New Frontiers in Ocean Exploration

The E/V *Nautilus*, NOAA Ship *Okeanos Explorer*, and R/V *Falkor* 2019 Field Season

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ON THE COVER
A close-up of bubblegum coral and shrimp associates in Baltimore Canyon seen during the Windows to the Deep 2019 expedition on NOAA Ship *Okeanos Explorer*. *Image credit: NOAA OER*

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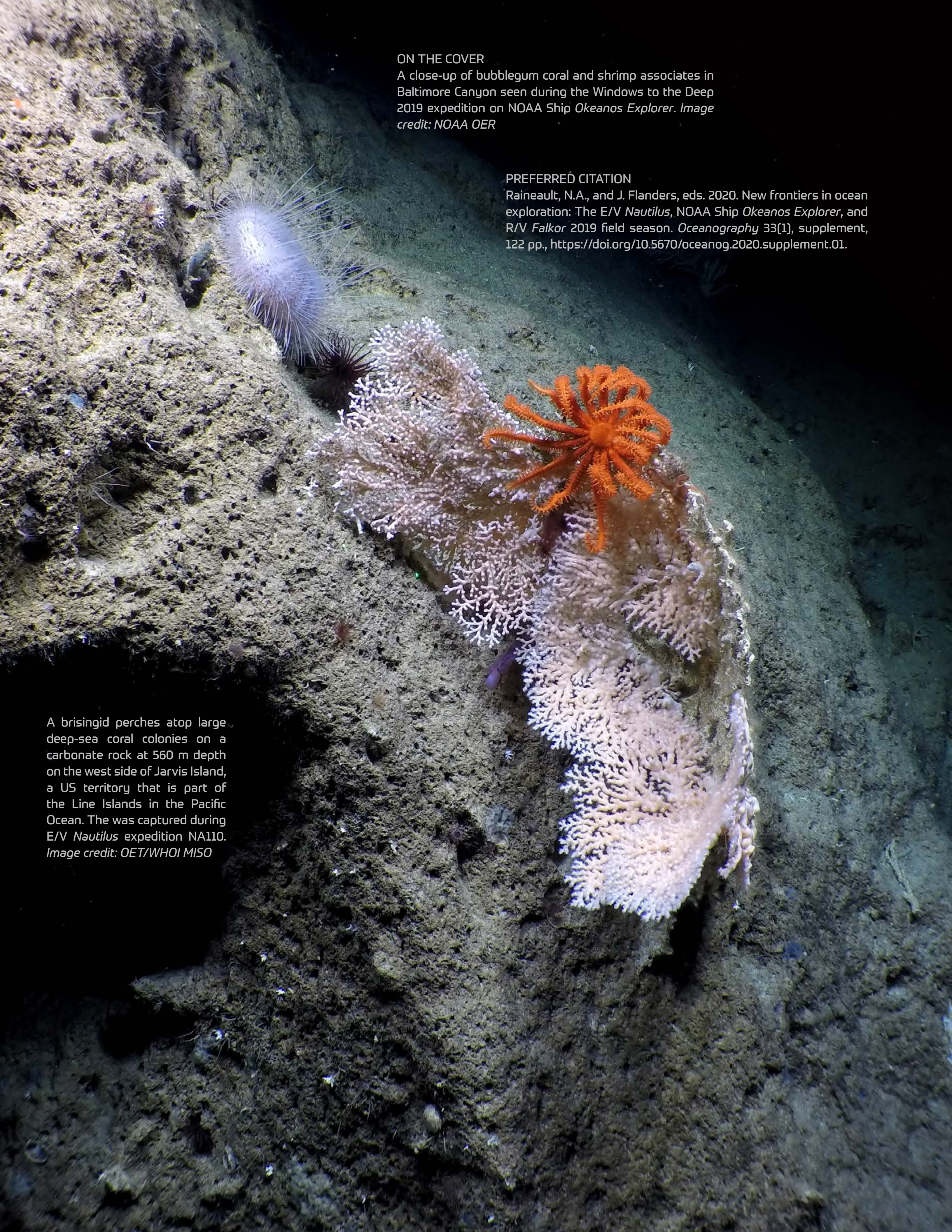

A brisingid perches atop large deep-sea coral colonies on a carbonate rock at 560 m depth on the west side of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

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A close-up view of the bow of a shipwreck "accidentally" discovered during NOAA Ship *Okeanos Explorer*'s shakedown and sea-trial expedition in the Gulf of Mexico. The wreck is likely a mid-nineteenth-century wooden sailing vessel. *Image credit: NOAA OER*

Introduction

By Nicole A. Raineault, Frank Cantelas, and Carlie Wiener

This is the tenth installment of the ocean exploration supplement to *Oceanography*, the official magazine of The Oceanography Society, with annual highlights of accomplishments aboard three vessels that explore the world ocean: the Ocean Exploration Trust's (OET's) E/V *Nautilus*, NOAA Ship *Okeanos Explorer*, and Schmidt Ocean Institute's (SOI's) R/V *Falkor*.

