. Aside from Japan, the United States has likely collected more data for its ECS Project than any other country, and it has attained the bathymetric coverage it needs for the Project, unless, in a very unlikely case, future analyses indicate otherwise. NOAA's Office of Ocean Exploration and Research, Office of Coast Survey, and National Centers for Environmental Information have been critical partners responsible for bathymetric mapping of the seafloor and analyzing and managing project data, along with key sub-seafloor and legal affiliates at the US Geological Survey and the US Department of State.

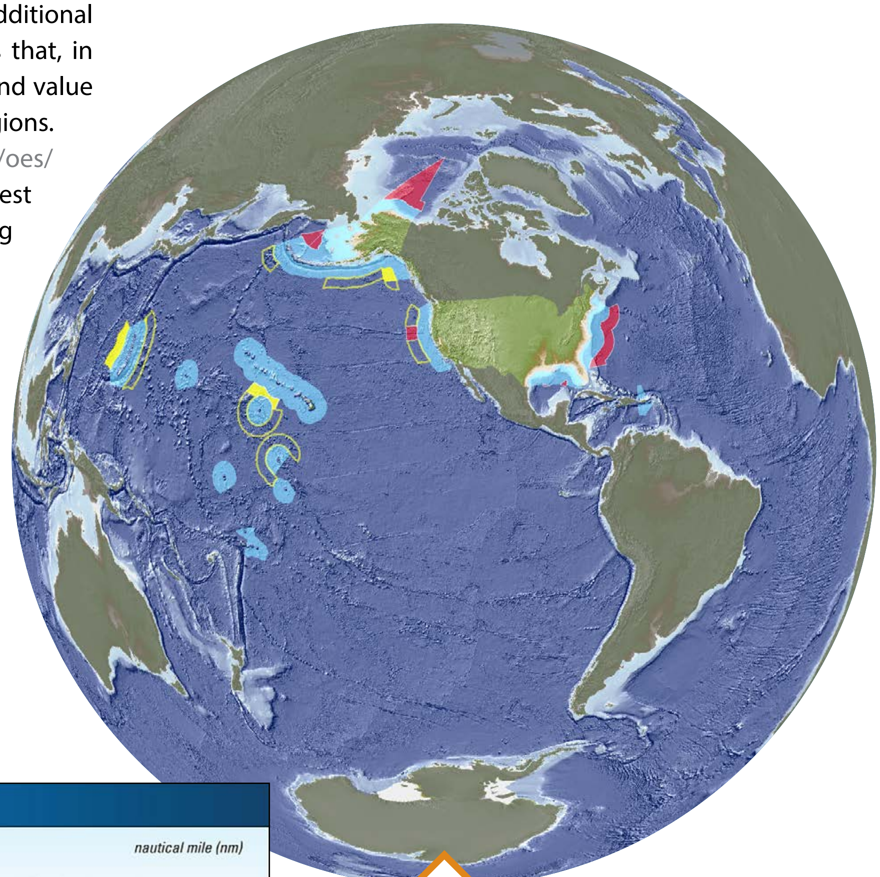


Figure 2. Global Perspective of US Extended Continental Shelf Project survey coverage (in yellow, blue, and red). *Image credit: D. Hutchinson, USGS*

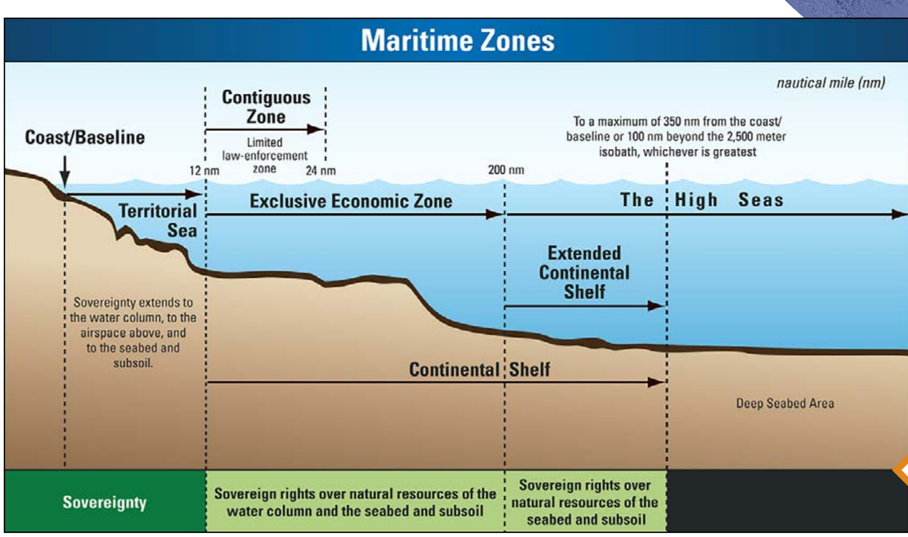


Figure 1. Under the United Nations Convention on the Law of the Sea (https://www.state.gov/e/oes/lawofthesea/), the continental shelf is that part of the seabed over which a coastal State exercises sovereign rights with regard to the exploration and exploitation of natural resources, including oil and gas deposits, as well as other minerals and biological resources of the seabed. The legal continental shelf extends out to a distance of 200 nautical miles from its coast, or further if the shelf naturally extends beyond that limit.

All told, the US ECS Project has carried out 36 wide-ranging surveys, encompassing more than 900 days at sea (Figure 2). Over 3.3 million square kilometers (967,810 nm^2) of bathymetric data (equivalent to a land area the size of Alaska, California, Texas, Montana, and Kentucky combined; Figure 3) and over 27,000 linear kilometers of seismic data (comparable to the distance from New York City to the South Pole) have been collected.

All ECS Project data and products are available in an open access archive (https://www.ngdc.noaa.gov/mgg/ecs/cruises.html), with a digital infrastructure built by the National Centers for Environmental Information. These archived data already are yielding new seafloor maps that display, in high-resolution, previously unknown deep-sea features such as seamounts, submarine volcanic terrain, seafloor channels, faults, and submarine landslide scarps.

They are expanding our grasp of the morphology and geology along our continental margins in the deep-sea frontier and providing a rich baseline for setting future exploration, research, and resource management priorities. Undoubtedly, increased understanding of this maritime zone will improve insights into the extent and value of the resources in these frontier ocean regions, and will guide NOAA and its agency partners to make informed and sustainable management decisions that ultimately will influence the strength of our nation's security and economy.

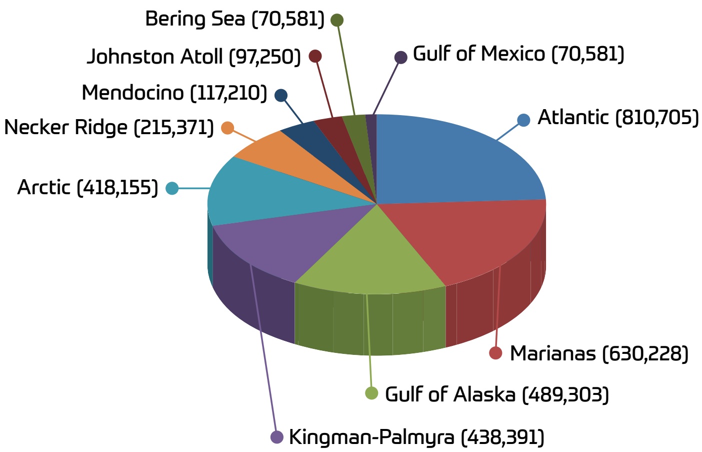
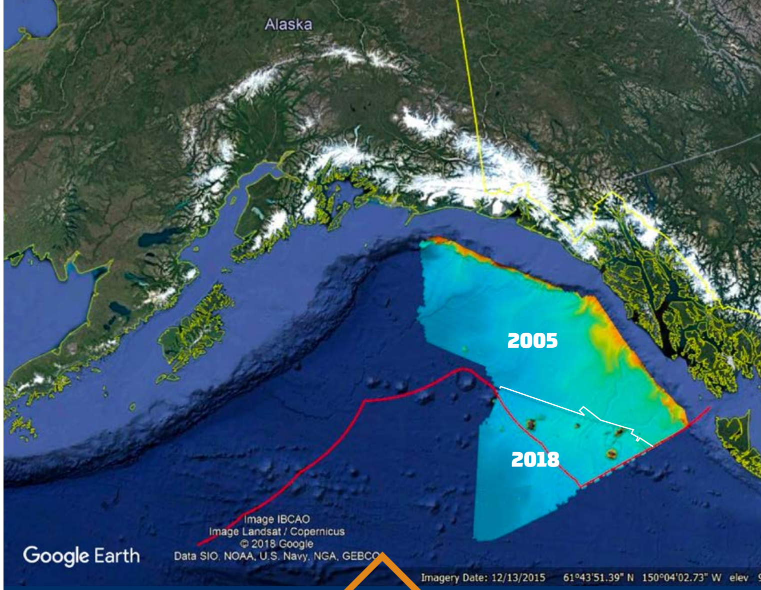


Figure 3. Areas mapped (km^2) for the US ECS Project, FY02–18.



Combined bathymetric coverage from 2005 and 2018 R/V *Kilo Moana* cruises in the Gulf of Alaska (Gardner and Mayer, 2005). *Image credit: UNH/CCOM/JHC*

US ECS CRUISE TO THE GULF OF ALASKA AND EASTERN PACIFIC

By Andy Armstrong

NOAA's Office of Ocean Exploration and Research, in collaboration with scientists from the US Geological Survey, NOAA's Office of Coast Survey, and the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center (UNH/CCOM/JHC), conducted a multibeam and subbottom profiler survey aboard R/V *Kilo Moana* from July 1 to August 3, 2018, in the eastern Gulf of Alaska in water depths of approximately 500 m to 4,000 m. This cruise followed up on earlier NOAA bathymetric surveys and USGS seismic surveys in the region.

Important morphologic and geologic data were collected that will allow the US Extended Continental Shelf Project to determine whether or not the United States has an entitlement to extended continental shelf in this area, pursuant to Article 76 of the Law of the Sea. Complete multibeam coverage and coincident subbottom profiles addressed the processes of sediment erosion, transport, and deposition in this high-latitude setting adjacent to a transcurrent plate boundary.

The 22-day survey mapped a total area of 98,777 km^2 (28,799 nm^2). Specifically, the survey collected data in the middle and lower portions of the Baranof Fan complex, including regions where the fan interacts with the Kodiak-Bowie Seamounts and with the abyssal Pacific seafloor.

Ancillary to the primary project objectives, Argo floats were deployed during the northern portion of the ship's transit from Honolulu to the Gulf of Alaska.

Mapping Deepwater Areas off the Southeast US in Support of the Extended Continental Shelf Project

By Michael P. White

As an integral partner on the US Extended Continental Shelf Project and in support of ECS Project objectives, OER continues to leverage NOAA Ship *Okeanos Explorer* time to acquire data to identify the extent of the continental shelf beyond the US 200 nautical mile limit, in accordance with the Convention on the Law of the Sea. In 2018, the "Mapping Deepwater Areas off the southeast United States in Support of the Extended Continental Shelf Project" focused on a priority area approximately 400 nautical miles east of Cape Canaveral, Florida, known as the Blake-Bahama Ridge area. From October 3 to October 24, the expedition mapped over 58,000 km^2 of largely unexplored deep seafloor (Figure 1).

TARGETING OF EXTENDED CONTINENTAL SHELF PRIORITY AREAS

Much of the bathymetric data from the Blake-Bahama Ridge area will assist the United States in establishing the outer limits of its continental shelf in this region. In addition, the United States and the Commonwealth of The Bahamas are engaged in maritime boundary negotiations, including with respect to the Blake-Bahama Ridge area. The two sides have a mutual interest in locating the base of the continental slope in this area. Thus, in addition to strengthening US documentation establishing the outer limits of the continental shelf in the Blake-Bahama Ridge area, this mapping survey will help inform ongoing boundary negotiations between the two nations. Exploration mapping operations prioritize subsets of these priority areas for which there are no modern sonar data.

LEVERAGING EXISTING DATA

Like any OER expedition on *Okeanos Explorer*, existing data were examined to evaluate what mapping data (if any) were available for the operating areas. Data mining can involve a variety of steps, from accessing publicly available data sets, to working with regional hydrographic partners and networking within the ocean mapping community. Once the data are gathered, researchers inspect them, along with their metadata, to determine quality. The ECS priority area included transect mapping data and adjoined existing ECS data sets. For this cruise, public multibeam bathymetry was accessed from NOAA's National Centers for Environmental Information using the Bathymetric Data Viewer and AutoGrid services. Previous ECS data, also publicly available, were gathered from researchers at the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center.

SYSTEM ACCEPTANCE TESTS

In September 2018, a replacement EM 302 multibeam echosounder receive array and EK60 18 kHz single-beam echosounder transducer were installed on *Okeanos Explorer*. To ensure acquisition of quality data by these systems, the mission team began the expedition with system acceptance tests (SATs) east of Hudson Canyon. These shakedown and calibration operations included a multibeam patch test with verification lines, EK60 backscatter calibration using standard reference spheres for all frequencies and pulse lengths, speed noise testing lines for both sonars, and CTD casts to full depth. After the completion of the successful SATs, a small boat transfer of personnel and technical equipment occurred at Point Judith, Rhode Island, after which the ship began its transit down to the ECS priority mapping areas.

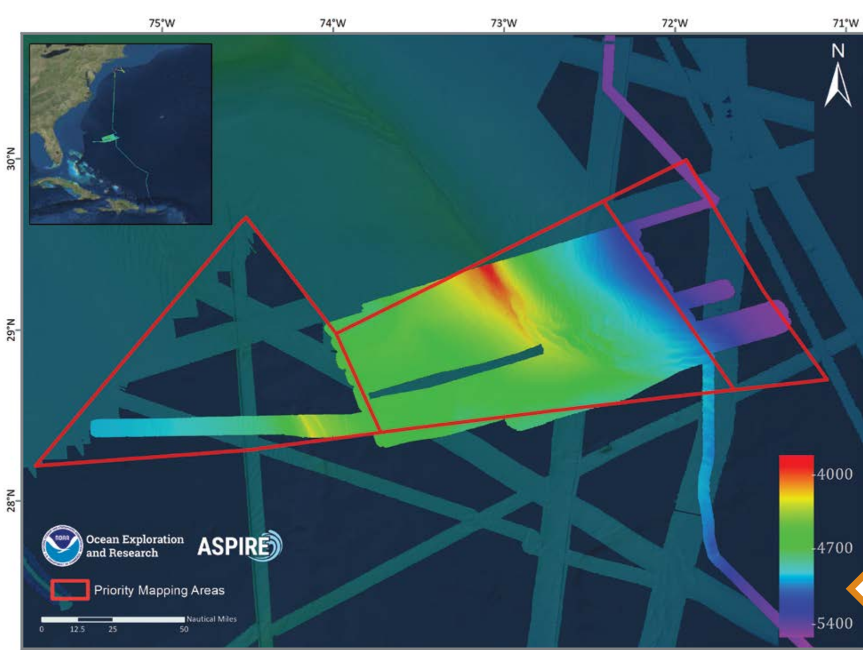


Figure 1. NOAA Ship *Okeanos Explorer* collected critical bathymetric data in a largely unknown deepwater region northeast of the Bahamas. Three adjacent areas designated as high-priority areas by the US ECS Project Office were targeted for surveying.

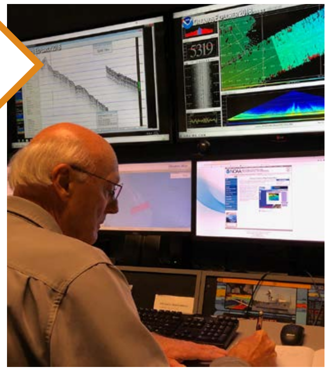


Figure 2. Andy Armstrong, Co-Director of the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center and advisor to the US ECS Project, monitors the live mapping acquisition screens at the Exploration Command Center at the CCOM/JHC. *Image credit: UNH/CCOM/JHC*

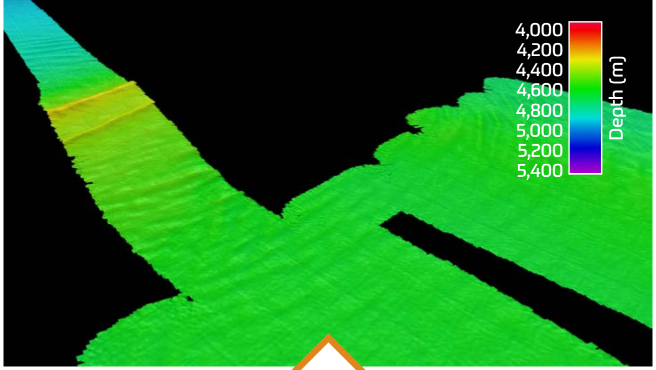


Figure 3. To determine the extent of the continental shelf, a base of slope (BOS) must be identified. The BOS is the demarcation between the continental shelf and the abyssal plain. During the cruise, onshore experts monitoring the live sonar acquisition screens communicated with the offshore lead to extend the survey lines on multiple occasions, until a potential BOS was observed in the multibeam and sub-bottom sonar systems.

TELEPRESENCE-ENABLED MAPPING

Through telepresence, the onboard mission team was able to leverage 24-hour onshore expertise and guidance during the expedition (Figure 2). Throughout the cruise, three live feeds of video were streamed from ship to shore, displaying sonar acquisition and processing screens, the ship's location, and deck operations. These video streams were monitored by members of the scientific community on shore in near-real time. In addition to the live streams, raw sonar data and full resolution field processed products were pushed to shore via the high bandwidth connection. The mapping products and data were assessed by offshore and onshore scientific leads and used to make adjustments in mapping coverage and locations (Figure 3). On multiple occasions, real-time ship-to-shore communications resulted in altering the ship's course to achieve mission objectives.

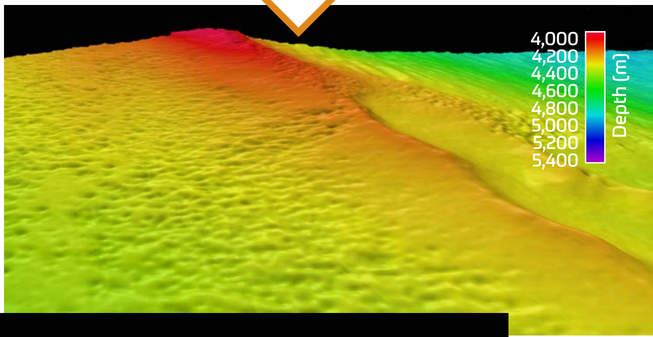
SUMMARY OF FINDINGS

This third expedition in support of the ASPIRE campaign, a major multi-year, multi-national collaborative field program, focused on increasing knowledge and understanding of the North Atlantic Ocean. These efforts extended seafloor mapping coverage in the US Exclusive Economic Zone and international waters in support of Seabed 2030. The expedition acquired and processed over 29 gigabytes of multibeam seafloor bathymetry and backscatter data, 110 gigabytes of multibeam water column data, 11 gigabytes of single-beam sonar data, 4 gigabytes of sub-bottom sonar data, and 85 expendable bathythermograph profiles. These data were made available in real time to support the expedition, and were made publicly available for analysis through the National Centers for Environmental Information after the expedition.

Exploratory mapping operations revealed numerous types of bedforms and soft sediment features, whose morphology can help scientists characterize bottom-water flow and erosional/depositional regimes in this region of the Atlantic Ocean (Figure 4). Scientists tracking the cruise on shore observed hyperbolic echoes in the subbottom data that are likely to be caused by sedimentary furrows created by deep current flow (Figure 5).

During the expedition, OER offered at-sea training to four early career scientists and recent graduates via its Explorer-in-Training (EiT) program. These EiTs learned to process varying onboard data types and to field custom product requests for these processed data from onshore participants. Since the cruise, one EiT has been hired as a hydrographic analyst for NOAA and one was able to leverage this and other experiences for admission to a deep-sea biology doctoral program.

Figure 4. Soft sediment features between 700 m and 900 m wide observed in the survey area. Sediments with a variety of grain sizes and cohesiveness respond to depositional and erosional process differently, leading to complex morphological features.



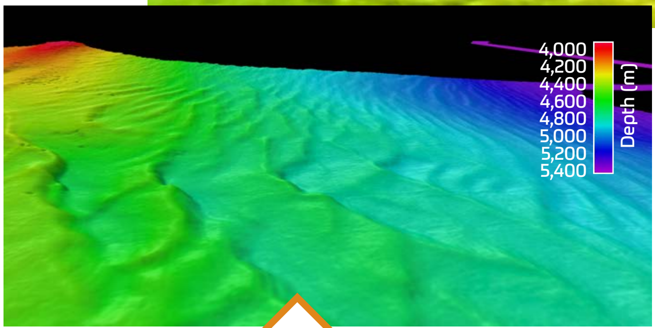


Figure 5. Longitudinal bedforms, likely to be sedimentary furrows, revealed in the multibeam bathymetry. These bedforms range in height from 40 m to 145 m as measured from trough to crest. Similar furrows have been detected by their distinctive echo patterns on 3.5 kHz echosounders (Flood, 1983).

Technology and Ocean Exploration

By Nick Pawlenko

We do what Jules Verne only dreamed of!

– Tim Gallaudet, PhD, Rear Admiral, U.S. Navy (Ret.),
Assistant Secretary of Commerce for Oceans and Atmosphere
Deputy NOAA Administrator

It's an exciting time for technology and ocean exploration when technology featured in science fiction novels is being realized and ocean exploration goals once thought to be inconceivable are now achievable. Exploring the vast, unknown ocean is a daunting task—we still have explored less than 10% of it. The digital age promises to unlock many of the ocean's secrets and enable some amazing discoveries.

In a world that has become increasingly connected, more and more ocean scientists are making discoveries sitting behind their computer monitors rather than at sea on ships. Many research vessels now sail with more engineers and technicians than researchers; scientists remain on shore and participate in near-real time via telepresence technology. Latency has improved such that scientists no longer need to travel to Exploration Command Centers for an Internet2 connection. They can now participate from their smartphones while traveling. Advances in augmented and virtual reality, holograms, and visualization will continue to push this experience from shore. Perhaps Exploration Command Centers of the future will fully immerse scientists in an experience, where they walk among digital coral gardens of the deep in real time. The technology is now available, and scientists are already leveraging these tools.

We are also becoming more connected by the Internet of things, whether it is in our personal lives, from connected doorbells and vehicles, to appliances that can send updates and exchange data between devices. It only makes sense this trend will continue to below the ocean's surface. With advances in sound and optic communications, industry and academia are already pushing data rates and distances for underwater communications. Semi-autonomous vehicles could work in tandem with ROV systems or other platforms to increase our exploration footprint and also provide an overview for baseline site characteristics. These connected vehicles working together and connected to shore will be a force multiplier when it comes to exploring the ocean.

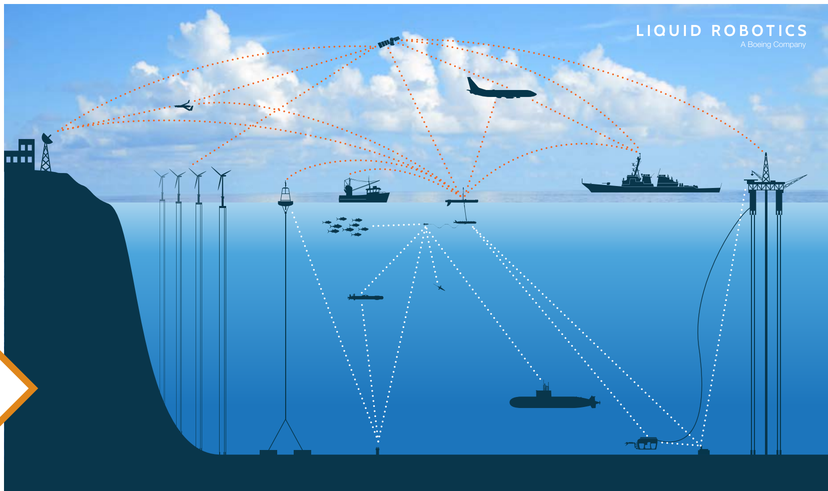
Connected robotic systems could collect thousands of hours of data in relatively short time periods. If we are collecting more data, faster, then we will need to analyze and manage the data on pace with collection efforts. Fortunately, artificial intelligence, machine learning, citizen science interfaces, and image analysis technologies are improving every year and are already being leveraged to systemize data collection. These tools will allow scientists to focus on discoveries and minimize time sorting through gargantuan data sets. Data managers and their systems will increasingly play a very important and active role in exploring the ocean.