In 2019, the programs expanded efforts in the Pacific Ocean with *Falkor* working in the southern and eastern Pacific, *Nautilus* in the central and western Pacific, and *Okeanos Explorer* in the Gulf of Mexico and along the Atlantic continental margin into the western North Atlantic. The pages that follow contain expedition summaries, including early discoveries, emerging technologies, new information on education and outreach programs, and exciting announcements about future endeavors.

The first section highlights OET and E/V *Nautilus* endeavors. The operations expanded beyond *Nautilus* with a mapping mission in Lake Huron that marked OET's first mobile system expedition, in partnership with Thunder Bay National Marine Sanctuary and the University of New Hampshire's Center for Coastal and Ocean Mapping (page 32). *Nautilus* ventured to Samoa and explored the vast central Pacific, including the Pacific Remote Islands Marine National Monument (pages 38–39, 42–43, 46–47). A summary of our technologies (pages 10–17), newly redesigned wet lab and specimen highlights (pages 18–21), and education and outreach programs (pages 22–27) showcases the ways in which OET continues to innovate. We mapped more than previous seasons, contributing important data to the Seabed 2030 initiative (pages 30–31). A continued partnership with the NOAA Office of National Marine Sanctuaries brought us to the American Samoa sanctuary along with a return to several other sanctuaries along the west coast of the United States (pages 48–49, 50–51). Finally, we are excited to be part of the newly awarded NOAA Ocean Exploration Cooperative Institute in partnership with four oceanographic academic institutions (pages 52–53).

The second section focuses on the NOAA Office of Ocean Exploration and Research (OER). It begins with an overview of *Okeanos Explorer* expeditions (pages 56–58) and the ship's unique mission (page 59) and is followed by OER's review of the deep-sea science and management communities' data requirements (pages 60–61). We highlight OER's exploratory midwater work (pages 62–63) as well as the Atlantic Seafloor Partnership for Integrated Research and Exploration (page 64) that formed the framework for 2019 exploration. The ship's shakedown cruise is described next (page 65) and then a mission that examined newly found deep-ocean seeps (pages 66–67). Technology demonstrations carried out utilizing *Okeanos Explorer* are showcased (pages 68–69), followed by collaborative work to enhance underwater video capture and annotation tools (page 70). We describe exploration of the US and Canadian Atlantic continental margin with Canadian and European partners in support of Atlantic Ocean Research Alliance and Seabed 2030 goals (pages 71–73) and then discuss open data sharing practices and a "data lake" concept that could store data

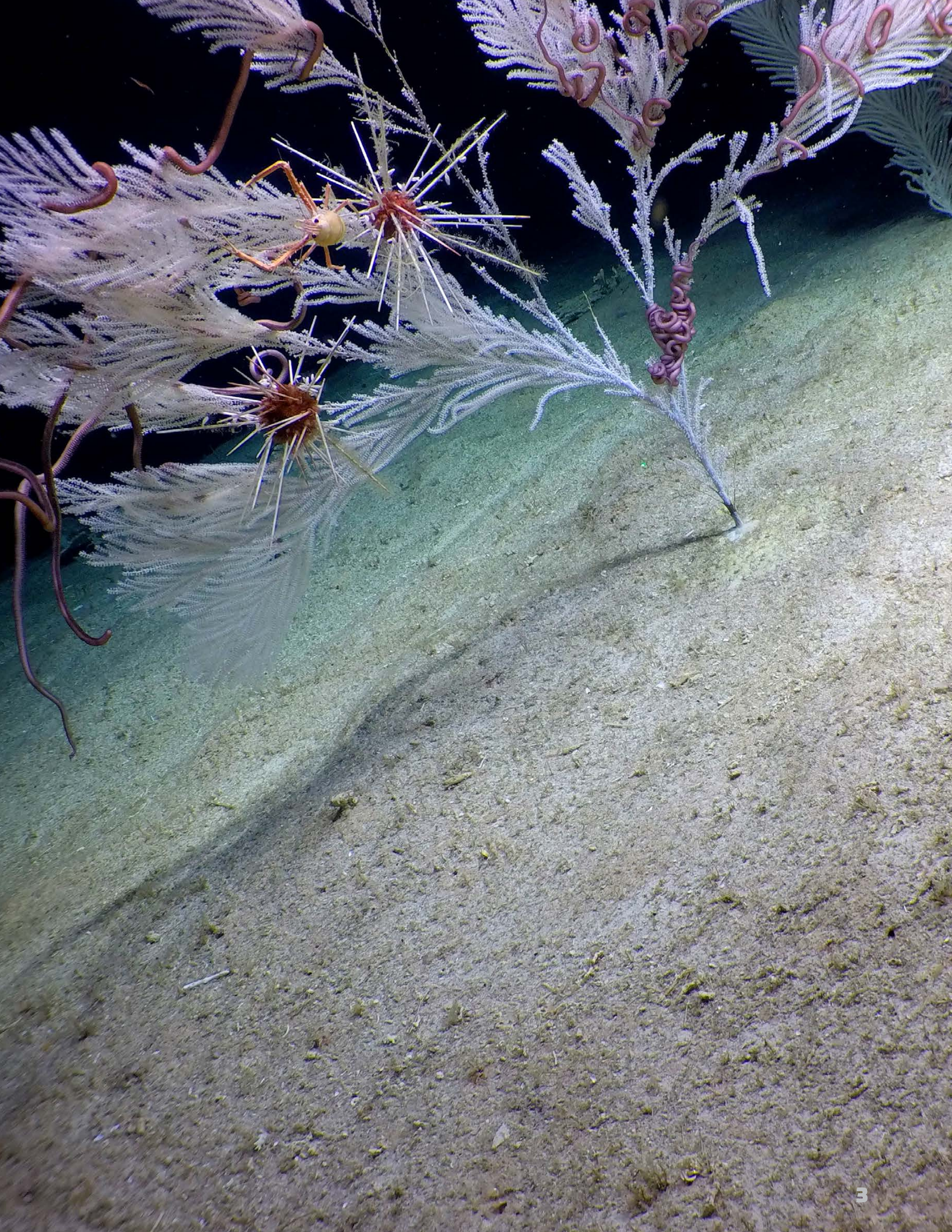
A large primnoid coral with squat lobsters, crinoids, and urchins was observed at 520 m depth on the west side of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

at any scale (pages 74–77). A synopsis of the current state of mapping of US waters (pages 78–80) and of US Extended Continental Shelf Project milestones (page 79) follows. We then summarize OER interagency projects external to *Okeanos Explorer* such as DEEP SEARCH (pages 81–82) and EXPRESS (page 83), before turning to OER advancement of telepresence technology and the Telepresence 2.0 concept (page 84). We also highlight OER's extensive engagement efforts (pages 85–87) and diversity and inclusion accomplishments (pages 88–89). OER's section closes with OER-sponsored projects that illustrate the broad spectrum of exploration supported through grants, cooperative agreements, and unsolicited projects (pages 90–99).

The Schmidt Ocean Institute continues to support innovative technology and research to explore new ocean realms. In the final section, SOI highlights some of its accomplishments made through collaboration with experts around the world (pages 100–109). Each of the 10 missions aboard *Falkor* brought impactful new scientific tools to address critical questions in ocean science. Advancements in technology led to new breakthroughs, from characterizing novel benthic ecosystems to examining the role of the sea surface microlayer on the ocean's heat budget. These expeditions employed coordinated technology that combines robotics, precise observations, software, and data platforms working together to study the ocean in new regions and on advanced temporal and spatial scales. Each robotic system, sensor, and method undergoes long-term development before it is applied at sea on *Falkor*. This section highlights expeditions that are essential to understanding the dynamic ocean and whose results will lead to better ocean policies and management. Through exhibits, ship-to-shore connections, the observations of students and artists at sea, and social media, homes, and classrooms all over the world became part of the SOI research team in 2019. With its philanthropic efforts, SOI aims to demonstrate how scalable innovation can tackle important scientific and societal challenges.