Explorers like Jacques Cousteau, who developed the Aqua-Lung and invented an underwater camera, continue to shape and influence generations of explorers. Significant ocean explorers of the twenty-first century will also be those who push and leverage technology for ocean exploration.

Anything one man can imagine;
other men can make real.

– Jules Verne

Microsoft HoloLens conceptual image for augmented or mixed reality, used with permission from Microsoft.



Digital ocean. *Courtesy of Liquid Robotics*

Mapping Rhode Island's Historic Submarines Using Synthetic Aperture Sonar

By Rod Mather, Jeff Bartkowski, and Nick Pawlenko

A team from the NOAA's Office of Ocean Exploration and Research, Kraken Robotic Systems Inc., and the University of Rhode Island Applied History Lab conducted a project to image Rhode Island's sunken historic submarines using a new synthetic aperture sonar system. During the first phase of the project, three of the four submarines were mapped—USS *G-1*, USS *L-8*, and German *U-853*—along with *U-853's* last World War II victim, a merchant ship called *Black Point*.

This technology demonstration came about through a Cooperative Research and Development Agreement between OER and Kraken Robotic Systems Inc. This partnership combines Kraken's technology capability to design and manufacture advanced mapping and imaging systems with OER's ability to test and evaluate that technology for ocean exploration and marine archaeology applications. Technologies such as synthetic aperture sonar provide more detailed imagery than the traditional side-scan sonar often used to image archaeological sites. High-resolution imagery enables more accurate assessment, characterization, and understanding of the ocean environment and of our marine cultural heritage.

The project used the Kraken Active Towfish (KATFISH™), which includes Kraken's Miniature Interferometric Synthetic Aperture Sonar (MINSAS) system. KATFISH™ is designed to be portable and can be quickly installed and removed from vessels as needed. The system collects three-dimensional bathymetry and ultra-high-resolution seabed imagery in real time, allowing researchers to analyze imagery during the survey and make mission changes on the fly.

U-853 was a type IXC/40 German submarine launched on March 11, 1943, and commissioned June 25 of that same year. The submarine measured 251 feet, 10 inches in length; 22 feet, 6 inches in the beam; and drew 15 feet, 4 inches. The submarine was equipped with four torpedo tubes in the bow and two in the stern, and also carried a 4.1-inch deck gun and two anti-aircraft guns. *U-853* was sunk in Rhode Island Sound in May of 1945 after sinking the collier ship *Black Point*.

More information can be found on the OER website: https://oceanexplorer.noaa.gov/technology/development-partnerships/18kraken/welcome.html

High-resolution synthetic aperture sonar image of the German *U-853* showing the submarine largely intact. *Image courtesy of Kraken Robotic Systems Inc.*

Kraken KATFISH™ and Tentacle™ intelligent winch system aboard R/V *Discovery. Image courtesy of Kraken Robotic Systems Inc.*

Gulf of Mexico Technology Demonstration

By Michael Twardowski, Fraser Dalgleish, Thomas Coleman, Brian Amaral, Brian R.C. Kennedy, Nick Pawlenko, Amanda N. Netburn, and Chris Beaverson

The Gulf of Mexico Technology Demonstration, held March 23 to April 5, was the first operational cruise for NOAA Ship *Okeanos Explorer* in 2018. Three technologies were demonstrated during this cruise as part a new effort to provide ship time dedicated to testing emerging technologies that may advance ocean exploration.

MIDWATER PROFILING SYSTEM

In partnership with the Cooperative Institute for Ocean Exploration, Research & Technology (CIOERT) at Florida Atlantic University's Harbor Branch Oceanographic Institute, a new midwater profiler system was tested aboard *Okeanos Explorer*. This technology is used to study the "twilight zone" of the ocean, the region below the surface where organisms such as fish, squids, and zooplankton live in a low-light environment because it enhances their survival. Every evening, these organisms undergo the largest migration on the planet, swimming hundreds of meters from the depths to the surface ocean to feed through the night. The system is designed to explore the distributions and dynamics of organisms ranging from microbes (microns) to large nektons (meters) in mesopelagic zones of the ocean (from about 200 m to 1,000 m depth).

The CIOERT team integrated numerous technologies into a test package, including a Spatial Plankton Analysis Technique (SPLAT) camera, imaging lidar, and digital holographic microscopy (Figure 1). The newly developed SPLAT camera for detecting bioluminescence consists of a suspended screen imaged onto a special low-light camera. As the sensor cage descends, bioluminescent organisms hit the screen and glow blue (Figure 2). The size, shape, and duration of the glowing light allow some level of classification of organism type. The imaging system, which noninvasively monitors marine life when compared to typical camera and strobe systems, is a game changer. At the finest scales, we are making measurements of the scattering properties of microbial particles and collecting holographic imagery of these particles for classification with a prototype system (Figure 3).

Testing new technologies (in some cases for the first time) can be challenging, requiring a lot of troubleshooting and patience. This midwater profiling system was very much a success due to a terrific team of dedicated postdocs and engineers.

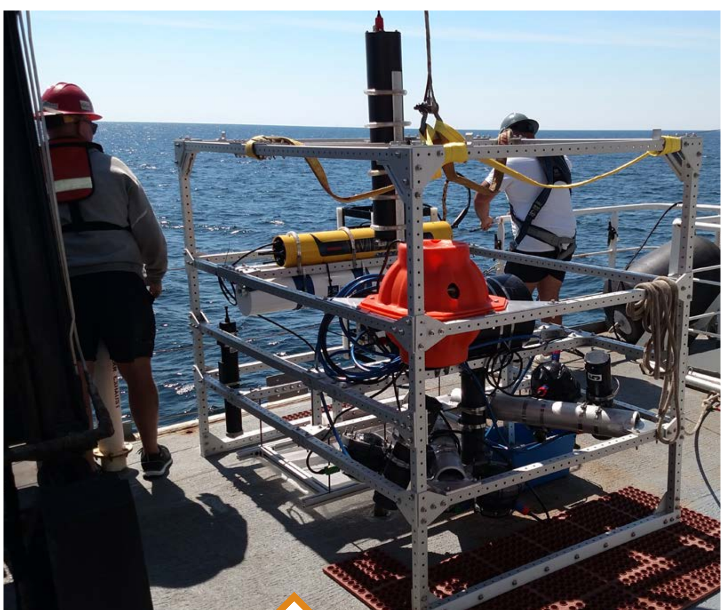


Figure 1. Photo of the new a new midwater profiler system that was tested during the emerging technology demonstration cruise aboard NOAA Ship *Okeanos Explorer*. *Image credit: Florida Atlantic University*

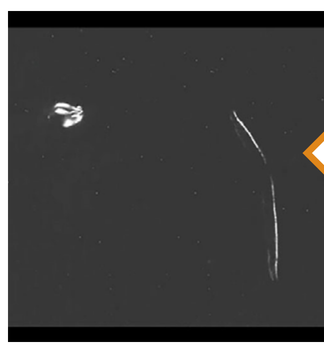


Figure 2. A SPLAT camera image of a ctenophore (comb jelly) and a chaetognath (arrowworm). *Image credit: Florida Atlantic University*

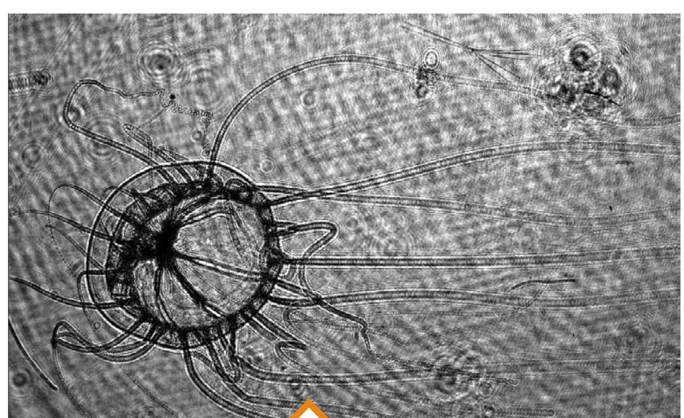
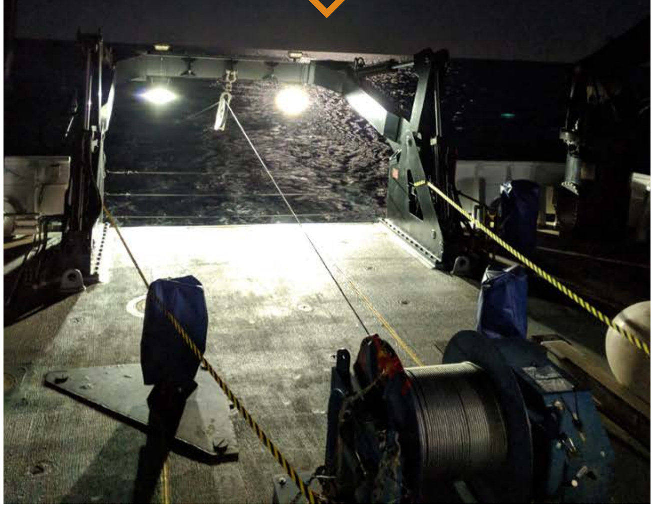


Figure 3. Holocam high-resolution image of a Rhopalonematid. *Image credit: Florida Atlantic University*

TECHNOLOGY DEMONSTRATION MAJOR GOALS

- Understand tow cable behavior and effects on the integrated optical fibers
- Test multiple distributed temperature sensing (DTS) calibration techniques to allow for optimized DTS measurements to be collected
- Determine the performance of distributed acoustic sensing on a towed cable
- Evaluate the spatiotemporal temperature data when compared to traditional measurement techniques
- Identify improvements that can be made to the deployment methods and system hardware

Figure 4. Towed cable array the night of March 31, 2018.



INSTRUMENTED TOW CABLE

The second project was in partnership with the Naval Undersea Warfare Center, the Global Foundation for Ocean Exploration, and Silixa to test a new technology called the Instrumented Tow Cable (Figure 4). This cable looks similar to a standard CTD cable and has the same strength, but by taking advantage of advanced fiber optics, the Instrumented Tow Cable is able to measure temperature along the entire cable. This technology is a vast improvement in ocean sensing and may be able to even record the passing of internal waves in real time.

Temperature and acoustic data were collected from a 1,300 m fiber optic tow cable using distributed temperature sensing (DTS) and distributed acoustic sensing (DAS). DTS permits measurement of temperature at all locations along a fiber optic cable simultaneously, with submeter spatial resolution (Figure 5). Temperature profiles can be recorded as rapidly as every few seconds, and for longer measurement times, temperature resolution can be as fine as 0.01°C.

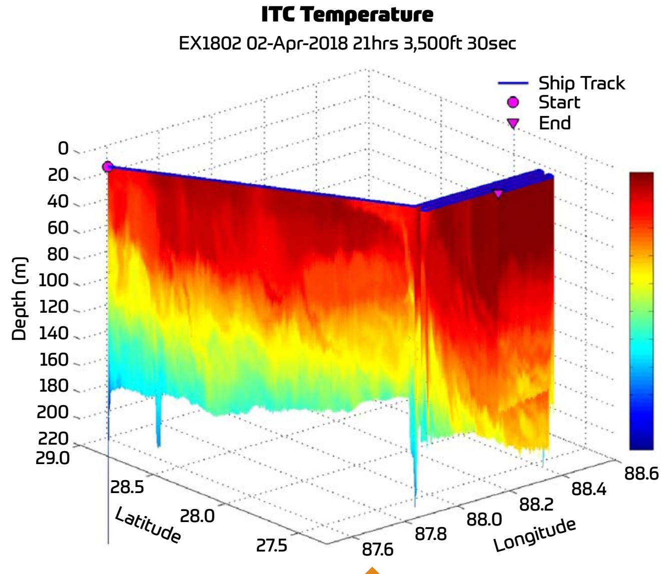


Figure 5. Instrumented Tow Cable (ITC) temperature data. *Image credit: Naval Undersea Warfare Center*

Data collected using this temperature profiling method will allow a more detailed understanding of temperature distributions with depth and will permit measurement of dynamic processes that cannot be captured using alternative techniques. In addition to DTS, DAS can act as a continuous array of hydrophones, with the potential to monitor acoustics (sound) from a towed array. Both techniques are being simultaneously tested using multiple optical fibers within the tow cable. Analyses of the data sets will provide a baseline understanding of how best to incorporate distributed sensing into towed cables and will demonstrate the capability of the techniques for oceanographic purposes.

SIMRAD EK80

The final project was in partnership with the University of New Hampshire Center for Coastal and Ocean Mapping to utilize a new Simrad EK80 split-beam sonar in an operational environment and test its seep detection ability in conjunction with *Okeanos Explorer*'s multibeam and EK60 split-beam sonars. EK80 wideband split-beam echosounders collect data over a broader range of frequencies, allowing scientists to gather more information about various objects in the water column. The data collected were used to detect gas bubbles and organisms in the water column at a high resolution. Due to its success on this expedition, the split-beam echosounder is being incorporated into standard *Okeanos Explorer* operations in 2019.

All three technology demonstrations were very successful, and collected high-quality data in new ways to advance ocean exploration.

DEEP SEARCH: Deep Sea Exploration to Advance Research on Coral/Canyon/Cold Seep Habitats

By Erik Cordes, Amanda Demopoulos, Michael Rasser, and Caitlin Adams

Now in its second year, the Deep Sea Exploration to Advance Research on Coral/Canyon/Cold seep Habitats (DEEP SEARCH) project had a successful 2018 field season with three separate efforts on NOAA Ship *Okeanos Explorer,* R/V *Atlantis*, and R/V *Brooks McCall*.

PROJECT BACKGROUND

Led by the Bureau of Ocean Energy Management, the US Geological Survey, and NOAA's Office of Ocean Exploration and Research, and sponsored by the National Oceanographic Partnership Program, DEEP SEARCH is an interagency partnership to explore and characterize sensitive US Mid- and South Atlantic deep-sea habitats. The study brings together scientists from six US academic institutions and five USGS science centers for a multiyear research program.

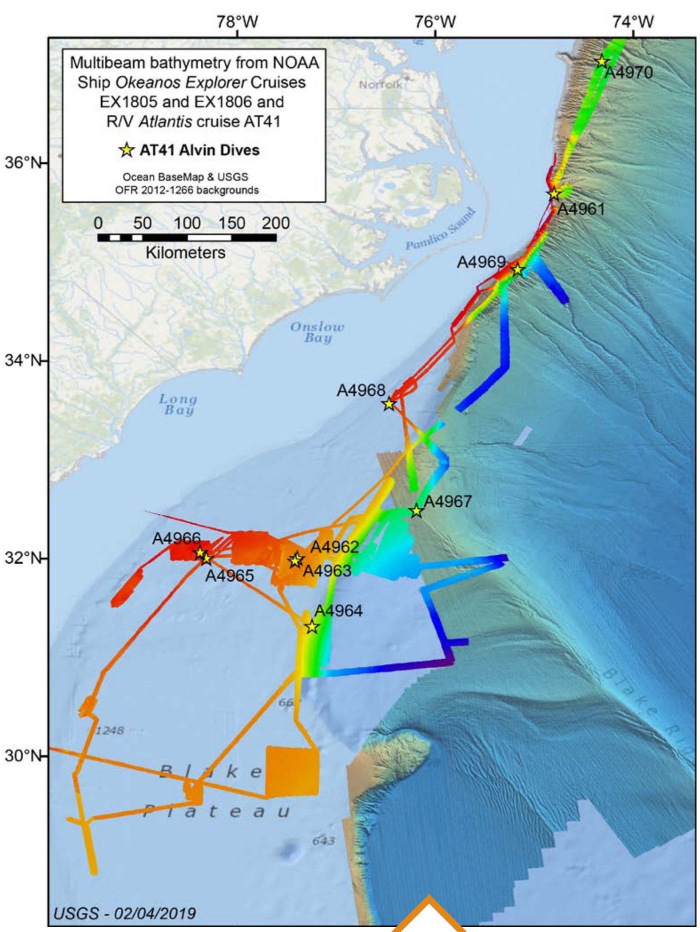


Figure 1. Map showing the study area and multibeam bathymetry data collected by NOAA Ship *Okeanos Explorer* and R/V *Atlantis*. Yellow stars indicate dive sites explored by HOV *Alvin*. *Image credit: USGS*

By exploring and characterizing biological communities in the study area, examining their sensitivity to natural and human disturbance, and describing the oceanographic, geological, geochemical, and acoustic conditions associated with each habitat type, DEEP SEARCH will improve our ability to predict the locations of seafloor communities off the coast of the southeast United States that are potentially sensitive to disturbance. This area encompasses a variety of different habitat types, including submarine canyons, methane seeps, coral mounds, and soft sediments.

COLLABORATION WITH NOAA SHIP *OKEANOS EXPLORER*

After fieldwork in 2017 was disrupted by hurricanes, DEEP SEARCH planned an ambitious 2018 cruise schedule that originally included a 25-day expedition aboard NOAA Ship *Nancy Foster*. When that cruise was canceled due to emergency repairs, the multibeam mapping objectives were shifted to *Okeanos Explorer*, and the Windows to the Deep expedition team (see pages 82–85) worked quickly to incorporate DEEP SEARCH mapping priorities into an extended mission.

The highly successful *Okeanos Explorer* cruise acquired detailed bathymetry over the coral habitats of the southern DEEP SEARCH study area. These locations were selected using a combination of prior coral observation data and the results of preliminary predictive habitat models. The subsequent *Okeanos Explorer* ROV mission, Windows to the Deep, co-led by DEEP SEARCH co-PI Cheryl Morrison made a number of exploratory dives to coral, canyon, and seep habitats. This cruise provided the first glimpses of some of the new habitats that would become the core of the DEEP SEARCH program.

R/V *ATLANTIS* EXPEDITION

In August 2018, the DEEP SEARCH team completed a 15-day expedition on Woods Hole Oceanographic Institution (WHOI) operated R/V *Atlantis* using HOV *Alvin*. Eleven dives were completed at three canyons, two seep sites, and four coral sites, ranging in depth from 403 m to 2,169 m. Mapping data from the earlier *Okeanos Explorer* cruises were augmented by 8,233 km^2 (Figure 1). Biological, geological, and chemical samples were collected by *Alvin* and with CTD, monocore, and multicore instruments.

Figure 3. Squid circle *Alvin* during collection of images of abundant bacterial mats at Pea Island seeps. *Image credit: BOEM, USGS, NOAA, ©WHOI*

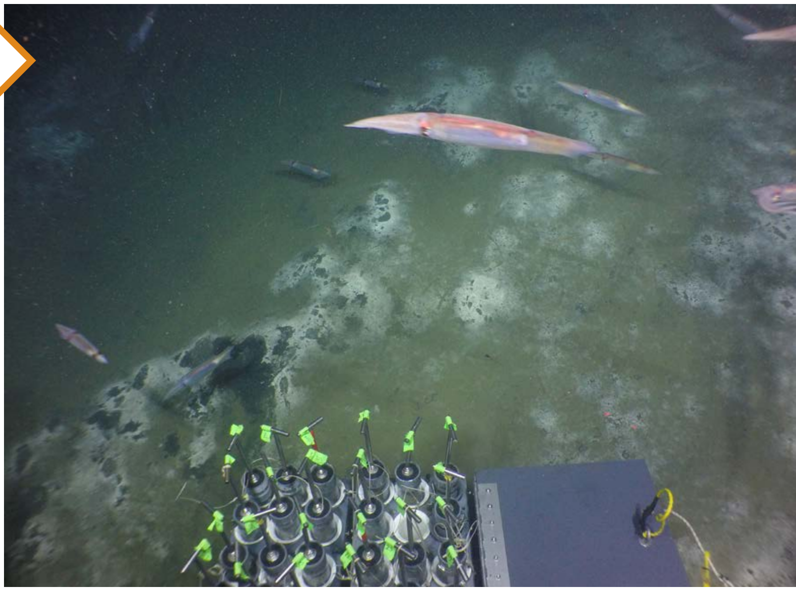
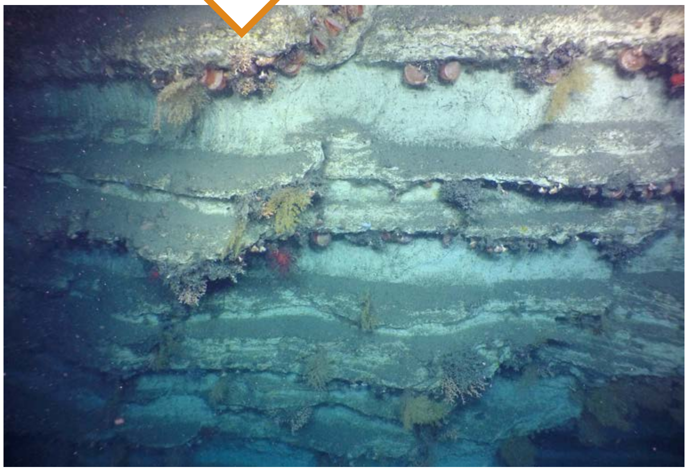


Figure 2. *Alvin* explored Pamlico Canyon off the coast of North Carolina and observed stunning rock walls covered in a diversity of corals. *Image credit: BOEM, USGS, NOAA, ©WHOI*



The expedition enabled more intensive investigations of seafloor environments previously covered only by preliminary visual surveys. Among these were the base of Pamlico Canyon, Pea Island seeps, and portions of Stetson Banks. The dives revealed persistent turbidity flows near the heads of the canyons and steep walls with numerous octocoral colonies throughout (Figure 2). The newly surveyed seeps were relatively shallow, located near the shelf break, and characterized by active methane bubble release and abundant bacterial mats (Figure 3).

One of the most exciting locations explored during the cruise was the series of long lines of cold-water coral mounds that together comprised approximately 140 km of coral reef beneath the Gulf Stream (Figure 4). While deepwater corals have been known to be in the area since the 1960s, modern mapping, imaging, and sampling tools are allowing the first comprehensive investigation of their complexity and extent.

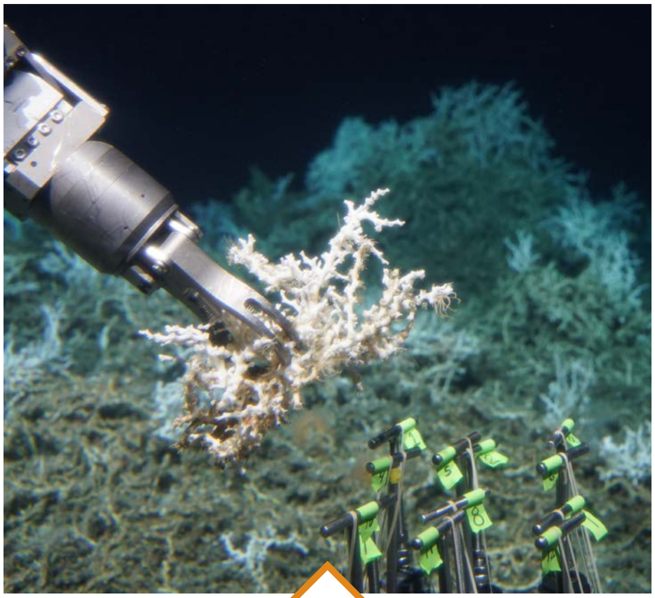


Figure 4. *Alvin* collects a sample of live *Lophelia pertusa*. On the third dive of the R/V *Atlantis* expedition, DEEP SEARCH explored thriving *Lophelia* reefs along a pronounced linear mound. These *Lophelia* reefs are among the deepest found to date along the US Atlantic coast. *Image credit: BOEM, USGS, NOAA, ©WHOI*

R/V *BROOKS McCALL*

In October 2018, the DEEP SEARCH team completed its final fieldwork of the year on the TDI-Brooks International Inc.-owned R/V *Brooks McCall*. *Brooks McCall* was chartered to complete the remainder of the planned work from the canceled *Nancy Foster* cruise. The vessel deployed two benthic landers, one at the newly discovered coral reefs and the other at a canyon site. The landers will remain on the seafloor for up to a year, collecting continuous environmental data. The ship was also equipped to retrieve long piston cores from the reefs, which will provide valuable data on the age and geological history of these structures.