The year 2020 will bring new partnerships and opportunities to grow our abilities to explore as the NOAA Ocean Exploration Cooperative Institute joins several oceanographic institutions with a common goal of exploring the US Exclusive Economic Zone. *Nautilus* will explore along the west coasts of the United States and Canada and continue exploration and mapping of West Coast National Marine Sanctuaries as well as Thunder Bay in Lake Huron. *Okeanos Explorer* will conduct three regional expeditions, starting with the US southeastern continental margin, working within the US EEZ near Puerto Rico, expanding to the Mid-Atlantic Ridge near the Azores, and then into the high seas in the North Atlantic. Both OET and NOAA will engage multidisciplinary teams of scientists, technicians, and engineers to conduct seafloor mapping and ROV explorations of the geological, biological, oceanographic, and archaeological resources of these ocean areas, the majority of which remain largely unexplored. *Falkor* will embark on its first year-long initiative to conduct seven science expeditions along all four sides of the Australian continent, with important implications for the sustainability and protection of underwater ecosystems—and for similar habitats worldwide that are in peril because of rising ocean temperatures. SOI will also continue to focus on projects that utilize advanced and coordinated robotic systems, artificial intelligence, and other cutting-edge technology that can offer effective tools to accelerate ocean research, conservation, and management at scale.

We invite you to follow along with our explorations online, and we look forward to sharing highlights of our discoveries with you next year.



From Pole to Pole: Connecting Explorers Across the Globe

By Colleen Peters, Dwight F. Coleman, and Alex DeCiccio

The year 2019 was noteworthy for the University of Rhode Island's Inner Space Center (ISC). Not only was it the tenth anniversary of the facility, it was also the first time live, interactive broadcasts were conducted from both the Arctic and the Antarctic. To augment the missions of ISC's two main partner vessels, NOAA Ship *Okeanos Explorer* and Ocean Exploration Trust's E/V *Nautilus*, mobile telepresence units (MTUs) were installed on a record six additional vessels throughout the year: research vessels *Atlantis*, *Neil Armstrong*, *Connecticut*, *Endeavor*, and *Laurence M. Gould*, and the icebreaker *Oden*. MTUs provide vessels of opportunity with the technology that enables those aboard the ships to establish a relatively high bandwidth Internet connection to stream live video and audio. The MTUs are customized for each project, installed, and supported by ISC engineers.

As a leader in the application of telepresence technology to connect scientists remotely to missions of exploration, this year the ISC focused on using this same technology to boost public engagement and broader impacts through live, two-way broadcasts from the vessels to various audiences around the world. In March 2019, aboard R/V *Atlantis*, ISC staff provided live streaming and production capabilities directly from the vessel to the BBC's London studios through a dedicated transmission link. The ISC facilitated collaboration among Woods Hole Oceanographic Institution (WHOI), Verizon (the satellite and network service provider), the ISC, and the BBC to coordinate, configure, and connect the existing satellite antenna system aboard *Atlantis* to the high bandwidth link. *Blue Planet Live* engaged audiences by bringing them into five highlighted sites around the globe in real time. Operating off the coast of California, the broadcasts involving *Atlantis* showcased the human-occupied vehicle *Alvin* as it dove beneath the sea to explore a recent discovery by E/V *Nautilus* in Monterey Bay National Marine Sanctuary called the "octopus garden" (Figure 1).

Hosting live interactions from the ISC rather than directly from the vessel allows staff to quickly manage transmissions from shore when challenges disrupt a clear connection to the ship. The shoreside host can keep the conversation flowing while standing by to reestablish connectivity. The host can spontaneously bring in guest expertise, and the production team can easily retrieve relevant video to visually demonstrate answers when the host takes questions from the audience. This capability not only ensures the audience will always receive a planned program, it also adds value to the broadcasts by showing additional video content.

In July, three ISC staff members joined a team of scientists and students aboard the Swedish icebreaker *Oden* to explore the Canadian Arctic Archipelago. One aspect of the expedition led by the ISC was the execution of 39 live broadcasts from inside the Northwest Passage to classrooms and informal science education centers via Skype, Zoom, and Facebook Live. Using social media platforms with direct links to the Smithsonian (Washington, DC), The Exploratorium (San Francisco, California), and the Alaska SeaLife Center (Fairbanks, Alaska), the onboard team covered topics about seabirds, marine mammals, the Arctic ecosystem, and the physical aspects of the Arctic Ocean.

FIGURE 1. Images from the 2019 E/V *Nautilus* expedition to the Monterey Bay National Marine Sanctuary "octopus garden." (left) ROV *Hercules* image shows an octopus hatchling escaping a predatory shrimp and (above) octopuses (*Muusoctopus robustus*) in the brooding position.

FIGURE 2. NOAA Education Specialist Hannah MacDonald hosting a live classroom connection from ISC Mission Control with National Geographic's Exploring by the Seat of Your Pants during the NOAA Stellwagen Bank National Marine Sanctuary project.

FIGURE 3. ISC Intern Ben Woods answers questions from students during a live classroom connection hosted by NOAA's Office of Ocean Exploration and Research Regional Program Manager Catalina Martinez.