NEXT STEPS

In 2019, a DEEP SEARCH expedition aboard NOAA Ship *Ronald H. Brown* will further investigate the deep-sea habitats of the US Mid- and South Atlantic, using ROV *Jason* to capture video of the seafloor and collect samples. Data from the 2017 and 2018 cruises will inform dive site selection and sampling needs for this major field effort. Though 2019 will be the final field season directly supported by the project, DEEP SEARCH team members will continue to analyze data and build their final report throughout 2021. BOEM plans to publish the final report for this project in 2022. The results of this study will be used to further BOEM's understanding of how to protect these sensitive deepwater habitats and inform management decisions.

It Takes a Village! Managing Data from *Okeanos Explorer*

By Barry Eakins, Susan Gottfried, Patrick Murphy, David Lovalvo, and Derek Sowers

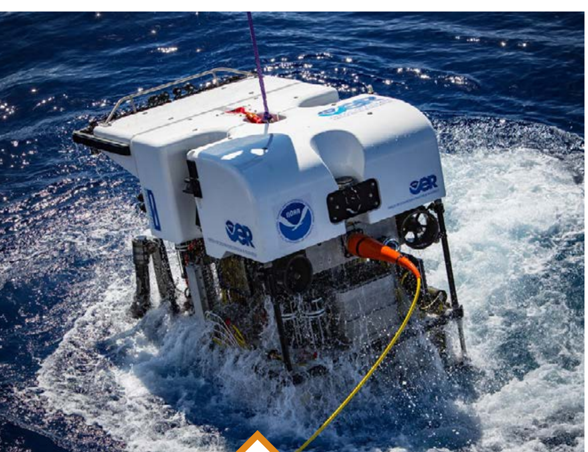
NOAA Ship *Okeanos Explorer* is a telepresence-enabled exploration vessel managed by NOAA's Office of Marine and Aviation Operations with mission equipment operated by NOAA's Office of Ocean Exploration and Research, in partnership with the Global Foundation for Ocean Exploration. Its purpose is to explore and map the world's marine environment. The vessel collects multibeam swath bathymetry, water column acoustics, and subbottom profiles, as well as meteorological data. It also deploys ROV *Deep Discoverer* and camera sled *Seirios*, capable of collecting along-track high-resolution video, oceanographic measurements, and biological and geological samples from the seafloor, as well as water samples. These complex operations are managed and operated by a successful partnership, founded on trust and collegiality, that shows that it really does take a village to achieve data management goals.

In 2018, NOAA's Office of Marine and Aviation Operations (OMAO) took over management of data from the ship's suite of passive environmental sensors, while the Global Foundation for Ocean Exploration (GFOE) installed a separate network and antenna aboard the ship to transmit submersible and mapping data to shoreside repositories for near-real-time data sharing. The OER mapping team pioneered "telemapping" workflows to enable near-real-time processing of bathymetric data from its shoreside facility at the University of New Hampshire (UNH). NOAA's National Centers for Environmental Information (NCEI) has been working to standardize data ingestion and access systems to better support data reuse.

MANAGING THE DATA

Data management is a complex end-to-end process. It requires thoughtful planning before the ship ever leaves the dock, careful monitoring of data streams during collection, and lossless transmission to partners, along with manifest checks, to ensure data fidelity. It also includes capturing of descriptive metadata, processing of data, and building of products, as well as public discovery and access to enable reuse. The goals are to preserve the data for future generations and maximize their value to the nation.

OER conducts all scientific and mission planning, OMAO provides and maintains ship systems and personnel, and GFOE engineers operate the two-body submersible system. The UNH mapping team operates the state-of-the-art multibeam survey system, post-processes the data, and builds bathymetric products. NCEI performs long-term data stewardship and provides public discoverability and access to all data and products. Data management for *Okeanos Explorer* is a coordinated and collaborative effort between OER, OMAO, GFOE, UNH, and NCEI that has proven enormously successful.

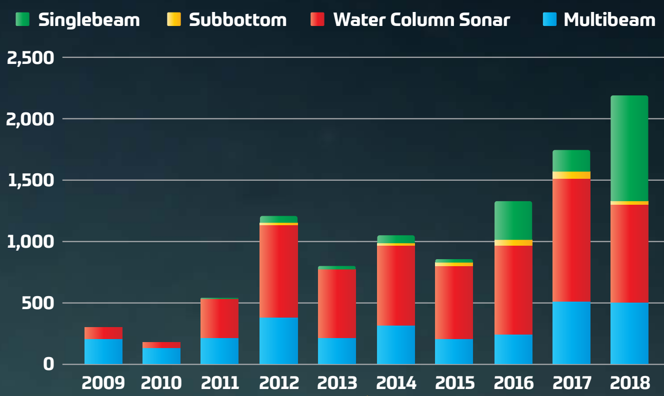


ROV *Deep Discoverer* goes into the water to explore deep-sea habitats off Puerto Rico on November 13, 2018.

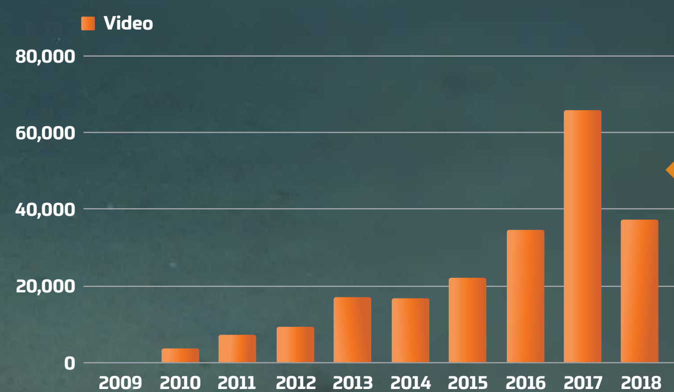
OER's data management team member Megan Cromwell acting as a Sample Data Manager aboard *Okeanos Explorer*.

10 YEARS OF DATA

Over the last 10 years, NOAA Ship *Okeanos Explorer* has conducted 99 surveys, ranging from the Atlantic Ocean to the far western Pacific. These cruises collected 2 TB of multibeam swath bathymetry (1.79 million square kilometers), 7 TB of multifrequency water column acoustics, and 209 TB of high-resolution ROV seafloor video, including footage from 2,207 hours on bottom. Since 2015, ROV *Deep Discoverer* has collected 480 primary biologic specimens and 321 primary geologic samples from which 714 associated biological specimens and 36 associated geological samples—attached to primary biological specimens—were also separated and catalogued.



Annual *Okeanos Explorer* data volumes, excluding ROV video.



Annual *Okeanos Explorer* video volumes.

NOAA's Office of Ocean Exploration and Research

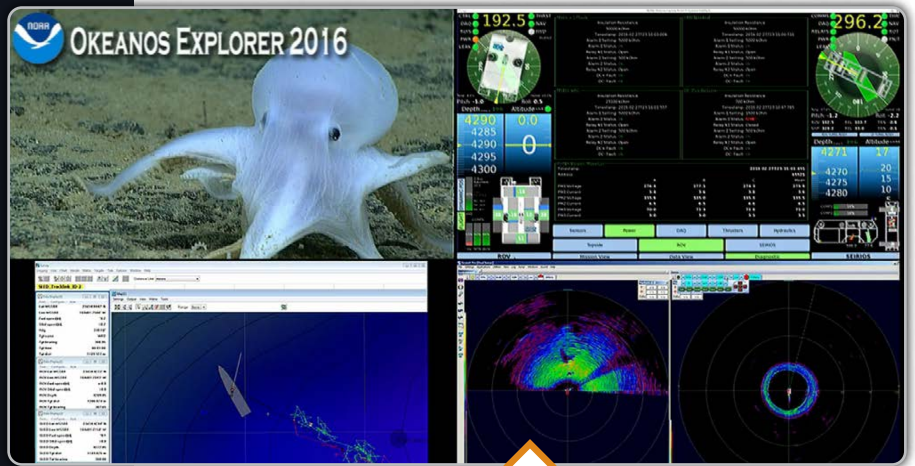
OER works with partners to explore the ocean and to make discoveries of scientific, economic, and cultural value; support innovations in exploration tools and capabilities; and encourage the next generation of ocean explorers, scientists, and engineers to pursue careers in ocean exploration and related fields. It leads all aspects of *Okeanos Explorer* cruise planning, including setting of scientific goals, developing detailed mission plans, and overseeing data collection and management activities. It develops the ship's schedule, ensures adequate at-sea staffing, and organizes and hosts port events. OER provides funding to its partners and external research scientists/principal investigators. It also leads efforts to advance marine science and technologies, and conducts extensive media outreach activities.

NOAA's Office of Marine and Aviation Operations

OMAO, in conjunction with OER, NCEI, and the Currents Group at the University of Hawai'i, manages assorted instruments aboard *Okeanos Explorer*. In 2018, environmental data from the suite of shipboard passive environmental sensors were taken over by OMAO, due to a change in network configuration and OMAO's intention to align its data management procedures across the entire fleet of large research vessels it oversees. OER has access to the raw data while they are being managed in accordance with OMAO's data management procedures. The acoustic Doppler current profiler (ADCP) aboard *Okeanos Explorer* is managed under an OMAO contract with the University of Hawai'i Data Acquisition System (UHDAS). This partnership provides daily remote monitoring by automated email to ensure readiness and functionality. Instruments supporting the ADCP, such as the POS MV (which provides ship's positioning and orientation), the ship's gyrocompass, and GPS, are also monitored by automated emails. These supporting instrument-status emails, coupled with regular communication between

VIDEO ANNOTATION INNOVATIONS

Thematic metadata in the form of video annotations are critical for successful search and discovery of archived video. Through a collaborative telepresence environment, scientists from across the world participate in real time in ROV dives. Their voice commentary and written observations form the keyword annotations for video recorded during *Okeanos Explorer* ROV missions. To improve the consistency, ease, and accuracy of these annotations, OER and NCEI initiated a collaboration with Ocean Networks Canada (ONC) to adapt its video browsing and annotation tools to OER's unique needs. Adaptions include implementation of a web-based annotation entry interface, the use of standardized taxonomy based on the World Register of Marine Species for annotation entry, and the ability to create and edit annotations after the expeditions. NCEI harvests these annotations and assigns them to five-minute video sections archived in the OER video portal. The timestamps of the video segments are then used to assign the keywords that fall within that timeframe. Improvements in ROV video annotations have resulted in a 400% increase in keyword assignments for video segments, enabling video data users to search and discover OER video more efficiently and reliably. For more information about the OER video portal and ONC annotation system visit: https://www.nodc.noaa.gov/oer/video/ and http://dmas.uvic.ca/SeaTube.



Screen capture of ROV *Deep Discoverer* live webcast via telepresence off Necker Island, Hawai'i. *Image credit: NOAA NCEI*

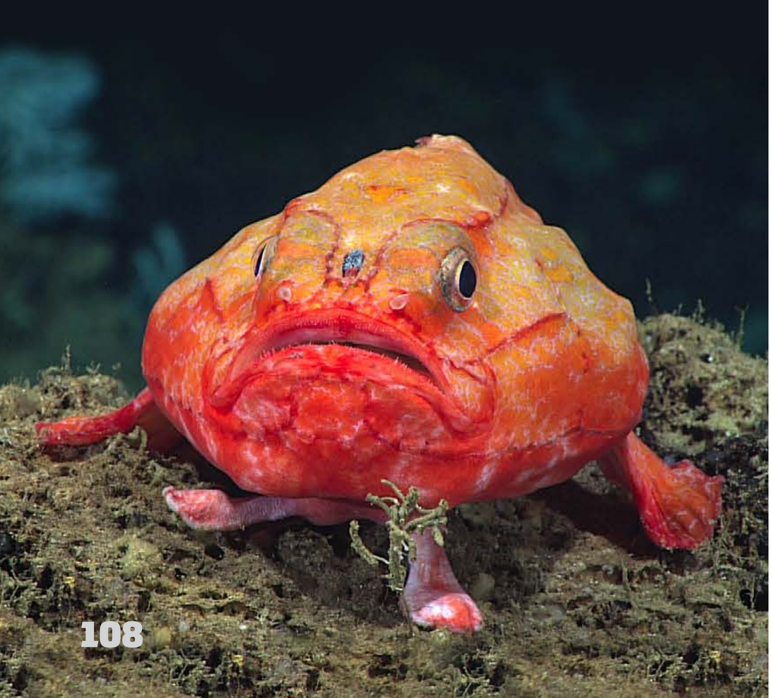
UHDAS, OMAO, and GFOE, help quality control larger instrument suites such as multibeams and ROVs. OMAO and NCEI, with input from OER, recently began work on robust procedures that restrict data access when mission partners want to protect sensitive locations, for example, for archaeological or national security purposes.

Global Foundation for Ocean Exploration

GFOE, through a grant from OER, is responsible for designing, building, operating, and maintaining all deep submergence assets aboard *Okeanos Explorer*. GFOE also trains engineers, collects and manages all data from ROV-mounted sensors, handles all VSAT (very small aperature terminal) operations, including the securing of high-speed bandwidth for webcast telepresence, and creates all summary and long-form video products. Additionally, GFOE handles all scientific sampling (biologic, geologic, and water), is responsible for navigation of the vehicles while underwater, and prepares all data collected for NCEI to archive. Communication and transmission of data from ship to shore occurs through the newly developed, standalone GFOE science network.

UNH Center for Coastal and Ocean Mapping

OER's mapping team, in coordination with the ship's Senior Survey Technician and ship's command, lead all ocean mapping activities conducted by *Okeanos Explorer*. The mapping team is primarily based at the UNH Center for Coastal and Ocean Mapping/Joint Hydrographic Center. The team is responsible for planning and running mapping operations, data acquisition and processing, overseeing sonar calibration operations and maintenance, providing high-quality products to meet OER operational and science



needs, and working closely with NCEI to archive all mapping data within 90 days after completion of mapping expeditions. Since 2017, the mapping team has been developing "telemapping" workflows for real-time data acquisition from shore and near-real-time processing of bathymetric data at its shoreside facility, often involving students through the OER Explorer-in-Training program. In addition to providing extended training opportunities to students who are not able to spend time at sea, telemapping has created value-added mapping products, such as bathymetric terrain models, seafloor backscatter maps, seafloor geology profiles, and GIS maps, all of which are difficult to produce quickly with limited ship-based mapping personnel.

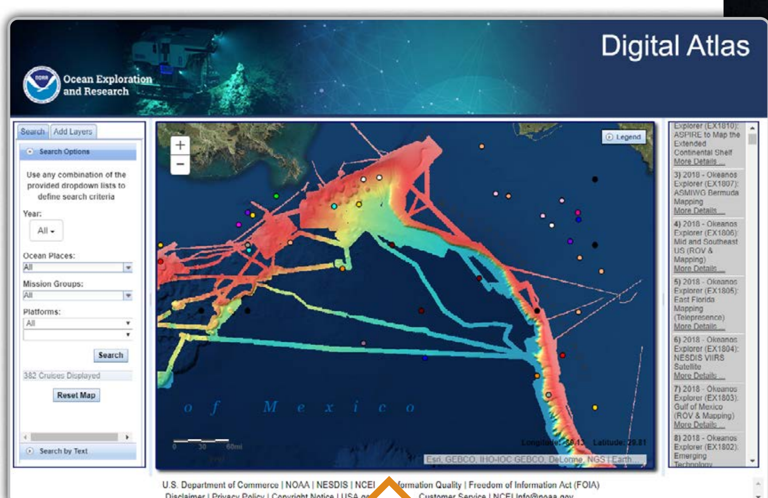
NOAA's National Centers for Environmental Information

NCEI is responsible for public discoverability and access to OER data, as well as long-term data stewardship—ingestion, description, archive, and maintenance. It also helps develop data management plans and provides at-sea data collection support, as needed. For public access, NCEI has built OER-specific data discovery tools. The OER Digital Atlas is a one-stop map-based interface that provides links to data and information. The OER Video Portal provides keyword-enabled search and discovery for video. NCEI also hosts and maintains the Benthic Animal Guide, which provides images of marine animals encountered during ROV missions, and the Sampling Operations Database Application, which contains information on seafloor samples stored at physical repositories—Smithsonian Institution for biological and water samples, and the Marine Geology Repository at Oregon State University for geological samples.

COLLABORATION

Collaboration is the act of two or more parties, or organizations, working together to achieve something meaningful. It requires teamwork, trust, compromise, respect, reliability, unique perspectives and ideas, and effective communication. For the *Okeanos Explorer* data management endeavor, collaboration includes documenting and continually updating standard operating procedures (especially lossless data transmission), assessing data quality at numerous points along the way, and frequent, friendly communication. This communication is typically in the form of emails, telecons, and webinars, and annual, face-to-face, end-of-field-season meetings called "hotwashes." Data liaisons (points of contact) have been identified to help facilitate good communication between groups. OER shares data quality control scripts with OMAO for incorporation into the next version of its data aggregation software called Scientific Computing System. OER, NCEI, and OMAO participate in the annual NOAA to NOAA (N2N) workshop to exchange ideas, set milestones, and strengthen partnerships within the organization. Shared Google Sheets are also used to collaborate on the input, tracking, and visualization of important data metrics. Through 10 years of collaboration, this successful partnership has explored the ocean floor around the globe, and collected and shared tremendous volumes of data and information that have furthered our scientific understanding of the deep-sea realm.

OER's data management team member Lauren Jackson acting as a Sample Data Manager aboard *Okeanos Explorer*.



Screen capture of updated OER Digital Atlas (https://www.ncddc.noaa.gov/website/google_maps/OE/mapsOE.htm), used by NCEI for public discovery of and access to OER data. Bright colors indicate seafloor mapped by NOAA Ship *Okeanos Explorer*. *Image credit: NOAA NCEI*

Engagement

Reaching Across, Beyond, and in Diverse Ways

Introduction and 2018 Overview

By David McKinnie, Emily Crum, Susan Haynes, Katie Wagner, Debi Blaney, and Joanne Flanders

"Reaching out in new ways to stakeholders and learners of all ages" was one of the four key objectives identified by the President's Panel for Ocean Exploration (2000). For more than a decade, NOAA's Office of Ocean Exploration and Research has been designing and implementing engaging and innovative programs to do just that. As OER evolved and NOAA Ship *Okeanos Explorer's* exploration paradigm advanced, so did the tools and channels used to reach audiences, including communities living on remote ocean islands when the ship was exploring off their coastlines.

Today, OER's engagement efforts cut across all age classes and most industries. We reach inside the formal education community through education programming, teacher professional development workshops, and webinars and online courses. We reach outside through public programming partnerships at museums and informal science centers such as the Smithsonian's National Museum of Natural History and the Coastal Ecosystem Learning Center Network. And we're reaching new audiences by partnering with independent media companies such as Silvergate Media, which develops world-class children's brands for multi-platform broadcasters and whose work includes *The Octonauts*, the popular children's television series about a team of underwater adventurers who explore the world ocean. For college students considering what comes next and seeking internship opportunities, OER offers its Explorer-in-Training program. By interacting with traditional media, we are delivering the OER story to outlets—and audiences—around the world. If we don't reach you through the above channels, perhaps you will tune into the live video from *Okeanos Explorer* and join an expedition or we will connect with you via our social media accounts.

From the young at heart to seasoned adults whose first undersea adventure may have been reading Jules Verne's *Twenty Thousand Leagues Under the Sea,* OER makes the adventure and value of ocean exploration relevant and accessible. It has been an exciting decade of engagement on the topic of ocean exploration and one we are proud of. The year 2018 was a great way to close *Okeanos Explorer's* first decade. Details from that year follow.

2018 Engagement Activities by the Numbers

WEB

Website Visits: ~5,866,000

Live Video Views: ~993,300

Expeditions Covered:

- 9 *Okeanos Explorer* cruises
- 8 non-*Okeanos Explorer* cruises

Expedition Content Added:

- ~160 content essays
- ~840 images
- ~95 videos

SOCIAL MEDIA

Facebook Likes: ~136,000 11%↑

Instagram Likes: ~39,850 315%↑

Twitter Followers: ~186,800 0.4%↑

YouTube Subscribers: ~77,400 19%↑

PUBLIC OUTREACH

Ship Tour Attendees: ~200

In-Person Event Attendees: ~700

Live Interaction Attendees: ~3,500

Media Mentions: 450+

EDUCATION

Educator Professional Development Workshops: 35

Educators Trained: 890

Estimated Number of Students Reached: 100,000+

Listserv/Newsletter Subscribers: 6,400+

OER Education Facebook page (initiated in May 2018): 639 followers

Teacher at Sea: 1

Webinars for Educators: 3

Webinar Attendees: 107

In July 2018, students and staff from Virginia Sea Grant toured NOAA Ship *Okeanos Explorer* dockside in Norfolk, Virginia. *Image credit: Art Howard, GFOE*

ONLINE COMMUNICATIONS

The centerpiece of OER's online communication efforts remains the OceanExplorer.NOAA.gov website, which allows visitors to follow along on expeditions and learn more about ocean exploration. In May 2018, OER launched a dramatic overhaul of the website, updating its look and feel as well as functionality. Highlights of the new website include increased usability for visitors on mobile devices; new image and video galleries that highlight "best of" multimedia elements from OER-funded expeditions; direct links to the OER Digital Atlas (https://www.ncddc.noaa.gov/website/google_maps/OE/mapsOE.htm) and access to expedition data; the ability to navigate OER-funded expeditions by topic, year, and location; and updated career information. New web elements will continue to be rolled out throughout 2019, enhancing the online reach of OER. Additionally, from November 2017 to November 2018, a total of 18 expeditions were featured on the site, highlighting activities from the Pacific and Atlantic Oceans, Gulf of Mexico, and US Great Lakes. The site received nearly 5.9 million page views during this same period of time.

OER continued to use social media to draw in and inform audiences about expedition activities, capitalizing on our compelling images and videos to keep the public engaged. Daily posts on Facebook, Twitter, and Instagram encouraged active dialogues with interested audiences, and OER hosted one Reddit "Ask Me Anything" session. Live video from expeditions aboard *Okeanos Explorer* posted on the OER YouTube channel received more than 990,000 views alone. In June 2018, OER once again joined the Schmidt Ocean Institute and Ocean Exploration Trust in celebrating World Oceans Day. During this Tri-Ship Connection streamed on YouTube (https://www.youtube.com/watch?v=h1TuKE9zCNU), we shared upcoming exploration plans with a worldwide audience.

Through a strategic combination of content on OceanExplorer.NOAA.gov and OER social media outlets, we were able to highlight the value and importance of ocean exploration and research in identifying, understanding, and managing ocean resources for this and future generations.

OUTREACH AND MEDIA

In 2018, OER engaged more than 4,000 people through in-person and telepresence-enabled events associated with *Okeanos Explorer* expeditions. More than 200 people toured the ship during port calls in Pascagoula, Mississippi; Key West, Florida; Charleston, South Carolina; Norfolk, Virginia; and San Juan, Puerto Rico. Live telepresence interactions were conducted with more than 50 groups and institutions, including the National Aquarium, Pew Charitable Trusts, the Exploratorium, South Carolina Aquarium, North Carolina Museum of Natural Sciences, OCEANS 2018 Charleston conference, the National Ocean Exploration Forum, and the Natural History Museum, London. Among notable in-person events were presentations on ocean exploration and expedition findings to the South Atlantic Fishery Management Council, at the Boston

In October 2018, media crews conducted interviews with the Océano Profundo 2018 expedition team and toured *Okeanos Explorer* dockside in San Juan, Puerto Rico. *Image credit: Art Howard, GFOE*

Some of the key media outlets that featured OER's 2018 work.

Ocean Day celebration at the New England Aquarium, and the EcoExploratorio: Museum of Sciences of Puerto Rico.

OER also interacted with local communities, agency partners, and schools around NOAA Headquarters and regional offices through events such as the annual NOAA Open House and NOAA Kids Day, and by hosting special events and seminars in Exploration Command Centers across the country.

Media continued to play a critical role in OER's public engagement efforts. Press releases and "Exploration Alert" emails kept media representatives, social media managers, and public affairs contacts informed of expedition activities and discoveries, helping to drive audiences to live video online. Stories were generated by hundreds of media outlets, including the Associated Press, CNN, NBC, ABC, *USA Today*, *Washington Post*, *National Geographic*, *Business Insider*, *Forbes*, *Daily Mail*, *Newsweek*, *Popular Mechanics*, *Live Science*, and local media outlets in Puerto Rico.

EDUCATION

Engaging educators and students in ocean science exploration expands the understanding of the human impact on the ocean, and the ocean's impact on humans, ultimately increasing understanding and stewardship of the ocean across the country and around the globe.

Staying Relevant and Up To Date

The current OER educator professional development workshop, Exploring the Deep Ocean with NOAA, was fully updated in the winter of 2017/2018 to include the most current ocean exploration science and to incorporate reference to a broad ocean exploration program that includes OER, the Ocean Exploration Trust, and Schmidt Ocean Institute as partners. This updated workshop puts fresh and timely ocean exploration information in the hands of educators, allowing them to engage their students in authentic ocean exploration science and technology.

In 2018, the Ocean Exploration Advisory Board conducted a thorough, independent external review of the OER education program, the first since the program's inception. This review will lead to a five-year implementation plan, currently in development (see page 117).

Educators learn about bathymetric mapping during the Wet Maps activity from the Exploring the Deep Ocean with NOAA professional development workshop at the South Carolina Aquarium. *Image credit: South Carolina Aquarium.*

Expanding Our Reach

In 2018, the Great Lakes Aquarium in Duluth, Minnesota, and the Albuquerque BioPark in New Mexico became full OER education partners, executing annual educator professional development workshops along with 13 other partners nationwide. By extending further into inland areas of the country, NOAA and partners are building capacity to reach a broader audience and increasing opportunities for underserved audiences and new groups, such as Native American populations, coast-to-coast.

In March 2019, OER conducted an all-day professional development workshop for teachers at the science museum called EcoExploratorio in San Juan, Puerto Rico. The workshop highlighted OER's most recent expedition, Océano Profundo 2018, that explored the waters around Puerto Rico (see pages 90–91). The workshop was offered in English and Spanish and was so successful that OER invited the EcoExploratorio to become an official Alliance Partner. The partnership will go into effect in June of 2019, and OER will fund the museum to hold teacher ocean exploration workshops regularly. This partnership will leverage OER's efforts to increase its reach in underserved Hispanic communities in Puerto Rico and elsewhere in the United States.

As a pilot program, OER incorporated a Boston College undergraduate deep-sea biology class directly into an ocean exploration expedition. In the spring of 2018, students participated as members of the shore-based science team during a telepresence-enabled cruise in the Gulf of Mexico. Activities included an introduction to OER and the expedition, guided involvement in reviewing the expedition plan, student participation in proposing ROV dive sites for science team consideration (two of which were selected by the science team!), a visit to the University of Rhode Island for a tour of the Inner Space Center, and a half day of participation and interaction with the Inner Space Center science team.

This experience provided undergraduates with a unique opportunity to apply what they learned throughout the semester to an authentic science challenge, get a behind the scenes look at the process of ocean exploration, engage in expedition planning, and experience deep-sea exploration firsthand.

Boston College Professor, Heather Olins (second from left), with her deep-sea biology class at the Inner Space Center at URI.

OER FACEBOOK PAGE FOR EDUCATORS

@oceanexplorationeducation

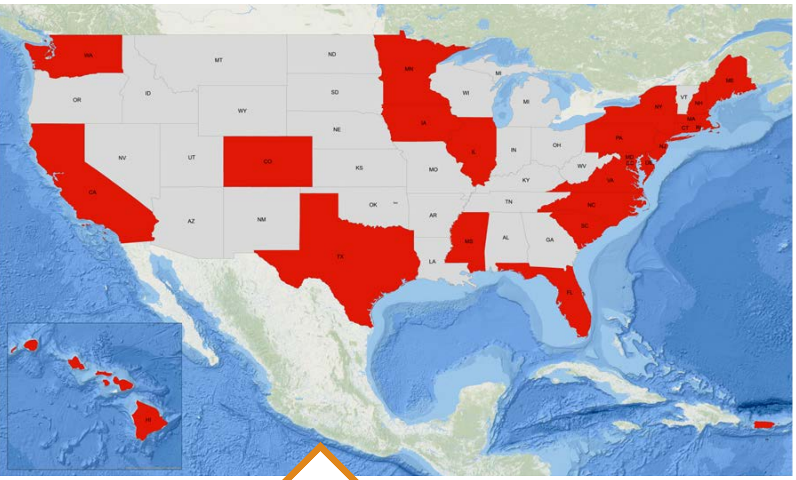
In response to requests from teachers, the OER Education Team launched an Education Facebook page in 2018. This page regularly shares educational resources and information with formal and informal teachers and students, highlights timely and classroom-relevant OER ocean exploration educational materials, including engaging imagery and multimedia tools, and announces professional development opportunities held at aquariums and science centers around the country. At the end of 2018, the page had over 600 followers and several "Likes" by the highest levels of NOAA leadership.

The NOAA Ocean Exploration and Research-Education Facebook page was established in 2018 to share ocean exploration expeditions, discoveries, and education resources with educators across the globe.

Over a Decade of Training the Next Generation: The Explorer-in-Training Program

By Derek Sowers, Mashkoor Malik, Elizabeth Lobecker, and Michael P. White

NOAA's Office of Ocean Exploration and Research Explorer-in-Training (EiT) program, developed in partnership with the University Corporation for Atmospheric Research, provides undergraduates and graduate students hands-on experience in seafloor mapping at the University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center, as well as aboard NOAA Ship *Okeanos Explorer*. In addition to directly learning the theory and practice of ocean mapping while at sea, these early career scientists get to contribute to the whole ocean exploration endeavor firsthand. These opportunities are also extended to students within NOAA's Educational Partnership Program (EPP), which provides scholarships and internships to students studying at minority-serving institutions.



Explorer-in-Training participants have come from across the country and US territories, as indicated by the states highlighted in red in the map.

Over 10 years of *Okeanos Explorer* operations (2008–2018), OER has provided 165 seafloor mapping training opportunities to 122 early career scientists, with many returning for second and third experiences to further develop their skills.

Recruitment efforts for the program also target involvement of local student scientists when *Okeanos Explorer* is working in more remote parts of the world ocean. The mission team benefits by having people on board who can share local knowledge, and the students benefit by returning to their place of work/study with in-depth knowledge of OER data sets relevant to their region.

The EiT program provides a pragmatic pathway to support advancement of the next generation of marine science academics and explorers. For many participants, it is their first at-sea expedition experience and an invaluable contribution toward their subsequent academic and career pursuits. Many EiTs have converted their new mapping skills into careers as hydrographers for NOAA or private survey companies, marine spatial planners, consultants, marine archaeologists, and marine resource managers. Others have used their new skills to pursue or enhance their graduate school research (at both the master's and PhD level) in marine science, geography, and ocean engineering.

The success of this training program is perhaps best exemplified by highlighting a couple of former EiTs who continue to work for OER as consultants or staff. Former EiT Neah Baechler (2015) now runs her own business as a private hydrographic contractor and works several cruises

American Sāmoa Community College student Claudia Thompson (left) was trained both onshore and onboard *Okeanos Explorer* as a hydrographer through NOAA's Explorer-in-Training program by Expedition Coordinator Meme Lobecker (right). As part of the science team, Claudia brought a unique perspective to the expedition while building a bridge to her local community.

a year for *Okeanos Explorer* as an at-sea Watch Lead. Neah has also completed work for the Ocean Exploration Trust aboard E/V *Nautilus*. The most recent addition to the OER Mapping Team is Shannon Hoy—a former EiT (2010) who participated in numerous research expeditions, working for multiple institutions, including the US Geological Survey, Ocean Exploration Trust, and the University of Bristol. She is completing a MS degree in ocean mapping at the University of New Hampshire.

The mission team from the 2017 *Okeanos Explorer* trip through the Panama Canal and transit mapping through the Caribbean. Back row (from left to right): Miya Pavlock McAullife (EPP), Derek Sowers (OER Expedition Coordinator/Mapping Lead), Daniel Freitas (Watch Lead), Susan Haynes (OER Education Program Manager), Charles Wilkins (Senior Survey Technician), Ko Barrett (NOAA Office of Oceanic and Atmospheric Research Deputy Assistant Administrator). Front row (from left to right): Amanda Bittinger (Watch Lead), Rebekah Hernandez (EPP), Kelsey Lane (EiT), and Victoria Dickey (EiT).

Demonstrating Commitment to Diversity, Equity, and Inclusion 2018

By Catalina Martinez, Daniel Wagner, Mashkoor Malik, Derek Sowers, and Susan Haynes

A key recommendation of a recent external review of the OER education program was to develop new opportunities to engage a broader audience. As part of this effort, OER is collaborating with the NOAA Office of Education and the newly developed Ocean Discovery Institute (ODI) in San Diego, California, to develop and implement ocean science/exploration programming tailored to the diverse City Heights community served by ODI. Listening sessions, an effort OER began at the American Indian Science and Engineering Society Annual Conference in fall 2018, will be conducted through this partnership to ensure all efforts meet the specific interests, needs, and requirements of the particular communities and groups OER hopes to reach.

OER continues working with teams across NOAA on a more visible and coordinated presence at key minority-serving conferences focused on relevant STEM fields. The strategy includes student-centered networking, engagement, and professional/career development opportunities, as well as recruitment efforts, leadership engagement, and a more deliberate approach to staffing and participation overall.

NOAA personnel worked with Kendall Moore, a University of Rhode Island professor of journalism, on a documentary titled "Can we Talk? Difficult Conversations with Underrepresented People of Color: Sense of Belonging and Obstacles to STEM Fields," that includes interviews with

Global Foundation for Ocean Exploration Engineer Fernando Aragón explaining ROV operations in Spanish during ship tours of *Okeanos Explorer* while docked in San Juan, Puerto Rico, prior to the Océano Profundo 2018 expedition. Close to 50 local partners participated in the tours, including representatives from local management agencies, academic institutions, nongovernmental institutions, school groups, and the private sector. Ship tours, as well as other science and outreach activities, where given in both Spanish and English in order to engage a wide diversity of audiences in ocean exploration.

The telepresence-mapping team for the Windows to the Deep 2018 Expedition. EiTs were trained and led by OER Expedition Coordinator Meme Lobecker. Via telepresence, EiTs participated as watch standers during mapping surveys and assisted in the post-processing of sonar data throughout the cruise while at the Exploration Command Center at the University of New Hampshire's Center for Coastal and Ocean Mapping. From left to right: Michael White (OER Physical Scientist), Trey Gillespie (EiT), Mikia Weidenback (EiT), Harrison Watson (NOAA Education Partnership Program), Meme Lobecker (OER Physical Scientist), Derek Sowers (OER Physical Scientist), and Charles Wilkins (Senior Survey Technician for *Okeanos Explorer*). *Image credit: UNH/CCOM/JHC*

In 2018, Kendall Moore's documentary "Belonging" screened at the American Geophysical Union and the Society for Advancement of Chicanos/Hispanics and Native Americans in Science annual conferences and premiered at the University of Rhode Island's InclusiveSciComm Symposium. All were followed by panel discussions with the filmmaker and documentary participants.

In 2018, NOAA had unprecedented success with engagement at the Society for Advancement of Chicanos/Hispanics and Native Americans in Science Diversity in STEM annual conference. Through dedicated personnel support for two NOAA booths and six science sessions, NOAA personnel made contact with over 250 conference attendees, sharing life stories, career journeys, and student and early career opportunities throughout each day.

several NOAA colleagues and collaborators. The documentary captures the socio-emotional experiences of students and faculty of color who are pursuing, in, and or have left, STEM fields. There is a great deal of interest in using the film as an educational tool to engage in dialogue around challenging topics, both inside and outside of NOAA.

Since its inception in 2001, OER has hosted 15 John A. Knauss Marine Policy Fellows, hiring several into federal and contract positions. OER has also hosted 16 Ernest F. Hollings Scholars and Educational Partnership Program students, providing a variety of onshore and at-sea experiences, enhancing their academic and career trajectories through specialized training and development of unique skill sets. In partnership with the NOAA Office of Education, OER continues to help identify and remove barriers to entry for underrepresented minorities in these gateway scholarship and fellowship programs, developing best practices that can ultimately translate across many agencies and industries.

As part of a "campaign" exploration model, the *Okeanos Explorer* team engages local communities wherever the ship operates, works with local scientists and educators, and emphasizes hosting a variety of events to provide access and opportunity to as many local residents as possible. For example, during the Océano Profundo 2018 expedition to Puerto Rico and the US Virgin Islands, OER used science and outreach communications in both Spanish and English to reach a wide diversity of audiences, including bilingual coverage on the expedition website, narration of the live video feeds, ship tours, seminars, school group presentations, media articles, and live interactions. Over the course of the expedition, close to 6,500 people from Puerto Rico and the US Virgin Islands were reached in person through these avenues, with another one million engaged through online content.

Education Review

By David McKinnie, Susan Haynes, and Debi Blaney

NOAA's 2009 statutory mandate for ocean exploration education requires the agency to coordinate education and outreach activities under a national ocean exploration program. Over the past year, OER Education has worked with external partners to leverage NOAA and foundation investments in ocean exploration education resources and materials. OER education products developed over the past 18 years use results from expeditions to the deepest parts of the world ocean to illustrate key scientific concepts, support ocean science literacy, and share the excitement and wonder of the deep ocean with the next generation of ocean explorers, engineers, and scientists. Combined with exploration results from other ocean explorers such as the Ocean Exploration Trust and Schmidt Ocean Institute, teachers and other educators have access to an increasingly rich body of material to support their classroom curriculum.

Education and outreach are key to raising awareness of the importance of the ocean, ocean exploration, and STEM education. Given that ocean science understanding and knowledge is expanding exponentially, it is essential to regularly review and update ocean exploration education programming in order to remain effective and relevant.

In the spring of 2018, education and ocean exploration experts conducted a two-part external review of the OER education program under the auspices of the Ocean Exploration Advisory Board (OEAB). Participants included members of the OEAB, Education Alliance Partners, OER workshop facilitators, classroom teachers, education standards experts, education staff from the Ocean Exploration Trust and Schmidt Ocean Institute, and the director of NOAA Education. The first independent review of the program since its inception, this effort ensures OER's education programs are effectively building the public's ocean literacy while incorporating best practices and addressing modern science education reform.

Review recommendations were summarized into the following major categories.

1. Promoting and strengthening the community of ocean exploration education programs.
2. Enhancing the relevance and value of expeditions to the education community.
3. Revising and enhancing the workshops to make them more effective professional learning opportunities with more relevance and greater impact.
4. Improving and enhancing the organization of the educational materials and the website to make searches more user-friendly and effective.
5. Updating and developing educational materials to reflect research on teaching and learning as described in a *Framework for K–12 Science Education* (NRC, 2012).
6. Expanding the Alliance to reach more educators and students with an emphasis on the interior of the country.
7. Enhancing diversity in program participants.

As a result, OER is developing a five-year education implementation plan that addresses several notable items, including expanding strategic partnerships, adding inland education Alliance Partners, considering new approaches to educator resource development, updating professional development workshop content, improving web presence, and thoughtfully reaching out to better engage diverse communities.

2018 OER EDUCATION REVIEW

PANELISTS

Jerry Schubel, Chair, Aquarium of the Pacific
Jacqueline Dixon, University of South Florida and Ocean Exploration Advisory Board
Allison Fundis, Ocean Exploration Trust
Catherine Halversen, Lawrence Hall of Science
Louisa Koch, NOAA Education
Tami Lunsford, Newark Charter School
Peter McLaren, Next Gen Education LLC
Debbi Stone, Florida Aquarium
April Tucker, Tamalpais High School
Carlie Wiener, Schmidt Ocean Institute

NOAA'S OFFICE OF OCEAN EXPLORATION AND RESEARCH

David McKinnie, Engagement Team Lead
Susan Haynes, Education Program
Debi Blaney, Education Program

NATIONAL MARINE SANCTUARY FOUNDATION

Allison Alexander, Vice President

Ocean Exploration Education panelists and subcommittee.

Sponsored Projects

NOAA's Office of Ocean Exploration and Research

Introduction

By Nathalie Valette-Silver, Frank Cantelas, Chris Beaverson, Amanda N. Netburn, James Murphy, Kelley Elliott, Stephen R. Hammond, Yvette Jefferson, and Joyce Woodford

NOAA's Office of Ocean Exploration and Research sponsors projects that explore and characterize the deep ocean. OER's mission is further leveraged through competitive grants and cooperative agreements to universities and nonprofit and for-profit organizations, as well as through intra- and interagency agreements with other parts of NOAA and other federal agencies. These efforts complement the systematic exploration conducted by NOAA Ship *Okeanos Explorer*, the only US vessel dedicated to exploring the largely unknown ocean (see pages 76–77).

OER publishes a Federal Funding Opportunity (FFO) annually that invites submission of proposals focused on ocean exploration, including maritime exploration for, and of, culturally important submerged sites, and technological innovations with the potential for increasing the pace and scope of ocean exploration. Projects are selected based on a competitive community-standard process of mail and in-person peer review, coupled with programmatic selection factors that are published in the FFO.

Funded projects benefit from proactive OER support, including assisting with cruise planning, fulfilling federal administrative reporting requirements, and communicating project discoveries and results through OER's website. Consistent with OER's open data policy, all data are made publicly available after quality and accuracy are assured.

Over the past 10 years, OER's competitive program supported 79 projects for a total of $24 million. In fiscal year 2018, OER supported 10 projects—seven focused on technology, two on archaeology, and one on exploration—for a total of $4.5 million (Figure 1). In June 2018, OER published a fiscal year 2019 FFO focused on exploration of the ocean in support of America's Blue Economy. Selected proposals will be announced in summer 2019.

In 2018, OER partnered with NOAA's National Centers for Coastal Ocean Science (NCCOS) and Office of National Marine Sanctuaries to announce two additional FFOs focused on the study of mesophotic coral ecosystems for a project up to four years in duration in American Samoa, and up to five years in the Hawaiian Archipelago. These FFOs build on a partnership begun with NCCOS in fiscal year 2006 to improve the understanding of these poorly known ecosystems found from 30 m to 150 m depth in the tropics and subtropics. Together, we have been able to shed light on these regions, which suffer from being too shallow for deep technologies and too deep for shallow technologies.

Highlights from a few of the seagoing projects funded through the fiscal year 2017 competition and executed during the 2018 (e.g., Figure 2) year follow.

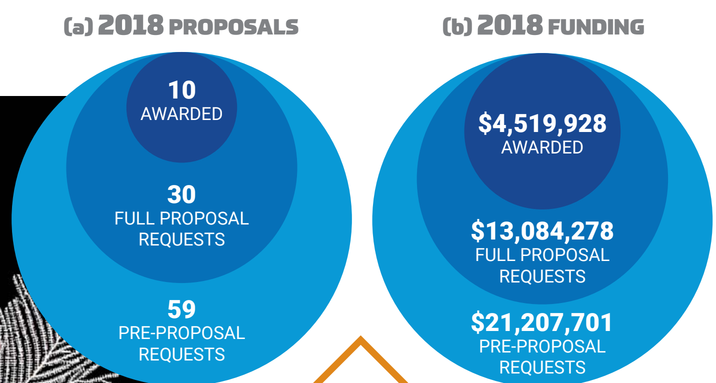


Figure 1. (a) Number of projects proposed vs. selected in 2018. (b) Funding amounts requested vs. awarded in 2018.

Figure 2. Octocoral (sea fan) with many associated brittle stars seen during the Océano Profundo 2018 expedition off Puerto Rico.

Cooperative Institute for Ocean Exploration, Research, and Technology

By Joshua Voss and Shirley Pomponi

NOAA's Cooperative Institute for Ocean Exploration, Research & Technology (CIOERT) is led by Florida Atlantic University's Harbor Branch Oceanographic Institute in partnership with the University of North Carolina Wilmington, the University of Miami, SRI International, and OER. CIOERT activities focus on three themes: exploration of continental shelf edge frontiers, research on vulnerable coral and sponge ecosystems, and development of advanced underwater technologies.

CIOERT has expanded water column exploration capabilities by developing new technologies to study the mesopelagic ocean. An integrated array of novel optical sensors created by CIOERT researchers, coupled with existing sensing technologies, has been developed to explore the distributions and dynamics of mesopelagic organisms at scales ranging from microbes to large nekton (Figure 1). The state-of-the-art system combines eight complementary technologies, including a novel digital holographic microscope (HOLOCAM), a next-generation Spatial Plankton Analysis Technique (SPLAT) camera to image bioluminescent organisms, and a new laser imager for marine life. The new mesopelagic exploration package was deployed during the March 2018 NOAA Ship *Okeanos Explorer* Gulf of Mexico Technology Demonstration expedition.

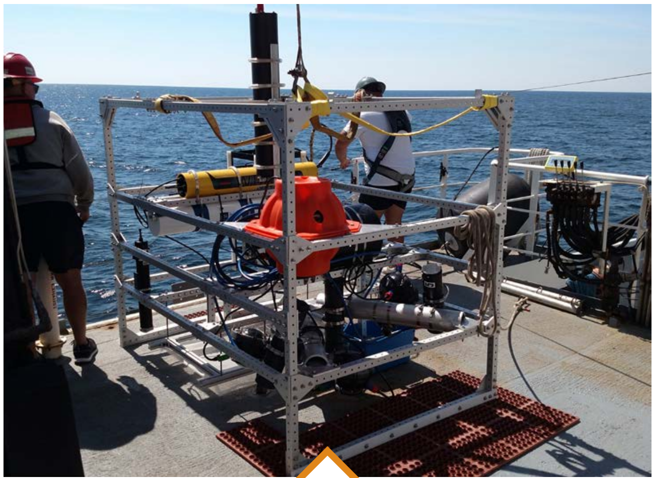


Figure 1. CIOERT's integrated mesopelagic exploration package being readied for deployment on *Okeanos Explorer* in the western Gulf of Mexico. *Credit: Twardowski Lab, CIOERT, FAU Harbor Branch*

CIOERT's efforts to explore and characterize mesophotic coral reef ecosystems via ROV and technical diving continued in July 2018 with a cruise to the Northwestern Gulf of Mexico (NWGOM) aboard R/V *Manta*. Employing an interdisciplinary, multiscale approach, CIOERT and Flower Garden Banks National Marine Sanctuary (FGBNMS) partners examined the connectivity processes that drive coral reef community structure, biodiversity, and ecological persistence in the NWGOM (Figure 2). In addition to demonstrating well-connected coral populations in the NWGOM and describing a novel strategy for light limitation in coral-algal symbiosis, CIOERT's research expeditions in the NWGOM have provided critical information regarding a proposed expansion of FGBNMS boundaries.

To advance exploration of deep coral and fisheries habitats in the South Atlantic Bight, CIOERT partnered with NOAA Fisheries to complete their seventh cruise aboard NOAA Ship *Pisces* in May 2018. In total, 29 ROV dives were conducted to evaluate benthic and fisheries communities associated with seven marine protected areas from Florida to the Carolinas. These annual expeditions are part of a long-term exploration program to discover new areas and document changes in specific areas before and after implementation of management actions.

Shore-based science teams at Florida Atlantic University's Harbor Branch's Exploration Command Center contributed to *Okeanos Explorer*'s Gulf of Mexico and Southeastern US Windows to the Deep expeditions in 2018 by supplying information for target dive sites, assisting in species identifications, and providing telepresence outreach opportunities for high school students in Florida.