Feedback from viewers suggested these broadcasts created a high level of emotional engagement.

In September, the NOAA Office of National Marine Sanctuaries and WHOI sponsored a cruise aboard R/V *Connecticut* to the Stellwagen Bank National Marine Sanctuary where live broadcasts were conducted while an ROV explored the wreck of the wooden-hulled paddle-wheel steamship *Portland* (Figure 2). Prior to the cruise, the ISC production team worked closely with the partners to guide the pre-production process of crafting scripts, gathering footage, and scheduling the broadcast days. The ISC established connection tests with each venue, oriented the guest(s) to the technology, and provided an overview of expectations during the program in order to create a smooth process for both the venues and the vessel. The ISC connected the program directly to schools, YouTube, and Facebook Live, with an estimated reach of 2,000 participants and 10,000 online viewers.

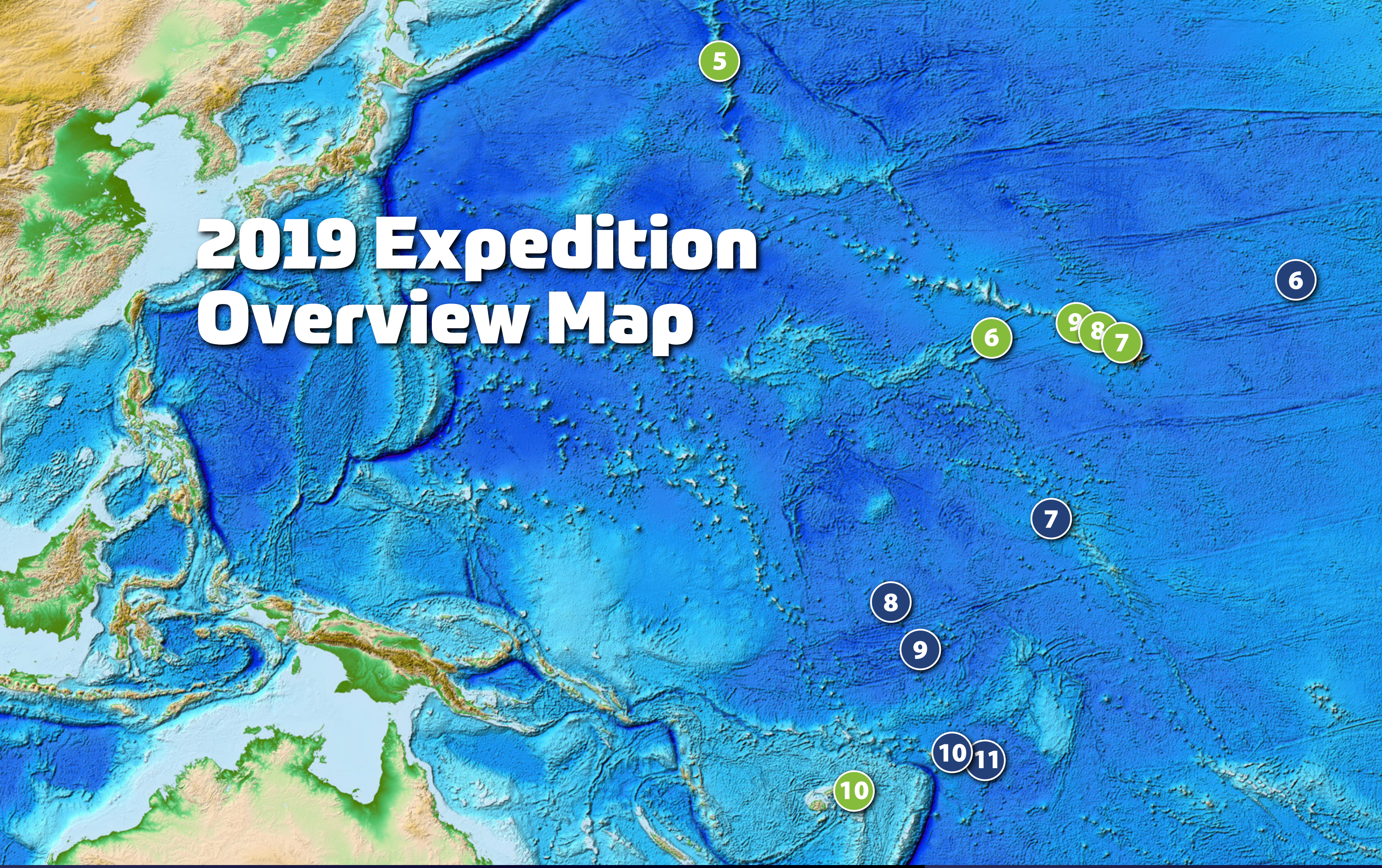
Throughout the year, the ISC tested a live interaction program that was based ashore rather than aboard NOAA Ship *Okeanos Explorer*. In collaboration with NOAA's Office of Ocean Exploration and Research engagement team, and using ROV *Deep Discoverer* footage, the ISC connected with classrooms, museum summer camps, and the Ocean Discovery Institute in San Diego via Skype (Figure 3).