Figure 2. Technical divers descend to explore mesophotic reefs in the Flower Garden Banks National Marine Sanctuary. *Credit: Voss Lab, CIOERT, FAU Harbor Branch*

Exploration of Biodiversity and Ecosystem Structure on Seamounts in the Western CCZ

By Jeffrey C. Drazen, Matthew Church, Thomas Dahlgren, Jennifer Durden, Adrian Glover, Erica Goetze, Astrid Leitner, Craig R. Smith, and Andrew Sweetman

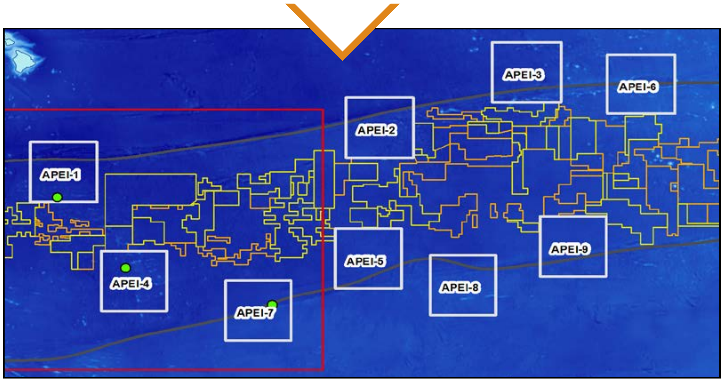
More than one million square kilometers of the abyssal Pacific seafloor called the Clarion-Clipperton Zone (CCZ) have been identified for possible nodule mining. Manganese nodules are a potential source of copper, nickel, cobalt, iron, manganese, and rare earth elements—metals used in electrical systems and for electronics like rechargeable batteries and touch screens. Mining is expected to destroy marine life and seabed habitats over large areas, both at sites that are directly mined as well as at adjoining areas that would be affected by sediment plumes created by mining activities. The DeepCCZ expedition was the first to explore the diversity of organisms on seafloor plains and seamounts in areas currently designated as "no-mining areas" in the western CCZ (Figure 1). A major goal is to determine whether these protected areas are adequate for conserving the region's biodiversity from destructive seafloor mining activities.

The expedition used a suite of state-of-the-art deep-sea technologies to study the biodiversity and ecology of abyssal organisms. Twelve dives were conducted with the University of Hawai'i's ROV *Lu'ukai*, which used robotic arms and deep-sea cameras to photograph and collect animals, manganese nodules, and sediments from greater than 4 km depth. An autonomous respirometer measured biological activity and food web structure of deep-sea sediment communities. Baited stereo cameras attracted and measured the mobile predators at the top of the deep-sea food chain (Figure 2). Water filters were deployed autonomously to the seafloor to capture the larvae of the benthic fauna and evaluate connectivity. Samples for subsequent DNA analyses were collected from the environment, and from individual animals, to test new approaches for assessing biodiversity and ecological functions of microbes and animals living in sediments, on manganese nodules, and in the overlying waters. DNA samples will also aid in the identification and description of the many new species, and in assessing their occurrence across the abyssal Pacific Ocean.

The data and samples are expected to substantially improve understanding of the biodiversity and ecology of the vast and poorly studied CCZ. More than 100 species of large animals were collected or videotaped at the seafloor (Figure 3). Many of these animals appear to be newly discovered species. In addition to being used to assess the adequacy of conservation measures, these data will also be incorporated into a regional synthesis of the CCZ to be used to make science-based recommendations to the International Seabed Authority and other stakeholders concerning environmental protection and management for deep-sea mining in the CCZ.

We thank OER, the Gordon and Betty Moore Foundation, the Pew Foundation, and the School of Ocean and Earth Science and Technology at the University of Hawai'i at Manoa for their support.

Figure 1. Map of the Clarion-Clipperton Zone showing exploration license areas and reserve mining areas in colored polygons. The white boxes indicate the no-mining zones called Areas of Particular Environmental Interest (APEI). Green dots are the locations of expedition dive sites in APEIs 1, 4, and 7. *Courtesy of the DeepCCZ expedition*



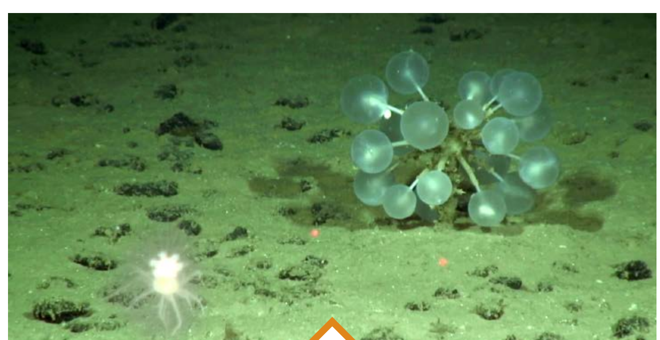


Figure 3. Two carnivorous Cladorhizid sponges at 5,000 m depth in the western CCZ. *Courtesy of the DeepCCZ expedition*

Figure 2. Very large aggregation of eels, *Ilyophis aryx*, attracted to a baited camera at a seamount in APEI 7. *Courtesy of the DeepCCZ expedition*

Kiska: Alaska's Underwater Battlefield

By Andrew T. Pietruszka, Eric J. Terrill, and Mark A. Moline

In July 2018, Scripps Institution of Oceanography and University of Delaware scientists spent two weeks conducting a remote-sensing survey to locate and document World War II-era submerged archaeological sites in the waters off of Kiska Island, Alaska, one of the most remote islands in the Aleutian chain.

The Aleutian campaign was the sole World War II campaign fought on North American soil, and Kiska Island is one of the few US territories occupied by foreign forces in the last 200 years. Kiska remains one of the best-preserved historic battlefields from World War II, and is one of only two world-wide where neither previous nor later settlement obscure military developments. In recognition of its pivotal role in the Allied-Japanese campaigns of 1942–1943, Kiska Island was designated as a National Historic Landmark in 1985. While the terrestrial component is well documented, the maritime component remained largely unexplored until the OER-sponsored expedition.

The survey focused on four distinct search areas, each relevant to a unique aspect of the battlefield's maritime cultural landscape (Figure 1). Home to the Japanese naval installation, Area 1, Kiska Harbor, was the most frequent target of the US bombing campaign. Historical records indicate many Japanese ships and aircraft, as well as US aircraft, were lost there. Area 2 encompasses the final resting place of the Japanese submarine I-7, which was lost while assisting the Japanese planned evacuation. Area 3, Gertrude Cove, garrisoned over 3,500 Imperial Army men, and it is the site of several US bomber losses and Japanese ships. Area 4 is associated with the US effort to retake Kiska. On August 18, 1943, USS *Abner Read* struck a Japanese mine while patrolling off the northwest landing beach causing the stern to break off and sink with 71 men trapped inside.

The project featured a wide spectrum of state-of-the-art marine technology. The primary tool employed was compact autonomous unmanned underwater vehicles (UUVs) equipped with side-scan sonar, magnetometers, multibeam sonar, and low-light imaging capabilities (Figure 2). Additional coverage and high-resolution acoustic imaging were provided by a hull-mounted multibeam sonar system. About 35 km^2 were surveyed with side-scan sonar, 46 km^2 were surveyed during the multibeam survey, and the team conducted 40 cold water scuba dives. Analysis is ongoing, but several significant finds are already confirmed including the stern of USS *Abner Read*, three Japanese submarines (I-7, RO-65, and a midget submarine; Figure 3), portions of a US B-24 aircraft, and the remains of multiple Japanese and American landing craft.

Figure 1. Map of Kiska Island indicating the four areas surveyed during the Kiska submerged cultural resource survey. *Courtesy of Scripps Institution of Oceanography*

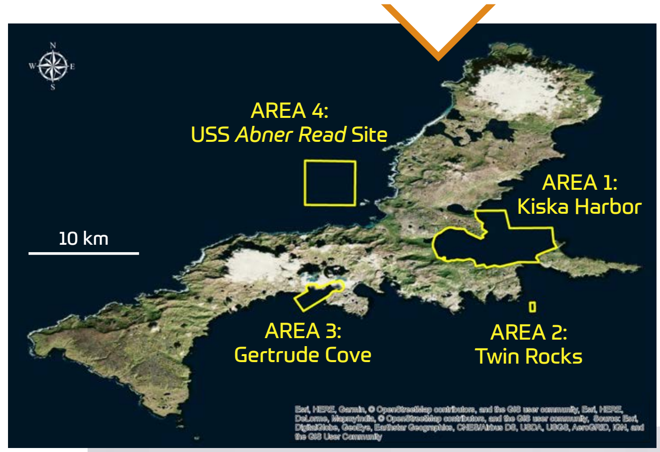


Figure 2. One of four REMUS 100 UUVs utilized during the Kiska survey to image the seafloor to detect potential archaeological sites. *Courtesy of Kiska: Alaska's Underwater Battlefield expedition, Scripps Institution of Oceanography*

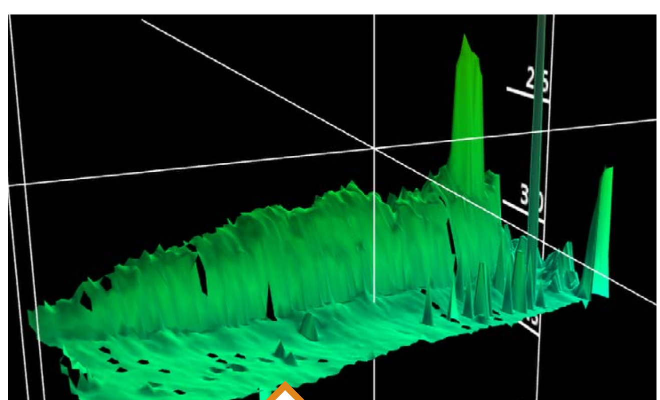


Figure 3. Preliminary multibeam sonar image of a Japanese midget submarine documented during the Kiska survey. *Courtesy of Kiska: Alaska's Underwater Battlefield expedition, Scripps Institution of Oceanography*

Aviators Down! The Search for Tuskegee and Free French World War II Aircraft in Lake Huron

By Wayne R. Lusardi

During World War II, Michigan was home to several African-American Army Air Corps units, including graduates of the Tuskegee pilot training program, and to pilots of the Free French Air Force. The pilots received training in the relative safety of the American Midwest with weather and geographical conditions that approximated what aviators could expect to encounter in Europe (Figure 1). Combat pilot training is not without risk. Mishaps, accidents, and mechanical problems caused accidents, some of which occurred over Lake Huron. A geospatial analysis of historical records determined five areas of Lake Huron within and adjacent to Thunder Bay National Marine Sanctuary where four military aircraft were lost in training accidents during World War II and two more were lost after the war.

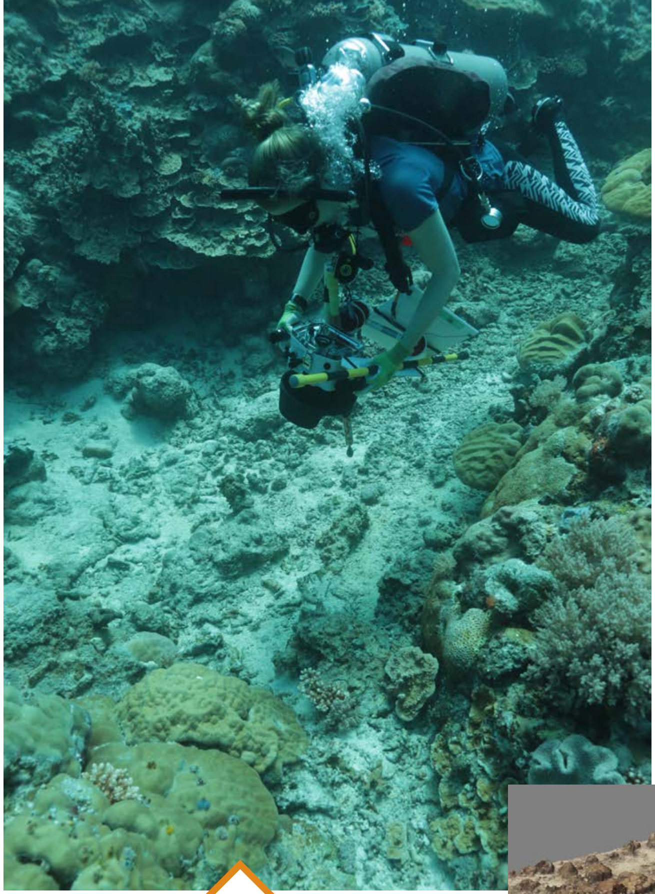
The State of Michigan and NOAA carried out the first year of a two-year search for these aircraft aboard NOAA's R/V *Storm* using multibeam sonar, side-scan sonar, and a cesium-vapor magnetometer. Archaeologists focused their survey of Lake Huron off Alcona and Iosco Counties in Michigan over 19 calendar days from June 27 to September 26, 2018. A total of 583 acoustic and/or magnetic anomalies were recorded during the survey. Ninety-two of the targets were examined, and all but two were geological features.

One acoustic and magnetic anomaly consisted of the ground tackle from a nineteenth-century vessel, including an iron anchor and chain and wooden windlass. The artifacts were not associated with other wreckage and may instead be equipment loss. Another acoustic and magnetic anomaly consisted of a military tow target manufactured in 1956 by Schweizer Aircraft Corporation of Elmira, New York (Figure 2). Positive identification of the Aero X-27A was made following discovery of the aircraft data plate. Targets like the Aero X-27A were towed using piano wire several thousand feet behind jets and used for target practice over Lake Huron. The aluminum targets replaced the older style cloth banners used over the lakes beginning in World War I. The Aero X-27A tow target more closely simulated aerial combat, and could be landed to assess number of hits. Although the wreckage is broken and largely buried in soft sediments, it retains its original red paint on the fuselage and variable pitch wings.

Surveying in Lake Huron will continue in 2019 to complete the five survey areas. All acoustic and magnetic anomalies recorded in 2018 will be investigated to determine whether or not they originated from previously undiscovered World War II aircraft.

Figure 1. The P-39Q Airacobra, a single-seat plane that was the primary aircraft used by Tuskegee airmen over Michigan beginning in September 1943. *Courtesy of the US Army Air Corps*

Figure 2. Michigan State Maritime Archaeologist Wayne Lusardi investigates the only aircraft found during the survey, a military tow target from the 1950s. *Courtesy of John Bright, Thunder Bay National Marine Sanctuary.* INSET. Schweizer Aircraft Corporation of Elmira, New York, manufactured 400 tow targets for the US Navy in the 1950s. How this particular target ended up in Lake Huron is unknown. *Courtesy of Paul Schweizer, Schweizer Aircraft Corporation*

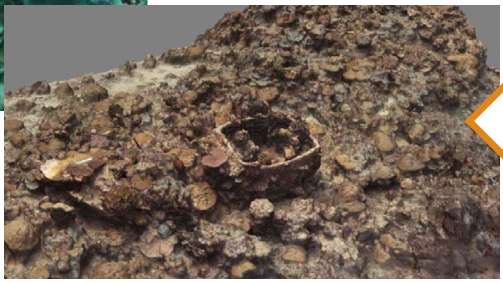


Peleliu's Forgotten World War II Battlefield

By Toni L. Carrell

A Ships of Discovery science team returned to the Peleliu World War II invasion beaches to search for the remains of the amphibious landing craft, airplanes, equipment transports, and tanks lost during the battle on September 15, 1944. They also looked for any evidence of the scars from the underwater demolition team's mission to blow access routes through the shallow reef into lagoon. This was the first project to focus on the landing beaches and survey the reefs to document the biological impacts from the blasting, document the submerged archaeological sites, and explore the amphibious element of the invasion.

Kailey Pascoe, University of Hawai'i at Hilo, documenting the underwater demolition team's blast zone. *Courtesy of Ships of Discovery science team*

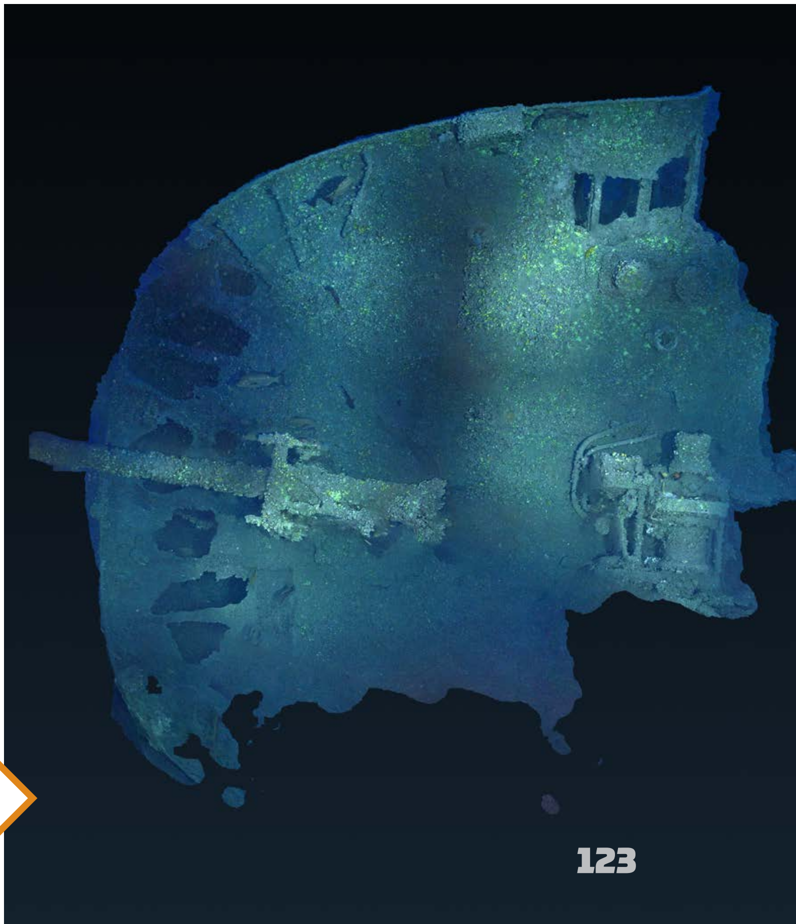


Three-dimensional photogrammetry image of an amphibious landing craft's turret, barely visible in the coral growth after 75 years underwater. *Courtesy Ships of Discovery science team*

The American Theatre of World War II and the KS-520 Convoy Battle

By Joseph C. Hoyt

In 2018, a collaborative team of archaeologists and explorers continued a long-term effort to locate and investigate the remains of World War II shipwrecks such as *Nordal* and *Ljubica Matkovic* off North Carolina believed to be associated with World War II's Battle of the Atlantic. Working from NOAA Ship *Nancy Foster*, Monitor National Marine Sanctuary partnered with Marine Imaging Technologies to deploy "cinema-class" ROV *Pixel* to collect high-definition video and photogrammetric information on several potential targets. The data collected during this expedition support NOAA's efforts to expand the boundaries of the Monitor National Marine Sanctuary to honor and protect shipwrecks of the World War II naval battlefield.



This partial photogrammetry model created from images collected by an ROV show a deck gun and windlass on the stern of a recently discovered but unidentified World War II era shipwreck. *Courtesy of Monitor National Marine Sanctuary*

Instrumentation to Assess the Untainted Microbiology of the Deep-Ocean Water Column

By Doug Bartlett and Alvaro Muñoz Plominsky

A study to explore deep-sea microbes' sensitivity to decompression collected samples at near in situ pressures and temperatures using a modified autonomous lander and associated seawater sampling system. Rotary actuators were used to improve control of seawater entry into titanium pressure-retaining samplers (PRSs), and multiple layers of high-density polyethylene insulation housing were fabricated to improve insulation. This new system was evaluated during a one-day cruise in the San Clemente Basin off the coast of San Diego.

Both the lander and the PRSs functioned well during sea trials (Figures 1 and 2). The lander descended to 2,000 m depth, collected a variety of seawater samples, released its ballast, and was recovered at the surface by virtue of its Iridium GPS signal. The in situ temperature was 2.6°C, and the temperature of the collected seawater samples did not rise above 7.1°C. The pressure retained within the PRSs was 62%–71% of in that situ. The activity of the microbes collected was highest when measured under the same physical conditions employed during their collection (Figure 3).

Additional samples will be collected in 2019 off the coast of Chile, down to ~ 8,000 m depth. The analyses of samples kept cold and pressurized could have profound implications for understanding the numbers, biogeochemical activities, and types of microbes in the deep sea.

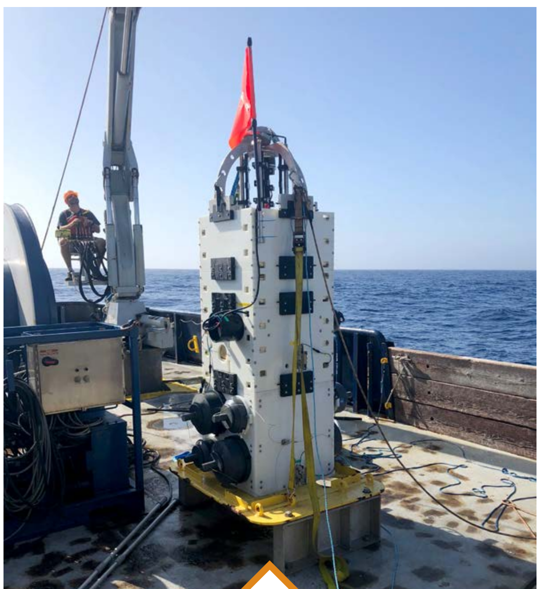


Figure 1. A view of the Bartlett lander during recovery at sea. *Image credit: Doug Bartlett, Scripps Institution of Oceanography*

Figure 2. The pressure-retaining seawater sampler outside of its housing. *Image credit: Doug Bartlett, Scripps Institution of Oceanography*

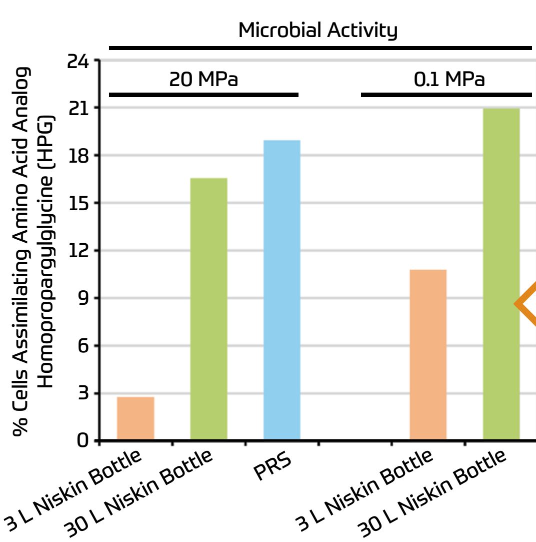


Figure 3. Measurements of the activity of collected microbial cells indicates samples recovered cold and pressurized (PRS) or just cold (30 L Niskin Bottle) have the highest activities when measured at their respective recovery conditions. In contrast, the seawater sample that was allowed to both decompress and warm (3 L Niskin Bottle) had greatly reduced microbial activity at cold temperatures and especially at cold and pressurized conditions. *Credit: Alvaro Muñoz Plominsky, Scripps Institution of Oceanography*

Comparison of Free Vehicle and Conventional CTD

By Wilford Schmidt, Danilo Rojas, Ryan Smith, and Manuel Jimenez

A series of banks south of the US and British Virgin Islands provides habitats and spawning sites for economically important fish species. Prior to 2007, when the ongoing Coral Reef Ecosystem Research study was initiated, the biological and physical processes that drive production on these banks, and the circulation connecting these areas, had not been quantified. A conventional CTD survey conducted aboard NOAA Ship *Nancy Foster* provided an excellent opportunity to ground truth the newly developed University of Puerto Rico – Mayagüez (UPRM), free vehicle (FV) in an operational setting (Figure 1).

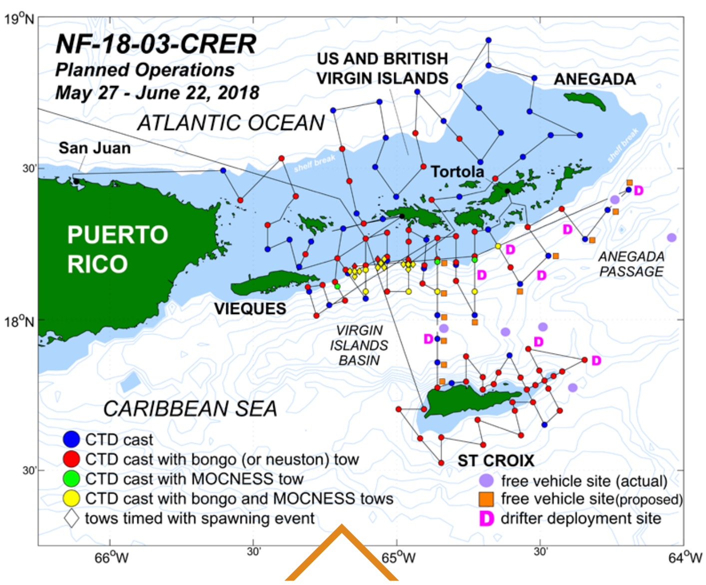
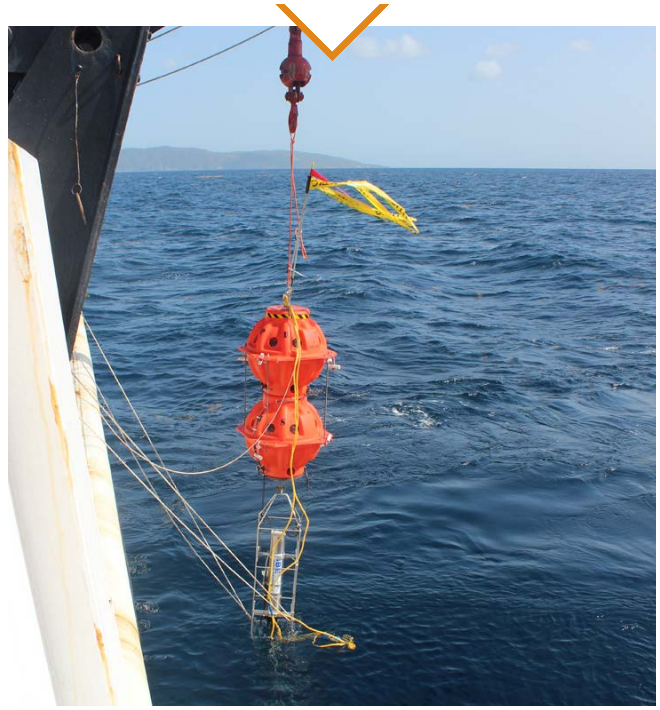


Figure 1. NF-18-03-Coral Reef Ecosystem Research (CRER) proposed activities and actual FV deployment locations. *Credit: NOAA, CRER*

The conventional casts used a 24-bottle rosette provided by NOAA's Atlantic Oceanographic and Meteorological Laboratory in conjunction with an SBE 9plus CTD (Figure 2). The casts were supposed to be to full water column depth, but spool problems limited the maximum depth to <3,000 m. The FV was subsequently deployed with a CTD scientific payload consisting of a full ocean depth SBE 19plus V2 CTD, augmented by inertial navigation sensors and multispectrum signaling capabilities (strobe, RF, and satellite position uplink).

The six FV deployments ranged in depth from approximately 1,100 m to 4,350 m. In one instance, the FV was programmed to "wait" on bottom for several hours while the ship conducted a plankton tow away from the deployment location. When the tow was completed, the ship returned to retrieve the concurrently surfacing FV. Figure 3 compares conventional (NF) and FV CTD temperature and salinity data. Analysis of the two data sets is ongoing, but initial indications suggest very good agreement.

Figure 2. Deployment of the Free Vehicle. *Image credit: Anonymous, NOAA Ship Nancy Foster*



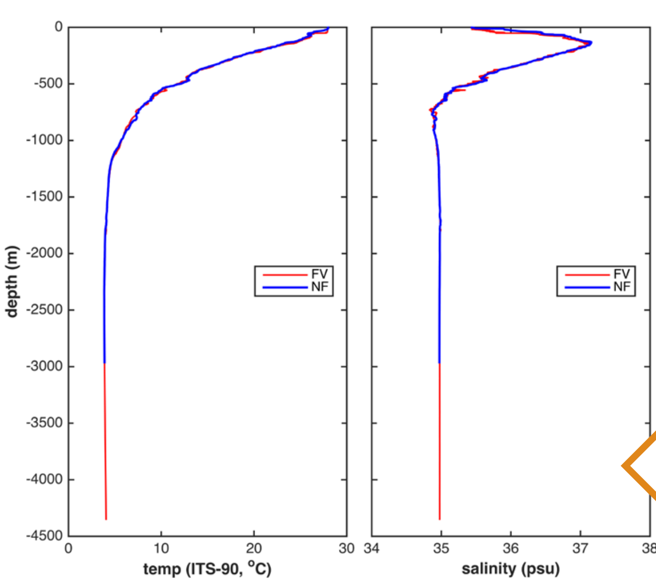


Figure 3. NF-18-03-CRER conventional and FV CTD data (June 17, 2018), 17°56.38'N, 64°51.49'W). *Credit: Wilford Schmidt, UPRM*

Midwater Acoustic Echosounding with the Wire Flyer Towed Profiling Vehicle

By Christopher Roman, Joe Warren, Erik Cordes, and Brad Seibel

Oxygen minimum zones (OMZs) are found throughout the world ocean. These regions are characterized by strong mesopelagic vertical oxygen gradients and hypoxic conditions that exert considerable influence on biogeochemical properties and organism distributions (Wyrtki, 1962; Karstensen et al., 2008; Wishner et al., 2018). This project integrated a dual-frequency (70 kHz and 200 kHz) EK80 echosounder into the Wire Flyer towed profiling vehicle to make detailed observations in OMZs (Roman et al., 2019). Shipboard acoustic echosounders are standard tools for measuring the abundance and distribution of marine organisms. Recently, vehicle-based acoustic systems have provided more detail at depths beyond the attenuation limits of surface systems (Benoit-Bird et al., 2016). By incorporating active acoustics on a profiling vehicle, it is possible to collect backscatter information with matching environmental data.

The Wire Flyer (Figure 1) slides up and down a towed 0.322″ CTD wire in a controlled manner using lift created by wing foils. The vehicle can achieve specific up and down velocities between 0 m s^{-1} and 2.5 m s^{-1} while profiling a prescribed region of the water column. The profiling pattern can repeat with kilometer spacing and provide spatial details that are otherwise difficult to obtain. The vehicle is equipped with sensors for temperature, salinity, oxygen, turbidity, and chlorophyll.

The echosounder and Wire Flyer were used in the Costa Rica margin OMZ to collect detailed hydrographic sections in the vicinity of several methane seeps (Figure 2). The data show a persistent acoustic scattering layer at the lower oxycline that is not affected by diel vertical migration. Further investigation of these data and future cruises will provide insight into these types of features and the links between niche midwater conditions and organism distributions.

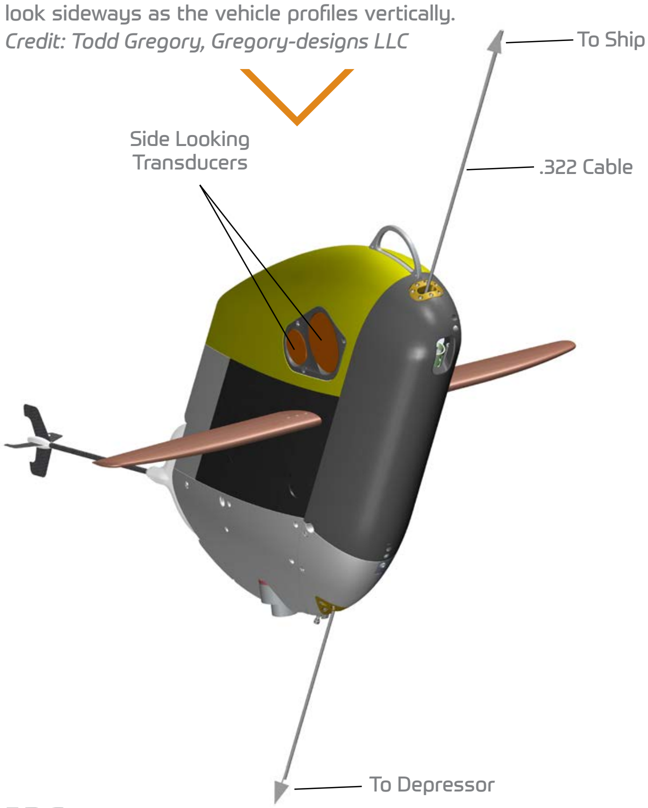


Figure 1. The Wire Flyer vehicle slides along a standard cable using controllable wings for propulsion. The echosounder is oriented to look sideways as the vehicle profiles vertically. *Credit: Todd Gregory, Gregory-designs LLC*

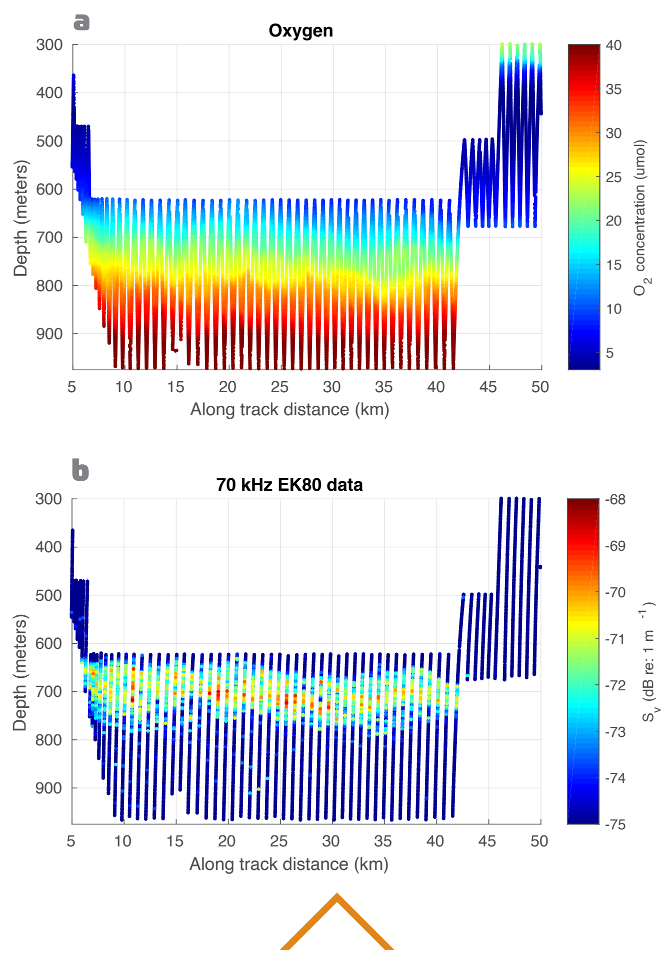


Figure 2. Example hydrographic sections showing (a) oxygen and (b) 70 kHz volume backscatter collected on an overnight tow at the Costa Rica margin (8°57′N, 84°18′W). *Credit: Christopher Roman, University of Rhode Island*

3D "Seismic Oceanography": The New Frontier in Ocean Water Column Exploration

By Leonardo Macelloni, Likun Zhang, Parsa Rad, and Zheguang Zou

Ocean mixing processes are fundamentally three dimensional (3D), thus features such as internal waves, tidal beams, solitons, and eddies are expected to change in both space and time. Their fine-scale structure is very difficult to reconstruct with the traditional sparse oceanographic observations (i.e., CTD and XBT casts, glider transects, moorings) especially in deep water.

Through this project, novel 3D images of ocean structures were constructed using high-quality 3D seismic data (courtesy of Schlumberger WesternGeco) collected in the northern Gulf of Mexico (Figure 1). A specific 3D processing workflow enhanced the inherently weak water column reflections, which were not the primary data collection targets. A seismic volume (20 km × 20 km) was created with a spatial resolution of 25 m inline, 6.25 m crossline, and a vertical resolution of about 6 m (Figure 2). Several ocean processes are observed at unprecedented resolution both laterally and vertically, including part of an eddy (Figure 3) and internal waves that are propagating and reflecting along the continental slope (Figure 2). Additionally, because the seismic survey was collected over a six-month period (from June to December 2002), we may be able to capture the temporal variability of some of these processes. Discerning the potential of 3D seismic oceanography has just begun. Beyond simply providing a novel way to visualize oceanic fine-scale structures, it can supply valuable quantitative information.

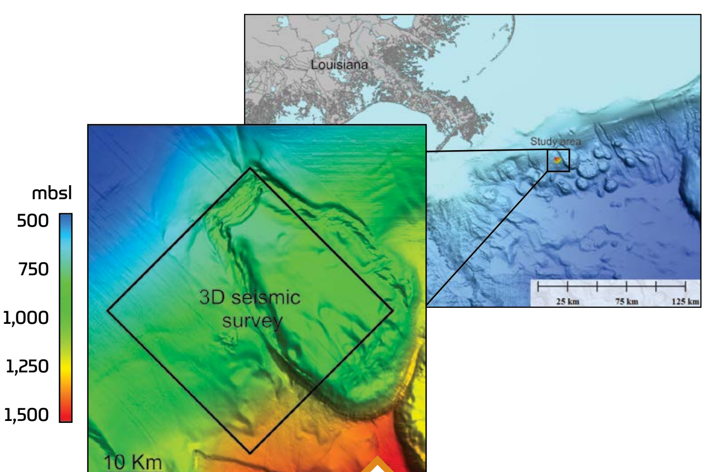


Figure 1. Location of the 3D seismic volume on the northern Gulf of Mexico continental slope. The seismic data cover an area of approximately 20 km x 20 km, water depth ranges from 800 m to 1,200 m. *Credit: Leonardo Macelloni, University of Mississippi*

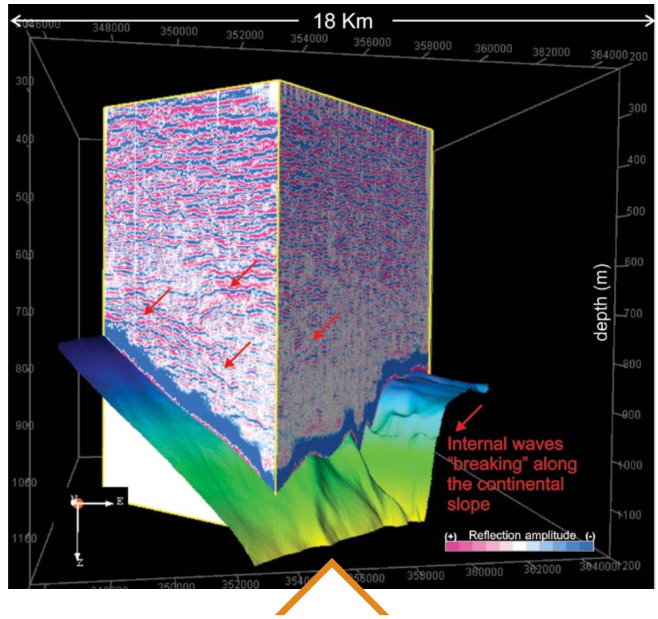


Figure 2. Tridimensional rendering of the water column 3D seismic volume, using Kingdome Vu-Pack. Internal waves captured by the seismic data are propagating and reflected along the slope. Because the acquisition geometry is designed to illuminate deep subseabed structures, seismic data optimally image water column beneath 200 m. The slope morphology from multibeam bathymetry is displayed for reference. *Credit: Leonardo Macelloni, University of Mississippi*

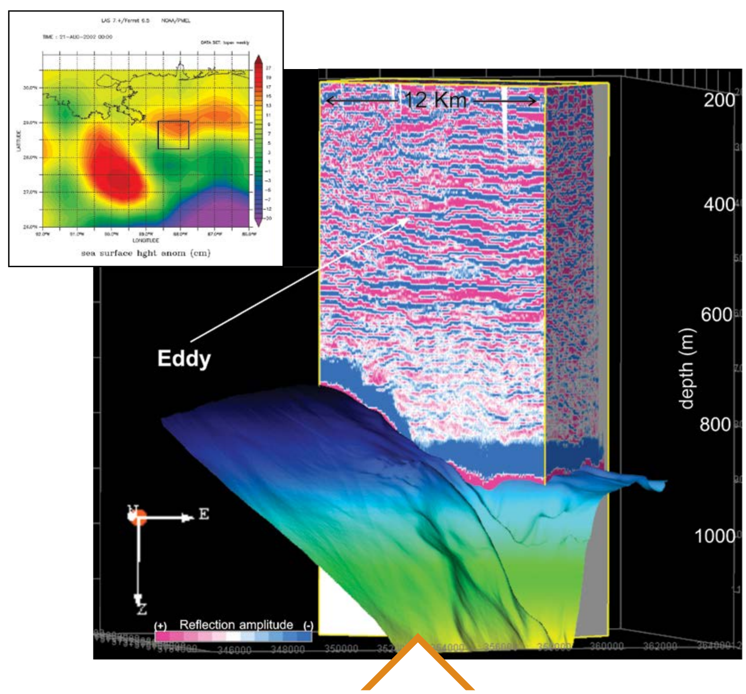
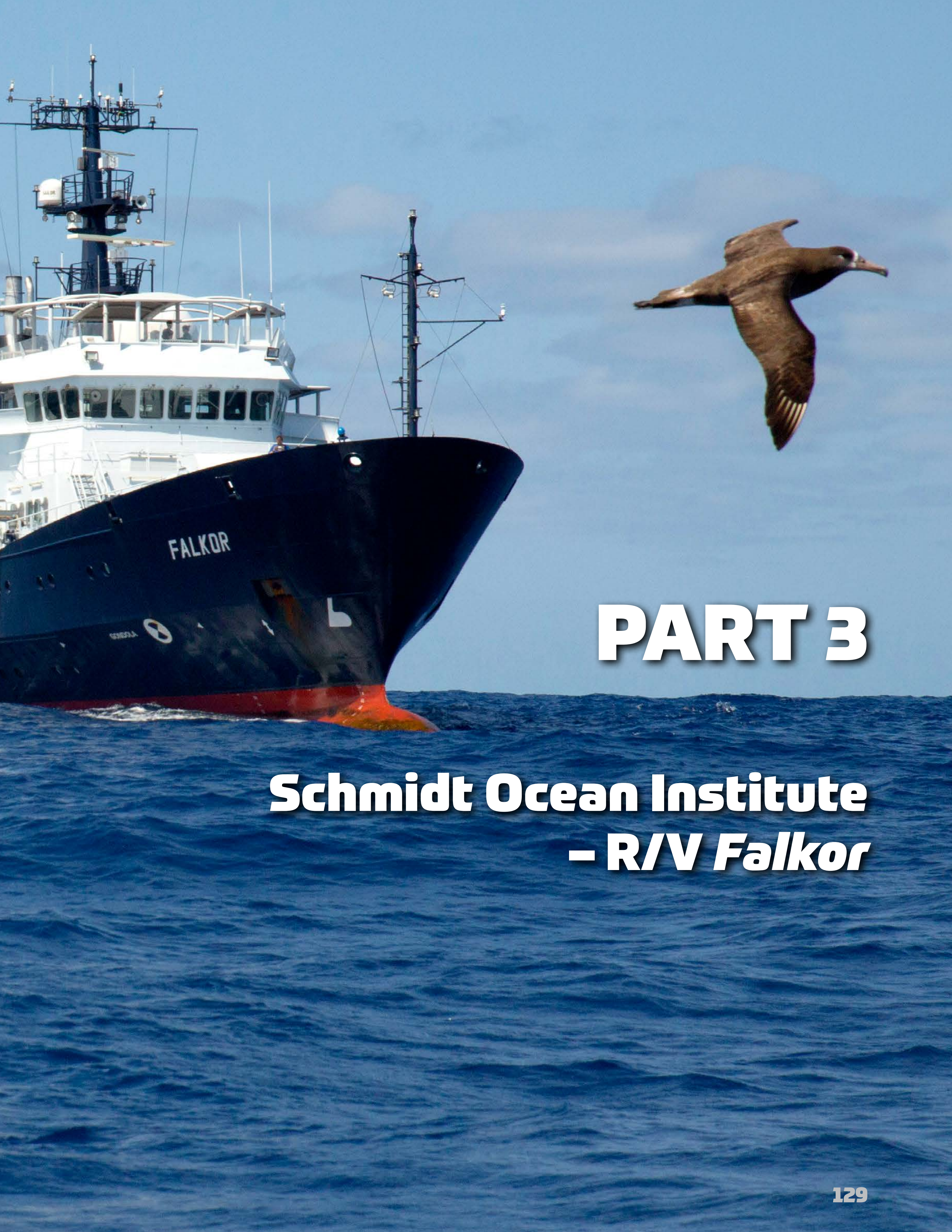


Figure 3. A portion of a Gulf eddy is captured in the seismic data. The eddy is present between 200 m and 600 m depth. Records of sea surface satellite anomalies, covering the same time window of the seismic data, confirm the presence of a large eddy in the area. *Credit: Leonardo Macelloni, University of Mississippi*

An albatross leads the way as long-range autonomous underwater vehicles (LRAUVs) are deployed from *Falkor* north of the island of Maui. The LRAUVs' mission is to characterize the forming eddy's physical, chemical, and biological features.

Note: All images in the Falkor *section of this publication are copyright Schmidt Ocean Institute unless otherwise indicated.*



PART 3

Schmidt Ocean Institute – R/V *Falkor*

Scaling Up Marine Science and Conservation with

Artificial Intelligence and Smart Robotics in 2018

The year 2018 was a landmark for software, robotics, and data platforms at Schmidt Ocean Institute (SOI). R/V *Falkor* was constantly on the move, with 11 expeditions that emphasized technology trials and software development. New technologies are changing the way work is conducted at sea, creating efficiencies and permitting greater discoveries in areas that had previously eluded scientists. Robotic systems working together to make critical decisions allow scientists to cover more ocean and make intelligent choices. A vast amount of time and development goes into each and every robot, program, and algorithm, but we know that these long-term investments will provide a better understanding of our dynamic ocean. New knowledge emerging from these investments can, in turn, be used to improve ocean policies and management. We describe here 13 outcomes that had an impact on ocean sciences in 2018.

Falkor crew recovering a University of Rhode Island Lagrangian float. The float covered 33 km of distance at a depth range of 23–85 m, while making 72,267 images over the course of 55 deployments.

1. TAUGHT ROBOTS TO COLLABORATE AND SHARE KNOWLEDGE TO IMPROVE MARINE SURVEY QUALITY, COVERAGE, AND COST-EFFICIENCY

CRUISE: Coordinated Robotics Part 2
CHIEF SCIENTIST: Oscar Pizarro, Australian Centre for Field Robotics, The University of Sydney

A team of scientists and engineers from the University of Sydney, Woods Hole Oceanographic Institution (WHOI), Massachusetts Institute of Technology (MIT), University of Rhode Island, and University of Michigan spent a month aboard *Falkor* in the Au'Au' channel between the islands of Maui and Lāna'i to test the utility of simultaneous deployment of multiple autonomous vehicles. The team used six autonomous underwater vehicles and two autonomous surface vehicles to accomplish many goals, including an automated survey planning framework for multiple vehicles operating simultaneously in the same area that can maximize the contribution of each platform to overall marine surveying. The group used several strategies, such as intelligent analysis of available and incoming sensor data, as well as efficient survey task allocation and reallocation. The acquired data were immediately applied to further guide the autonomous survey planning. Additionally, open source Maptracker software was deployed on *Falkor* to monitor and, if necessary, interactively control the robots in real time. It was used to broadcast operations online and was integrated with Squidle+ image annotation software to display geolocated scientific images as a data layer.

AUV *Sirius* is one of seven autonomous vehicles used in the 2018 "Coordinated Robotics" expedition. Specifically designed for high-resolution benthic optical and acoustic imaging work, the AUV is equipped with a full suite of oceanographic instruments, including a high-resolution stereo camera pair and strobes.

2. ACHIEVED THE LONGEST DEPLOYMENT OF ENVIRONMENTAL SAMPLING PROCESSORS ON LONG-RANGE AUVS

CRUISE: Eddy Exploration and Ecosystem Dynamics
CHIEF SCIENTISTS: Sam Wilson and Steve Poulos, University of Hawai'i

In a joint effort between the Simons Collaboration on Ocean Processes and Ecology (SCOPE), Monterey Bay Aquarium Research Institute (MBARI), and SOI, several long-range autonomous underwater vehicles (LRAUVs) worked together successfully on a voyage in the open ocean, gathering microbiological samples and oceanographic data down to 250 m in the water column for up to 100 hours. Deploying multiple vehicles from *Falkor* simultaneously allowed the research team to sample continuously within a moving eddy field, setting a new record for duration in this type of mission. The data collected were transmitted to *Falkor* in near-real time for assimilation and comparative display alongside data from the shipboard instruments. The LRAUVs intelligently tracked, mapped, and sampled the oceanographic eddy features with greater spatial and temporal fidelity than would have been possible using conventional shipboard observations. This was one of the earliest deployments of the AUVs integrated with Environmental Sample Processors—miniature robotic laboratories that collect and preserve seawater samples at sea. These miniaturized processors were designed specifically to fit inside the LRAUV, allowing researchers to capture snapshots of organisms' genetic material and proteins, advancing capabilities for studying marine microbial interactions in the open ocean.