Working with the Ocean Exploration Trust and the E/V *Nautilus* team, the ISC assists with providing most pre-2018 ROV *Hercules* video through a request system that often takes a long time to fill. New to the 2019 field season, a YouTube Channel (Nautilus Live Dive Recordings) was created to host the one-hour full dive recordings as captured through the live satellite link by ISC servers. The videos were then contributed to Lamont-Doherty's Ocean Video Lab, an underwater video portal (http://www.oceanvideolab.org/) designed both to make underwater video more accessible and to develop a mechanism to automate video annotations. Through the portal, citizen scientists can log in and add simple annotations (e.g., identifying a deep-sea coral), while registered scientific users can add manual annotations (e.g., the coral species name). Navigation data and shipboard annotations can also be ingested into the system, which can be downloaded by any user.

In late October 2019, the final MTU project supported Antarctic Broadcasts: Broader Impacts Through Telepresence (ABBIT) during an expedition aboard R/V *Laurence M. Gould* to Palmer Station on the Antarctic Peninsula that was funded by the National Science Foundation. This proof-of-concept project utilized the ship's telecommunications system to conduct live interactions from the Southern Ocean (Figure 4). The ISC team brought a variety of video encoding equipment aboard the vessel to run a series of tests on the limited bandwidth available in order to determine which devices, settings, bandwidth protocols, frame rates, and video quality provided the most robust experience so that future vessels operating in remote regions could connect with the highest quality end product. This project not only demonstrated the capabilities of the ship and the ISC to host broadcasts from an isolated area of the planet but also demonstrated the increasing need for both the science community and the general public to better understand our ocean and the federally funded work that occurs at remote field facilities.

FIGURE 4. ISC Media & Production Specialist Alex DeCiccio directs the Arctic broadcasts from Production Control with assistance from Daniele Myers.

2019 Expedition Overview Map



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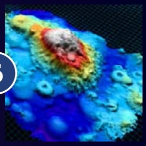
6 
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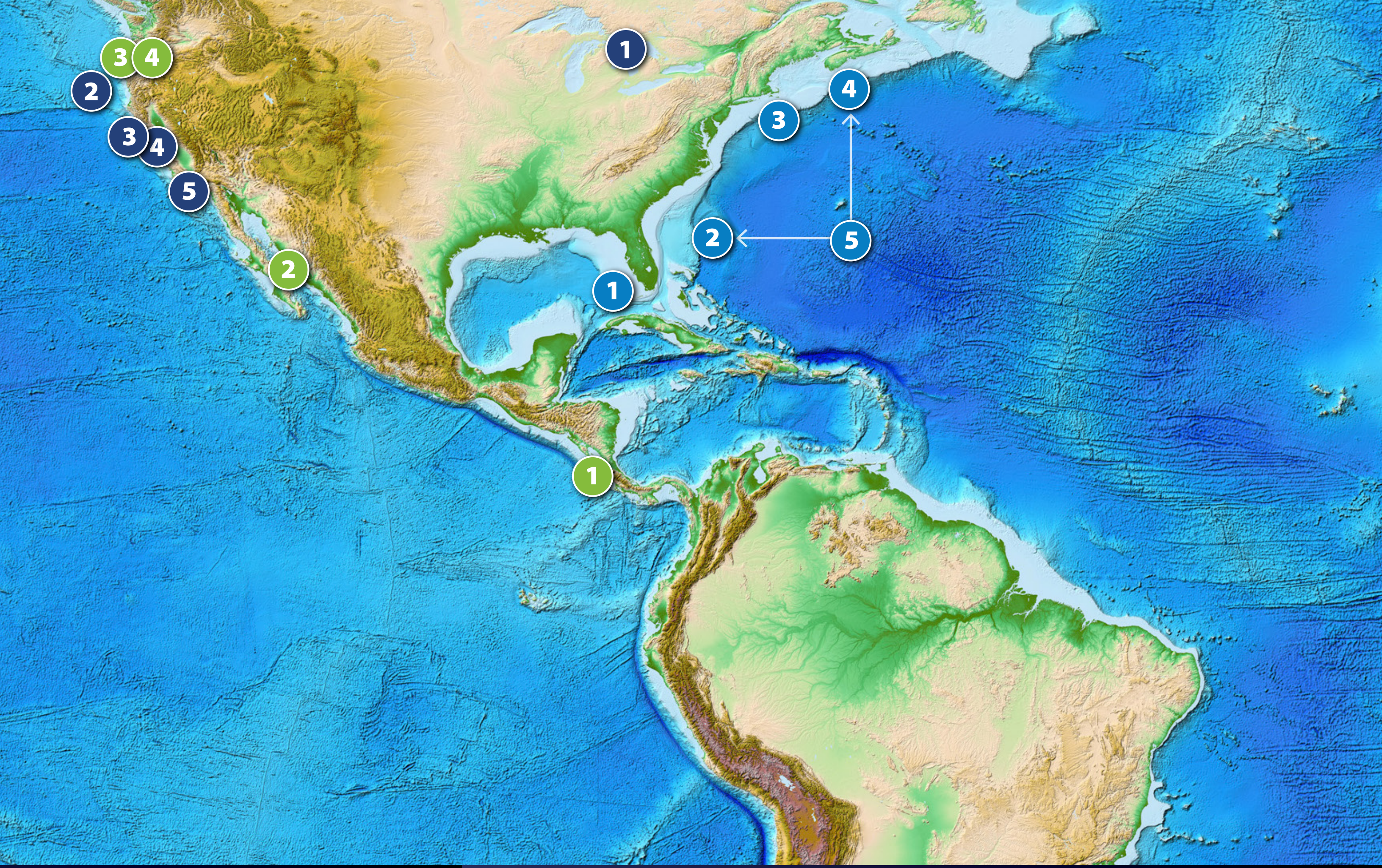