Researchers collect and secure water samples from a recovered sediment trap on *Falkor's* aft deck.

In early March 2018, two months before *Falkor* departed for the same mission, two Saildrones were deployed from San Francisco to be a part of the Voyage to the White Shark Café. These autonomous surface vehicles have been transmitting data in real time since then, listening for the acoustic tags that are attached to sharks while also scanning with sonar to detect the deep scattering layer.

3. FIRST DETAILED CHARACTERIZATION OF THE WHITE SHARK CAFÉ WITH SAILDRONES AND SHIPBOARD eDNA TO PROTECT WHITE SHARKS

CRUISE: Voyage to the White Shark Café
CHIEF SCIENTIST: Barbara Block, Stanford University

Scientists from Stanford University, MBARI, Monterey Bay Aquarium, the University of Delaware, and NOAA's Office of Ocean Exploration joined their efforts with SOI to learn what draws white sharks to the area known as the White Shark Café, located halfway between Hawaiʻi and Baja California. In a departure from a conventional open-ocean science pattern, two environmentally powered autonomous surface vehicles, called Saildrones, were launched from San Francisco Bay two months ahead of *Falkor*'s voyage to find and track tagged sharks congregating at the Café. By the time *Falkor* arrived, the Saildrones had located all 20 tagged sharks. Knowing exactly where to collect samples and other data increased the research team's productivity. Using ROV *SuBastian*, the team gathered extracellular DNA samples and sequenced them on *Falkor* to better understand what draws the large white sharks to this remote area—previously considered an "oceanic desert" and now re-discovered as a diverse and vibrant marine ecosystem. The new findings and observations will help make a case for designating the White Shark Café as the first high seas World Heritage Site.

Planctoteuthis (fragile deep sea squid whose tail structure mimics the shape of its prey) is an example of the unexpected variety of life seen during the exploration in the White Shark Café. The area had been assumed to be an "ocean desert," barren of food sources for predators. Our research revealed an unexpected oasis of biological productivity there.

4. LOCATED AND MAPPED A PACIFIC SUBTROPICAL OCEAN FRONT IN 4D USING A COORDINATED FLEET OF AUTONOMOUS ROBOTS

CRUISE: Exploring Fronts with Multiple Robots
CHIEF SCIENTIST: João Borges de Sousa, University of Porto, Portugal

On its way back from the White Shark Café, a Saildrone joined more than a dozen aerial, surface, and underwater robotic vehicles, supported from *Falkor,* in locating, exploring, and mapping in four dimensions a large, dynamic subtropical Pacific Ocean front. In a first-of-its-kind open ocean demonstration, a distributed robotic system acted as an intelligent and adaptive sensor network to autonomously track the front based on real-time analysis of the multiplatform sensor data. The science and engineering team from Laboratório de Sistemas e Tecnologia Subaquática, Universidade do Porto, NASA, and 10 other organizations successfully demonstrated an easier, faster, and more cost-effective way of comprehensively characterizing large and dynamic oceanic features with high resolution in four dimensions. Intelligent multi-vehicle open source control software, Neptus and Ripples, was refined throughout the expedition to automatically optimize the operations of all deployed robots and facilitate control of the robotic fleet based on real-time survey data. The software ran nonstop for most of the expedition with just one operator in *Falkor's* Science Control Room for safety monitoring.

The collection of robotics for the expedition—including underwater and aerial autonomous vehicles—on the aft deck of *Falkor*.

5. TESTED IN SITU MICROBIAL INCUBATORS TO UNDERSTAND HOW MARINE LIFE ADAPTS TO OXYGEN DEPLETION IN THE OCEAN

CRUISE: Solving Microbial Mysteries with Autonomous Technology
CHIEF SCIENTISTS: Karen Casciotti, Stanford University, and Andrew Babbin, MIT

In some oceanic oxygen minimum zones, microbial organisms evolve to use nitrogen instead of oxygen to survive. Though the effects of this evolution on marine life can be broad, they are poorly understood. Traditional methods of ship-based study require researchers to bring water samples aboard the vessel, which introduces several possibilities of exposing the recovered samples to oxygen contamination. To address this issue, a research team from Stanford University and MIT developed in situ microbial incubators to observe and document microbial processes over time while the samples were still underwater. A new multi-chamber incubator was tested and refined at a range of depths for up to 24 hours at a time during a research and development expedition on *Falkor*. This technology dramatically increases the efficiency and fidelity of observations, as well as the number of samples that scientists are able to collect, while decreasing the risk of sample contamination. These types of innovations are game changers in the understanding of the evolution of ocean microbes, allowing researchers to better predict how a warming climate and expansion of low oxygen "dead" zones will threaten the livelihoods of many coastal communities.

Diana Dumit connects water samples to her purge rack in the *Falkor* wet lab. Bubbling the sample with helium removes the oxygen, allowing Dumit and other members of the team to conduct their oxygen-deficiency experiments.

6. CREATED ARTISTIC VISUALIZATIONS AND CURATED ORIGINAL PRODUCTIONS OF MARINE DATA TO ENGAGE THE PUBLIC

CRUISE: The Seeping Cascadia Margin
CHIEF SCIENTIST: Susan Merle, NOAA Pacific Marine Environmental Laboratory

During an SOI expedition to the active Cascadia margin, six Artists-at-Sea and two Student Opportunities participants assisted in collecting multibeam mapping data and creating detailed maps of the midwater and the seafloor. The maps will be used to locate hydrocarbon seeps and determine the strengths of seafloor emissions, allowing scientists to ascertain if natural events such as earthquakes could result in sudden methane release with associated environmental impacts. Throughout the voyage, the artists captured the mapping work of *Falkor's* marine technicians with individualistic art forms, including a light painting performance, oceanscape resin art, woodworking sculpture, portrait painting, cyanotype prints, and a larger-than-life-size mural of the *Pseudoliparis swirei* ghost fish.

Susan Merle stands in front of the projection made by Artist-at-Sea Lori Hepner. Hepner moves and performs in her custom-made LED body suit to create light paintings. In this case, the light painting used Merle's multibeam sonar imagery to make a visual representation of the data on *Falkor's* aft deck.

7. GUIDED ROBOTIC EXPLORATION AND RESEARCH ON CHANGING SEAFLOOR HABITATS USING ARTIFICIAL INTELLIGENCE

CRUISE: Adaptive Robotics at Hydrate Ridge
CHIEF SCIENTIST: Blair Thornton, University of Southampton, UK

An international team of robotics researchers and ocean scientists from 10 institutions, including the University of Southampton, University of Tokyo, and Japan Agency for Marine-Earth Science and Technology, deployed a broad area surveying AUV from *Falkor* to acquire over 1.3 million seafloor images of changing microbial habitats surrounding methane seeps at Hydrate Ridge off the coast of Oregon. The team used shipboard high-performance computers with graphic processing units to quickly compose these images into the largest known centimeter-resolution color three-dimensional model of 12 hectares of seafloor. Using a form of unsupervised machine learning, the researchers promptly analyzed the huge volumes of acquired images, clustered them by visual similarity, and used the clusters to accurately locate the continuously changing microbial hotspots on the seafloor. Once found, they then conducted detailed surveys and sampling using a high-resolution mapping AUV and ROV *SuBastian*. This project demonstrates how the use of intelligent robotics, high-throughput data analysis, and machine learning at sea can augment the productivity and oceanographic research activities. These innovations allowed the scientists to make quick and well-informed decisions about how to direct their sampling and fine-scale surveys to study the rapidly changing marine habitats that would otherwise be virtually impossible to visit and observe in detail.

Blair Thornton guides one of ROV *SuBastian*'s dives using the maps and images acquired by the AUVs and processed by unsupervised algorithms. The expedition used a suite of AUVs with different mapping capabilities and specialties to gather the bathymetry data for the experimental artificial intelligence software to decipher.

WHOI Postdoctoral Scholar Veronique Oldham analyzes samples recovered from a CTD cast inside a methane plume. INSET. Gas bubble capture in a repurposed push core to observe hydrate formation—one of the many techniques used to gather data on methane seepage into the water column.

8. DEVELOPED NEW WAYS TO UNDERSTAND OCEAN CYCLES WITH STUDY OF METHANE BUBBLES

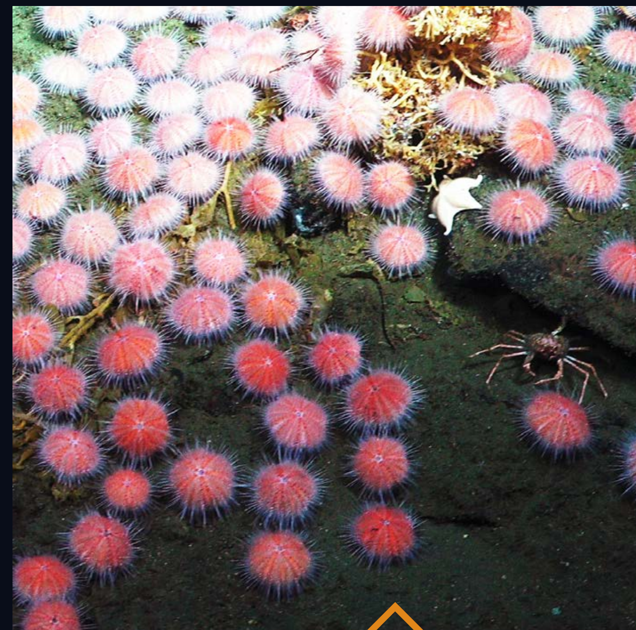
CRUISE: Hunting Bubbles: Understanding Plumes of Seafloor Methane
CHIEF SCIENTISTS: Scott Wankel and Anna Michel, WHOI

Historical, large-scale changes in Earth's climate are thought to be related to release of methane gas from the land and the ocean. Greater knowledge of methane seeps around the globe is needed to fully understand the impact this gas will have on the future environment. A team led by scientists from WHOI, Harvard University, and Texas A&M used *Falkor* and ROV *SuBastian* to study methane bubble release with a new in situ chemical and isotope sensor and a novel deep-sea stereo camera with bubble imaging capabilities. The scientists collected and analyzed bubbles within rising plumes and the nearby water column to understand the processes that govern methane escape and transfer from active release sites to the water column and the atmosphere. The in situ mass spectrometer measured the chemical composition of bubbles underwater for the first time, while at the same time using the laser spectrometer to periodically measure the isotopic fingerprints of the methane. These activities demonstrated a new way of gathering these types of data on the chemical dynamics of bubbles in situ. An alarming discovery was that the methane was reaching the atmosphere, despite this possibility being dismissed previously. However, quantification of the exact amounts of gas escaping the water column is yet to be carried out based on detailed sample and instrument data analyses.

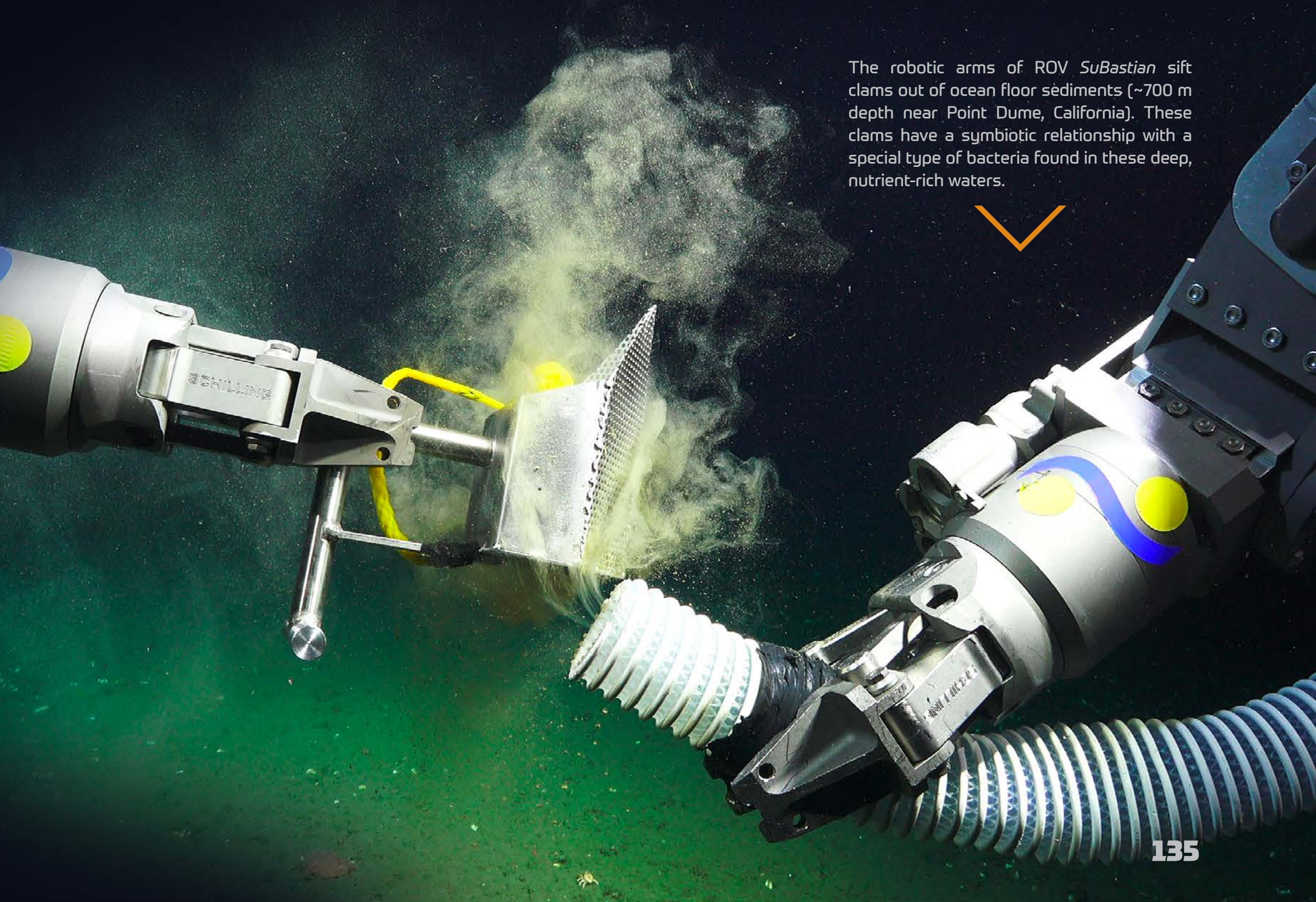
9. REVEALED NEW SITES AND SPECIES IN THE CALIFORNIA BORDERLAND

CRUISE: Characterizing Venting and Seeping Along the California Coast
CHIEF SCIENTIST: Peter Girguis, Harvard University

A research team led by scientists from Harvard University, WHOI, and NASA conducted an ROV-based expedition to determine whether the gas vents and seeps off Southern California represent a unique assemblage of habitats, or if they ecologically connected to vent sites located both north and south of California. Seventeen ROV *SuBastian* dives were completed, including visits to four sites previously uninvestigated with an ROV. Characterizing the geophysical, geological, geochemical, and biological aspects of the system, the team worked to understand the seeps' ecological roles, including their part in sustaining lucrative fisheries. Rare animals, such as the seven-legged octopus *Haliphron*, were observed in addition to several new species. The data collected will further understanding of how seep communities function and of the unique biological processes occurring at each vent. During the expedition, the team worked with the Autonomous Biogeochemical Sampling System (ABISS) lander in coordination with NASA. These observations will serve as a testbed for NASA technology intended for potential study of oceans on other planets.



Sea urchins line the ocean floor a few kilometers off the coast of Southern California.



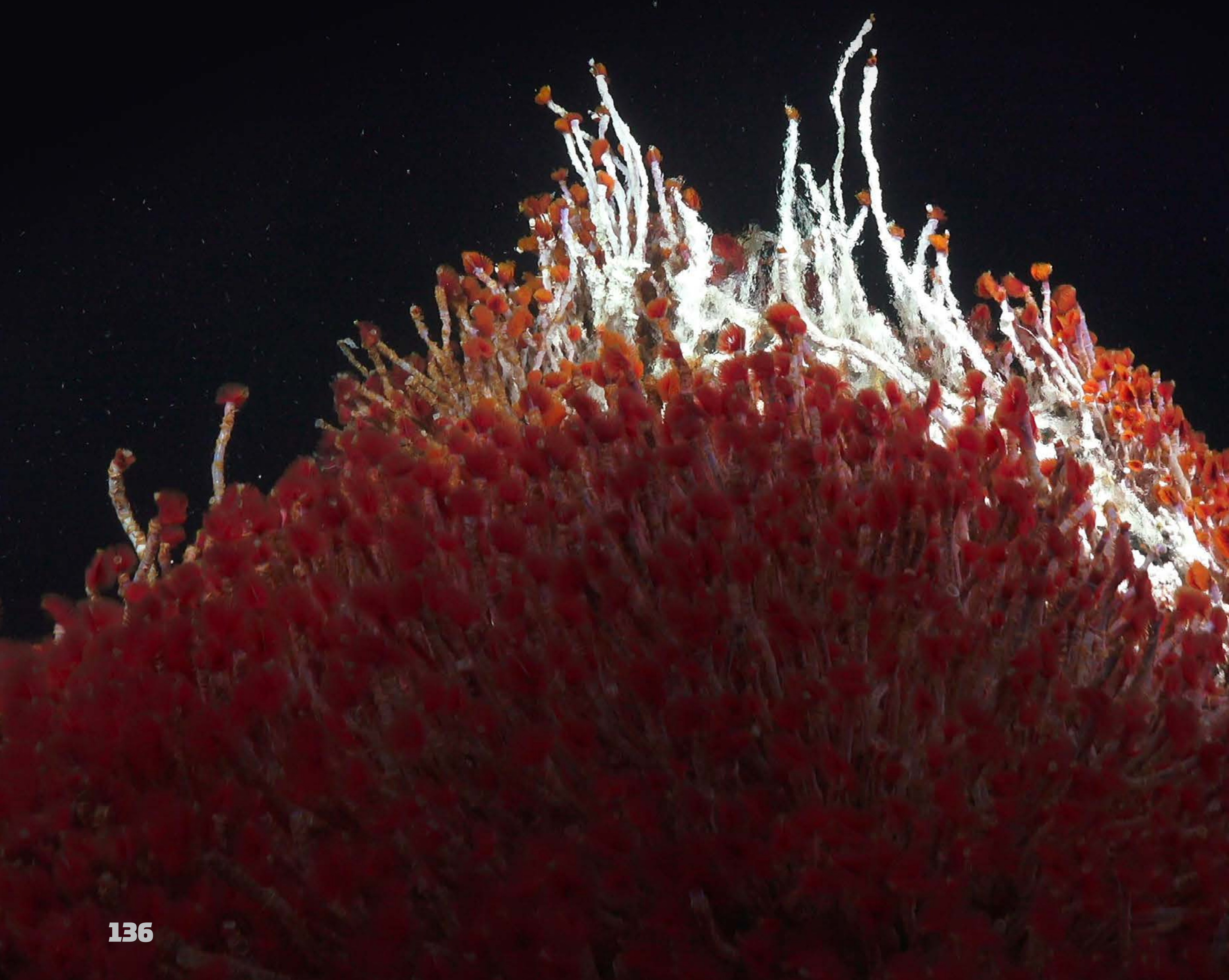
The robotic arms of ROV *SuBastian* sift clams out of ocean floor sediments (~700 m depth near Point Dume, California). These clams have a symbiotic relationship with a special type of bacteria found in these deep, nutrient-rich waters.

10. CONDUCTED THE FIRST CENTIMETER-SCALE AUV SURVEY OF HYDROTHERMAL VENTS IN SOUTH PESCADERO BASIN

CRUISE: Interdisciplinary Investigation of a New Hydrothermal Vent Field
CHIEF SCIENTISTS: Robert Zierenberg, University of California Davis, and David Caress and Victoria Orphan, MBARI

Following a 2015 MBARI research expedition to South Pescadero Basin, SOI conducted a full investigation of the tectonics, geochemistry, and microbial communities around hydrothermal vents discovered there. During the expedition, scientists from the University of California, Davis, and 11 other institutions discovered a new vent field at 3,600 m depth, naming it JaichMatt after the reflective hydrothermal fluid and seawater interface found at the site. Using MBARI's AUV and low altitude survey system, the team mapped the vent field at high resolution. The MBARI data were successfully integrated with those collected by ROV *SuBastian*, resulting in stunning maps and photo mosaics at centimeter scale. The maps led to the collection of the first volcanic rocks from the north and south basins, confirming that the basins are pulling apart and creating oceanic crust at a nascent seafloor spreading center. This expedition showcased new ways of mapping that will help scientists make real-time decisions at sea about the courses of their investigations.

An unusual mass of the tube worm *Oasisia* in the Pescadero vent field. The vents harbor unique biology compared to nearby vent sites. Detailed mapping will allow investigation of the geological and geochemical controls on habitat suitability for different animal and microbial communities.



11. TESTED AI-DRIVEN ROBOTS THAT SURVEY AND SAMPLE DEEP OCEAN ENVIRONMENTS FOR POSSIBLE APPLICATION TO EXTRATERRESTRIAL EXPLORATION

CRUISE: New Approaches to Autonomous Exploration at the Costa Rican Shelf Break
CHIEF SCIENTIST: Richard Camilli, WHOI

Broadcast latency between commands sent and robot actions can cause problems in ocean and space exploration. To counter this challenge, an engineering team made up from six organizations, including WHOI and MIT, worked aboard *Falkor* to test an intelligent platform that can make decisions to facilitate navigation of treacherous environments. Multiple robotic vehicles operated autonomously along the Costa Rican shelf break while the team worked on complex computer models that predict risk. Use of incoming data streams and planning tools allowed the vehicles to take data in situ and adjust missions based on the environmental context of new information recorded by sensors. The work done during this expedition will have important and lasting impacts on both ocean science and broader uses of robotic vehicles. The science team also tested new "smart" manipulators on ROV *SuBastian* for seafloor sampling, collecting data that will allow them to further develop technology for sampling and grabbing objects autonomously. Additionally, imagery from this expedition will be used in an upcoming exhibit about exploring space and the sea at the Barbican Museum in London.

Researchers work on programming and optimizing autonomous vehicles in *Falkor's* wet lab. The vehicles pictured are an Iver AUV and a Slocum Glider.

12. MADE SCALABLE IMPACT THROUGH THE DEVELOPMENT OF MARINE IMAGE ANNOTATION SOFTWARE AND WEB SERVICES

Since 2016, SOI has been supporting the development of Squidle+, an open source scientific image annotation software and web service. A version of Squidle+ was developed in 2017 to allow scientists aboard *Falkor* to annotate and log images collected with ROV *SuBastian*. This application has now been adopted by many international organizations, including the Australian National Environmental Science Program, as their preferred platform for underwater image annotation. Additional trials of the platform continue with the Canadian government's Department of Fisheries and Oceans. Squidle+ has been deployed on JAMSTEC research ships, and a portable version, GreyBits Box, has been developed for testing on NOAA vessels. The SOI-supported Maptracker program was also used on several expeditions aboard *Falkor* this year, with new functionality to connect to Squidle+ software and to provide the ability to visualize geolocated image annotations as a data layer. The program continues to become more sophisticated with support from SOI, coordinating multiple vehicles and offering the ability to predict behavior and play back data.

13. BROADENED PARTICIPATION IN OCEAN SCIENCES

From live video classes at sea reaching over 8,200 students to the online sharing of incredible ROV *SuBastian* 4K video footage from the deep, SOI continues to engage with audiences in new ways. In 2018, SOI hosted traveling Artist-at-Sea exhibits at Aquarium of the Pacific in Long Beach, California, the Ocean Sciences Meeting in Portland, Oregon, the Exploratorium in San Francisco, California, NOAA's Office of Ocean Exploration and Research Forum in Boston, Massachusetts, and the Mokupapapa Discovery Center, Hilo, Hawai'i. SOI hosted public ship tour days during the US port calls in Honolulu, Astoria, and San Francisco, bringing more than 1,000 people on board. Additionally, *Falkor* videos created by SOI are now showcased as part of a permanent exhibit at the Dundee Heritage Trust at Discovery Point, United Kingdom.

Epilogue

By Robert D. Ballard and Alan P. Leonardi

The human drive to investigate the unknown, wonder what lies beyond, has advanced civilization since time began. Still, only a small percentage of the ocean floor has been mapped using current technology. The United States has mapped the moon and Mars to a better resolution than our own seafloor—which means we know less about 71% of Earth's landscape than about the far side of the moon. More than half of the United States territorial jurisdiction lies in the 200-nautical-mile Exclusive Economic Zone that extends out from its shoreline, and 21% of the world's surface water is contained in the Great Lakes, the largest body of freshwater on Earth. In economic terms as it relates to energy, minerals, food, human health, and more, it would benefit all citizens to understand the deep ocean and the many resources and services it provides.

The Ocean Exploration Trust, NOAA's Office of Ocean Exploration and Research, and Schmidt Ocean Institute explore and map these waters through public and private funding to better understand what they contain, fill in data gaps, and address national objectives and priorities. We aim to accelerate the pace and scale of ocean exploration, enable technology development, and invigorate STEM education. Our efforts are further strengthened by OER's current chairmanship of the National Oceanographic Partnership Program, an entity that facilitates partnerships between federal agencies, academia, and industry to advance ocean science research and education.

The first E/V *Nautilus* field program in the Aegean Sea was conducted in 2009. Since then, the Ocean Exploration Trust has invested significantly to upgrade the ship's capabilities and those of various remotely operated vehicle systems. That effort continues, including additional enhancements taking place during the winter/spring of 2019. More specifically, OET is making significant improvements to the ship's wet lab; completing its recertification as a research vessel, required every five years; and installing a new traction winch below decks. OET will also install a new main engine during the winter/spring of 2020 to extend *Nautilus*'s life another 10 or more years.

In winter and spring 2020, working out of Gulfport, Mississippi, OET will conduct its first major cruise using a new mobile system funded by OET and OER. During a cruise to the Puerto Rico Trench, the new *ARGUS II* 6,000 m imaging vehicle will support ROV *Hercules* down to depths of 4,000 m and ROV *Little Herc* down to 6,000 m. Both ROVs will be linked to the Inner Space Center via a new mobile satellite system. A second cruise will be conducted in the Gulf of Mexico in support of NOAA's Office of National Marine Sanctuaries and possibly others interested in using this new mobile system either in the Gulf of Mexico or in the western Caribbean Sea.

With *Okeanos Explorer*'s return to the Atlantic and the ASPIRE campaign underway, in 2019 OER will map priority areas of the North Atlantic seafloor, and international partnerships will expand to address the priorities of Seabed 2030 and the Galway initiative. NOAA will install an EK80 sonar aboard *Okeanos Explorer* this year, making it the only deep-sea exploration vessel with this capability. OER will continue to explore concepts such as Telepresence 2.0 and, through emerging technology demonstration partnerships, will further utilize *Okeanos Explorer* as a testbed for technology. Investments will link ocean exploration results to NOAA's Blue Economy Initiative—the so-called Blue Economy amounts to approximately $320 billion of the US GDP. We will pay tribute to the successful conclusion of the Cooperative Institute for Ocean Exploration, Research & Technology and engage with the newest of NOAA's cooperative institutes, which launches this summer. Recommendations from OER's first national education review will also be implemented.

And OER has an eye toward exploration of the Mid-Atlantic Ridge in 2020. Confirmed by sonar in 1925, its discovery led to the theory of seafloor spreading. We envision a multi-ship, multidisciplinary exploration campaign that nearly 100 years later will use state-of-the art technologies to explore a feature that is part of a 40,000 km long essentially continuous system of mid-ocean ridges on the floors of all Earth's ocean basins.

We look forward to the next decade of ocean exploration aboard *Nautilus*, *Okeanos Explorer*, and *Falkor* and wonder where it will take us. As the pace of technology advancements quickens, what will the new platforms, new sensors, and new ways of seeing look like, and how will those data be transmitted and tallied?

Okeanos Explorer team launching ROV *Deep Discoverer* for a dive north of St. Croix during the Océano Profundo 2018 expedition. *Image credit: Caitlin Bailey, GFOE*


MADE IN
USA

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Squat lobster observed among coral and coral rubble in Cape Fear Lophelia Banks HAPC. *Image credit: NOAA OER*

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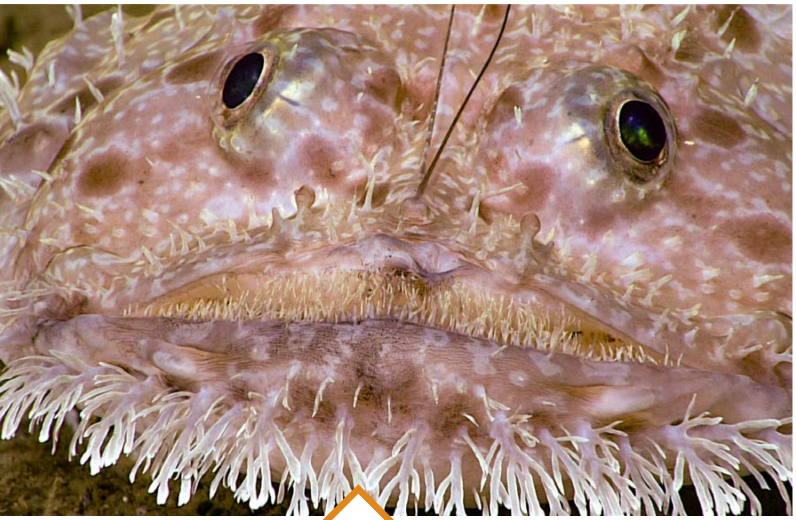

A goosefish (*Lophiodes beroe*) was observed at ~640 m depth. These fish are fairly common at about 600–800 m depth. A type of anglerfish, the lures are visible in the center of its face. *Image credit: NOAA OER*

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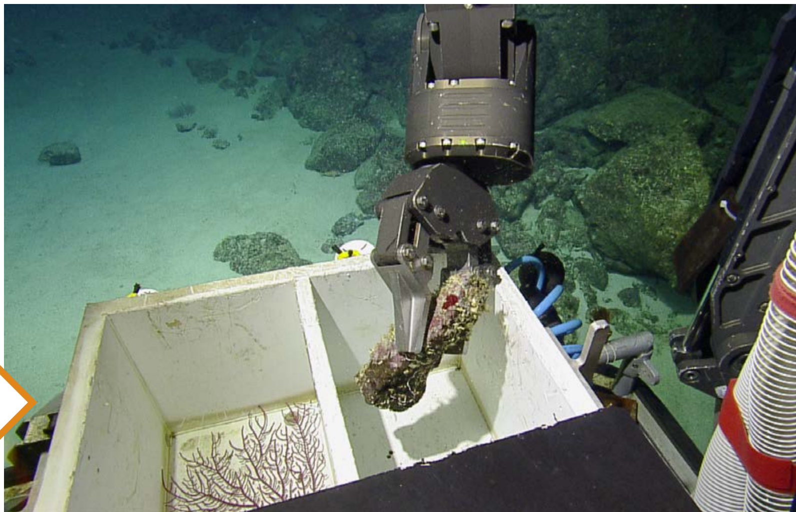

ROV *Hercules* takes a rock sample on Tanner Bank off Southern California during E/V *Nautilus* cruise NA104. *Image credit: OET*

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The year 2018 concluded a decade of ocean exploration for NOAA Ship *Okeanos Explorer*. With nearly two million square kilometers of seafloor mapped and the 100th expedition on the horizon, NOAA's Office of Ocean Exploration and Research is amazed at how quickly it occurred and humbled knowing it was possible only because of the people who worked with us and the extraordinary partnerships that were formed and leveraged the mission. Expertise and creativity and incremental and iterative approaches took us step-by-step, and then leap-by-leap, toward fulfilling the vision of the President's Panel on Ocean Exploration. The bends and curves of these collaborations, like those in some corals and diatoms, provided enormous surface area and remarkable strength, and led to a cascade of exploration. We look forward now to reaching out even further with partners and advanced tools and technologies, and to sharing the new discoveries and knowledge with others.

OER would like to acknowledge the expertise and creativity of Matthew King, Mashkoor Malik, Derek Sowers, and Michael White for compilation of the infographics and maps that appear in OER's section. These products allowed us to celebrate OER's 2018 exploration year and the decadal anniversary of NOAA Ship Okeanos Explorer.

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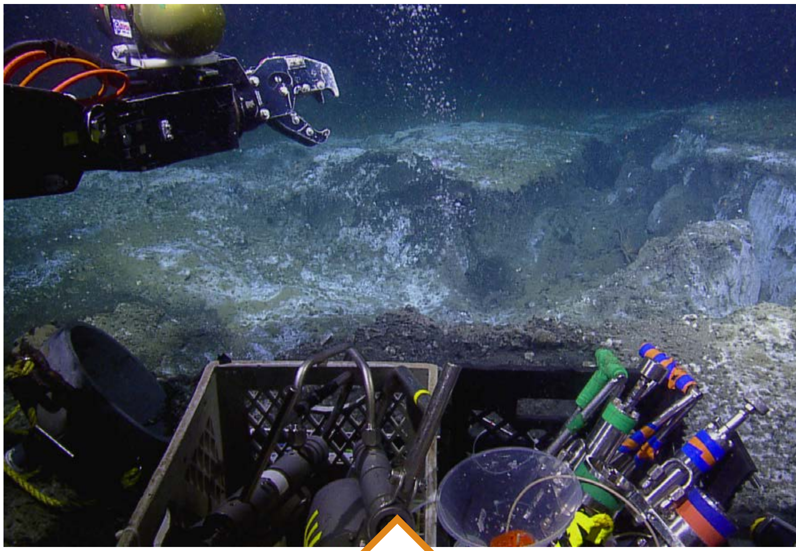

Deployment of the hydrophone and bubble collection at Heceta Bank at 500 m depth. Still photos taken with a Miso camera mounted on the manipulator arm of ROV *Hercules* during NA095. *Image credit: OET*

Octopus observed at Cape Fear Lophelia Banks HAPC during Windows to the Deep 2018. *Image credit: NOAA OER*

Purple plexaurid octocoral with commensal brittle stars photographed at 504 m depth on a dive north of Mona Island during the Océano Profundo 2018 expedition aboard NOAA Ship *Okeanos Explorer. Image credit: NOAA OER*

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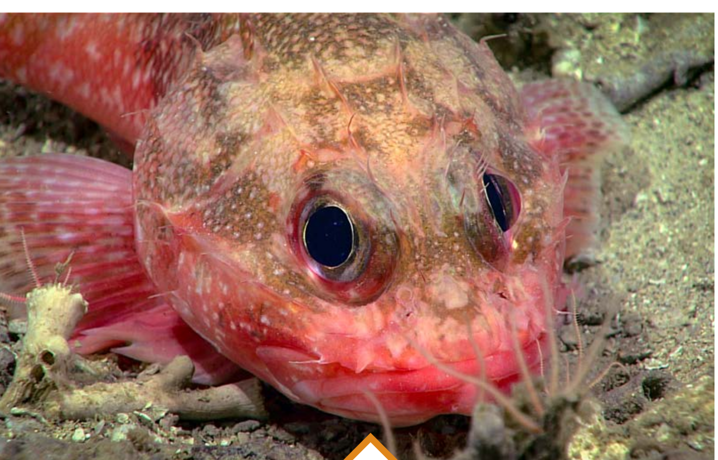
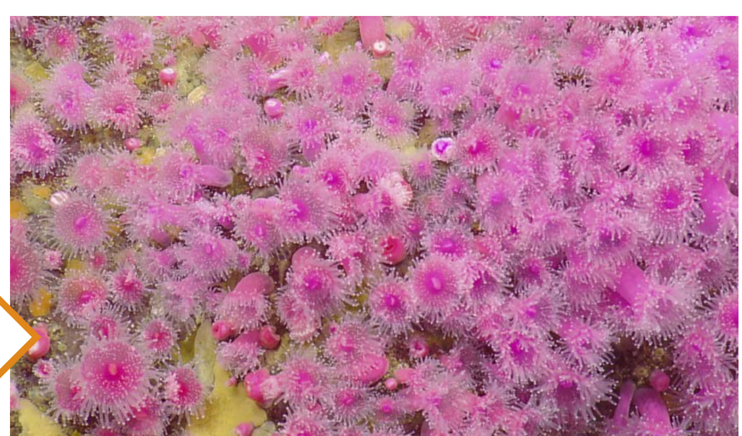
Acronyms

ABBITT .... Antarctic Broadcasts: Broader Impacts Through Telepresence
ABISS .... Autonomous Biogeochemical Instrument for In Situ Studies
ACUMEN .... Atlantic Canyons Undersea Mapping Expeditions
AOI .... Area of Interest
AOML .... NOAA's Atlantic Oceanographic and Meteorological Laboratory
AORA .... Atlantic Ocean Research Alliance
APEI .... Area of Particular Environmental Interest
ASMIWG .... Atlantic Seabed Mapping International Working Group
ASPIRE .... Atlantic Seafloor Partnership for Integrated Research and Exploration
ASV .... Autonomous surface vehicle
AUV .... Autonomous underwater vehicle
BOEM .... Bureau of Ocean Energy Management
CAPSTONE .... Campaign to Address Pacific monument Science, Technology, and Ocean NEeds
CCFZ .... Clarion-Clipperton Fracture Zone
CIOERT .... Cooperative Institute for Ocean Exploration, Research & Technology
CTD .... Conductivity, temperature, depth sensor
DAS .... Distributed acoustic sensing
DEEP SEARCH .... Deep Sea Exploration to Advance Research on Coral/Canyon/Cold seep Habitats
DFO .... Fisheries and Oceans Canada
DSMZ .... Davidson Seamount Management Zone
DTS .... Distributed temperature sensing
ECC .... Exploration Command Center
ECS .... Extended Continental Shelf
EEZ .... Exclusive Economic Zone
EiT .... Explorer-in-Training
E/V .... Exploration Vessel
FGBNMS .... Flower Garden Banks National Marine Sanctuary
FFO .... Federal Funding Opportunity
GEBCO .... General Bathymetric Chart of the Oceans
GFOE .... Global Foundation for Ocean Exploration
GSO .... Graduate School of Oceanography, University of Rhode Island
HAPC .... Habitat Areas of Particular Concern
HOV .... Human-occupied vehicle
INDEX-SATAL .... Indonesia-US Sangihe Talaud
ISA .... International Seabed Authority
ISC .... Inner Space Center
LRAUV .... Long-range autonomous underwater vehicle
MBARI .... Monterey Bay Aquarium Research Institute
MBNMS .... Monterey Bay National Marine Sanctuary
MCZ .... Harvard's Museum of Comparative Zoology
MIT .... Massachusetts Institute of Technology
MPA .... Marine Protected Area
NCEI .... NOAA's National Centers for Environmental Information
NMS .... National Marine Sanctuary
NOAA .... National Oceanic and Atmospheric Administration
OER .... NOAA's Office of Ocean Exploration and Research
OET .... Ocean Exploration Trust
OMAO .... NOAA's Office of Marine and Aviation Operations
OMZ .... Oxygen Minimum Zone
ONC .... Ocean Networks Canada
PMEL .... NOAA's Pacific Marine Environmental Laboratory
PMNM .... Papahānaumokuākea Marine National Monument
ROV .... Remotely operated vehicle
R/V .... Research Vessel
SEIP .... OET's Science & Engineering Internship Program
SK-B MPA .... SGaan Kinghlas-Bowie Seamount Marine Protected Area
SOI .... Schmidt Ocean Institute
STEM .... Science, technology, engineering, and mathematics
SUBSEA .... Systematic Underwater Biogeochemical Science and Exploration Analog
UAS .... Unmanned aircraft system
UCAR .... University Corporation for Atmospheric Research
UNH CCOM/JHC .... University of New Hampshire Center for Coastal and Ocean Mapping/Joint Hydrographic Center
URI .... University of Rhode Island
USGS .... United States Geological Survey
USS .... United States Ship
UUV .... Unmanned underwater vehicle
VSAT .... Very small aperture terminal
WHOI .... Woods Hole Oceanographic Institution
XBT .... Expendable bathythermograph



A blackbelly rose fish observed during Windows to the Deep 2018 at the Cape Fear Lophelia Banks HAPC. *Image credit: NOAA OER*



Close-up of cup coral encrusting a pinnacle on Pilgrim Bank off Southern California. The photo was taken during E/V *Nautilus* cruise NA104. *Image credit: OET*

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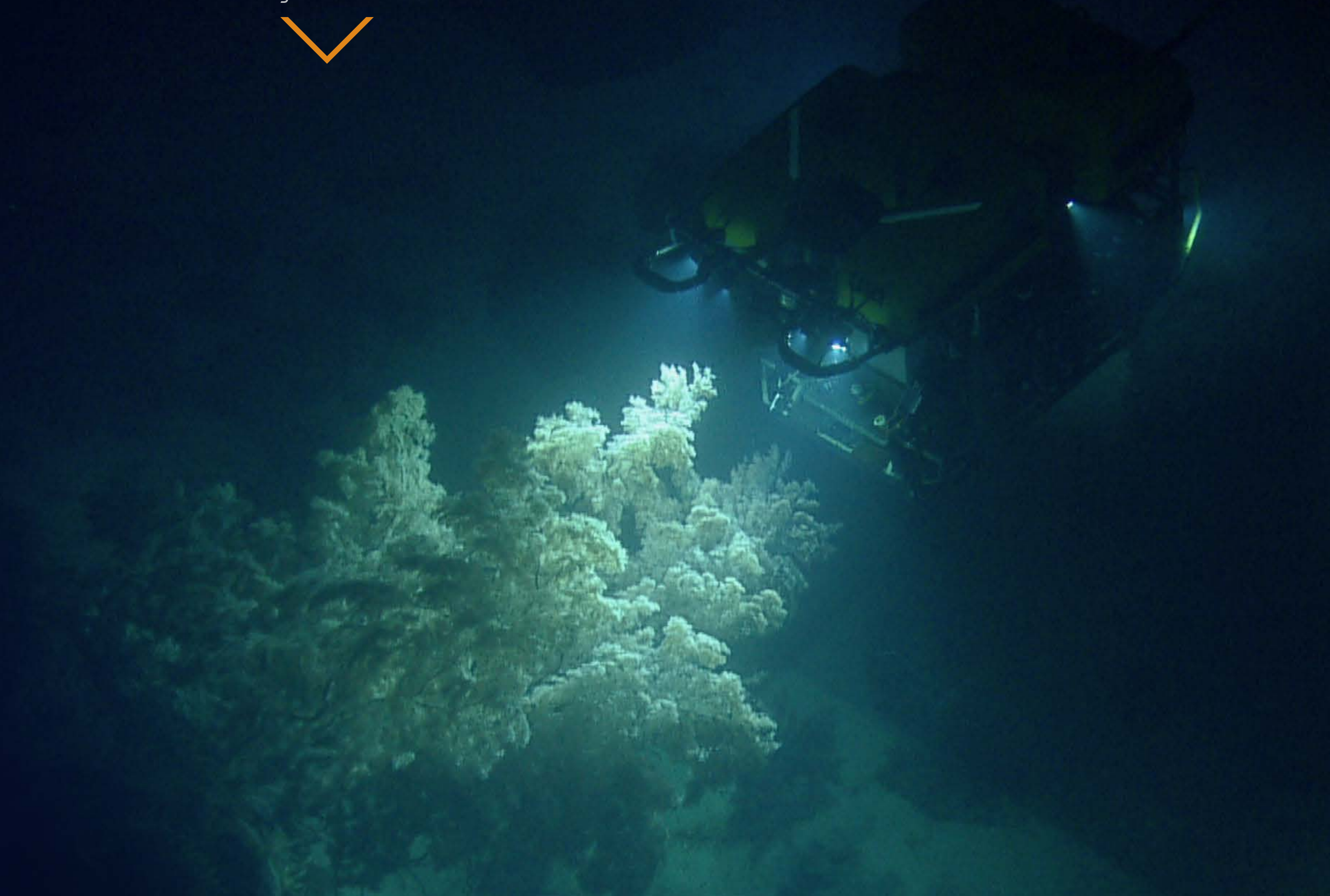
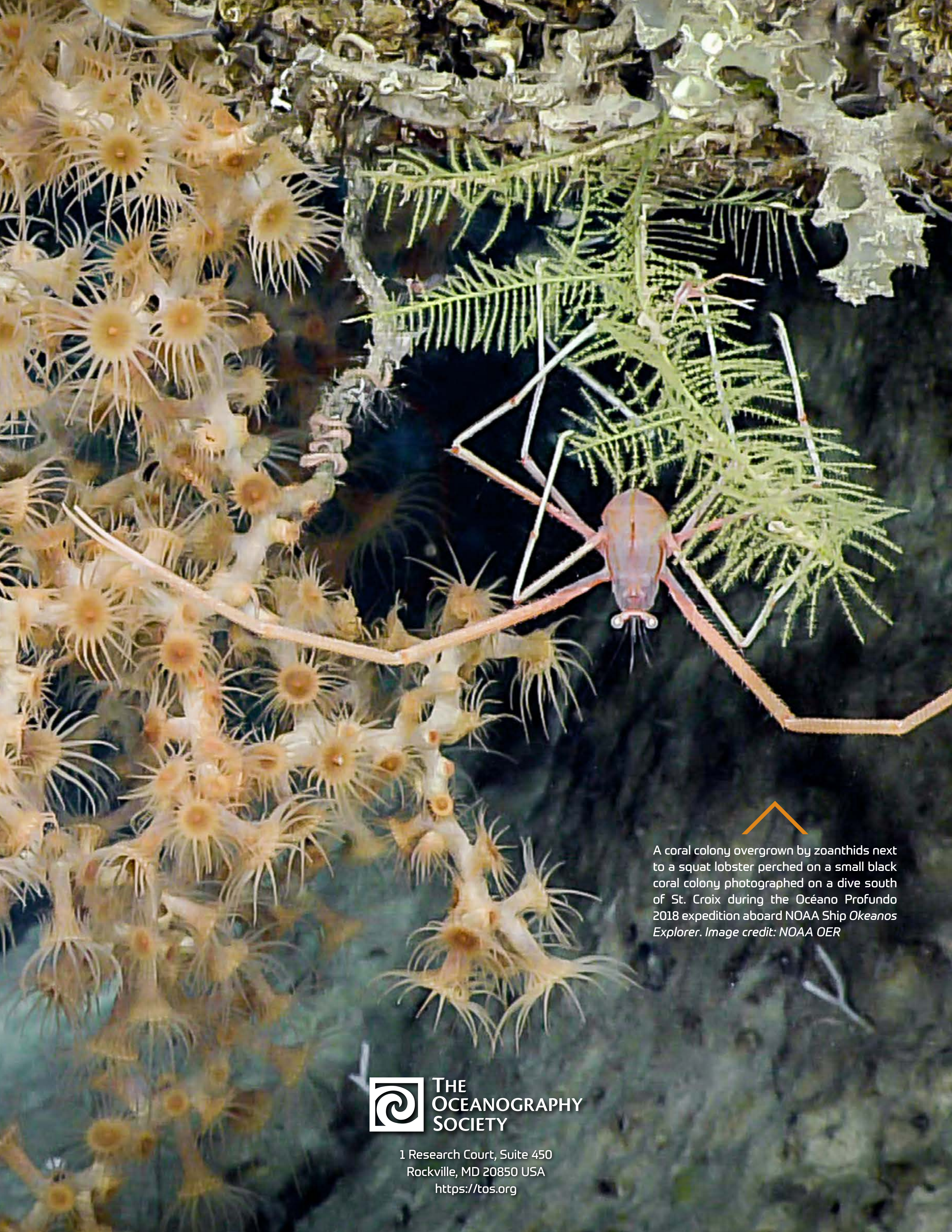
ROV *Hercules* hovers over a large coral at Pilgrim Bank off Southern California during E/V *Nautilus* cruise NA104. *Image credit: OET*





A coral colony overgrown by zoanthids next to a squat lobster perched on a small black coral colony photographed on a dive south of St. Croix during the Océano Profundo 2018 expedition aboard NOAA Ship *Okeanos Explorer*. *Image credit: NOAA OER*

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