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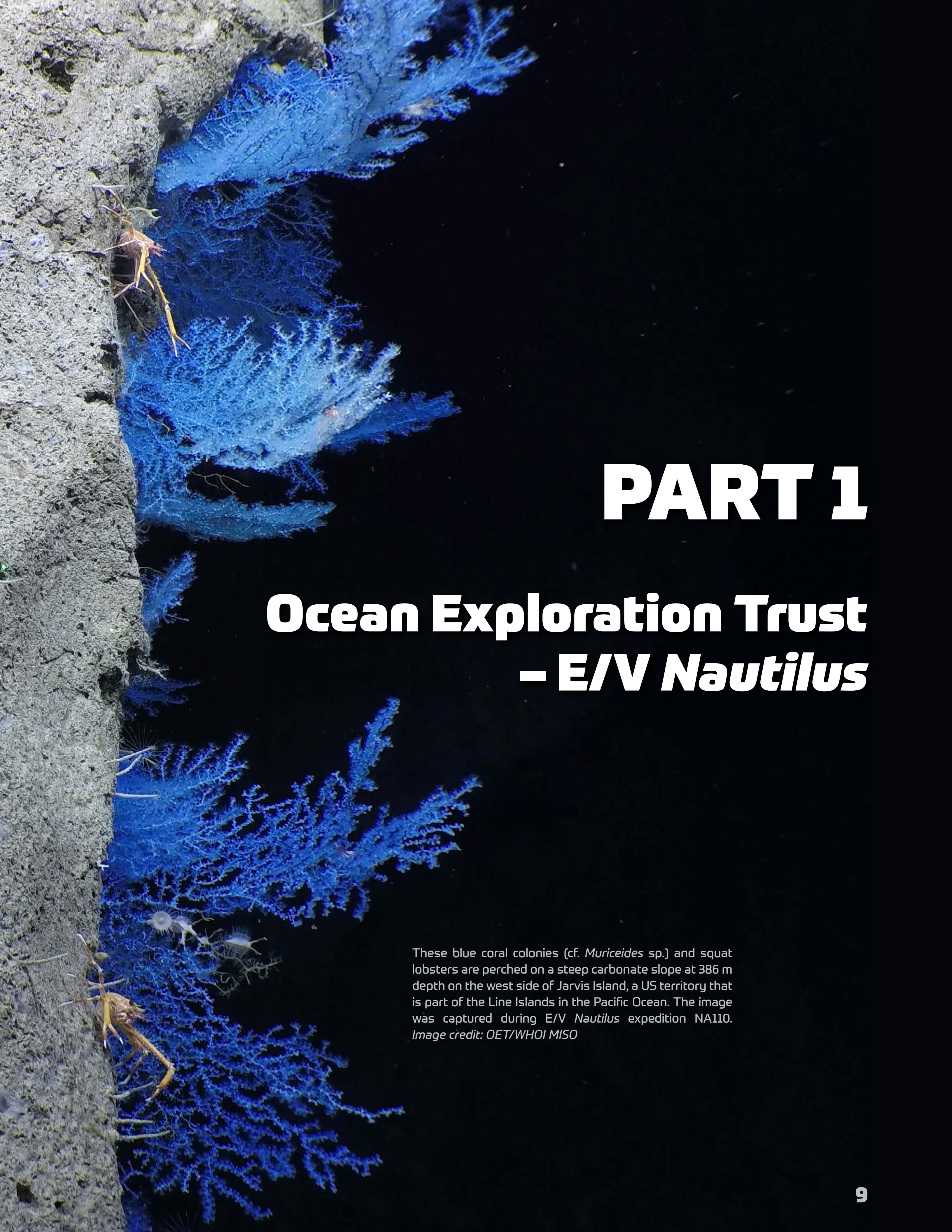
*ASPIRE

Note: All images in the Nautilus *section of this publication are copyright Ocean Exploration Trust Inc. unless otherwise indicated.*



PART 1

Ocean Exploration Trust – E/V *Nautilus*

These blue coral colonies (cf. *Muriceides* sp.) and squat lobsters are perched on a steep carbonate slope at 386 m depth on the west side of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

Technology E/V *Nautilus*

Nautilus is an efficient 64-meter exploration vessel (E/V), with 17 berths for permanent crew members in addition to 31 berths for members of the rotating Corps of Exploration. The ship is equipped with a Kongsberg EM 302 multibeam echosounder and two ROVs, *Hercules* and *Argus*. E/V *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. Two 6.1-meter (20-foot) vans

COMPLEMENT. 17 crew; 31 science and operations

FLAG. St. Vincent and the Grenadines

HEAVY EQUIPMENT

- Dynacon 369i ROV winch with 4,500 meters (14,800 feet) of 1.73 centimeter (0.681 inch) diameter electro-optical 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 tonnes
- Two rescue boats; davit with SWL 0.9 mtn
- Oceanscience UCTD 10-400 profiling system; max depth 1,000 meters (3,280 feet)

TELEPRESENCE TECHNOLOGY

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

REAL-TIME VIDEO STREAMING. Six Haivison X encoders streaming live video via satellite to the Inner Space Center ashore (including spares)

CAMERAS. 15 high-definition pan/tilt/zoom cameras: aft deck and port rail; Command Center; wet lab; ROV hangar; winch hold

COMMUNICATIONS

- Ship-wide RTS Telex intercom system for shipboard communications and connection with shoreside participants
- 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

Image credit: Nolan Salyer

DATA PROCESSING & VISUALIZATION LAB

AREA. 44.5 square meters (480 square feet)

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

RACK ROOM

AREA. 17.3 square meters (185 square feet)

DATA STORAGE. 22 TB online storage for non-video data; 150 TB disk storage for video data

EMERGENCY COMMUNICATIONS. Iridium phone, 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 in studio, Canon FX-305 for live deck television broadcasts

WET LAB

AREA. 19 square meters (204.5 square feet) with 5.3-meter-long (17.5-foot) stainless steel bench and 2.3-meter-long (7.6-foot) worktop

REFRIGERATION

- –80°C/–86°C scientific freezer, 0.085 cubic meters (3 cubic feet)
- –20°C scientific freezer, 0.14 cubic meters (5 cubic feet)
- Two science refrigerators, approximately 0.57 cubic meters (20 cubic feet) each

HAZMAT

- Fume hood
- Two HAZMAT lockers 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 video recorders that capture ROV footage in three simultaneous codecs, 2x LTO-6 archive media drives

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 meters to 7,000 meters (33 feet to 22,965 feet) 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 kilometers (5 miles)

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

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. 50–5,000 meters (164–16,404 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. 14.2–19.8 kHz

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

Image credit: Nerelle Que

Remotely Operated Vehicle (Towsled) *Argus*

ROV *Argus* was first launched in 2000 as a deep-tow system capable of diving to 6,000 meters. *Argus* is mainly 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 deepwater 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 head and Fujinon HA 10 × 5.2 lens, 1080i SMPTE 292M output format, 2 MP still image capable on tilt platform
- Three utility cameras (fixed mounted) 480 line NTSC format
- One DeepSea Power & Light Wide-i SeaCam, downward-looking standard definition camera (fixed mounted)

LIGHTING

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

VEHICLE SENSORS & NAVIGATION

SYSTEM. NavEst integrated navigation system solution

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

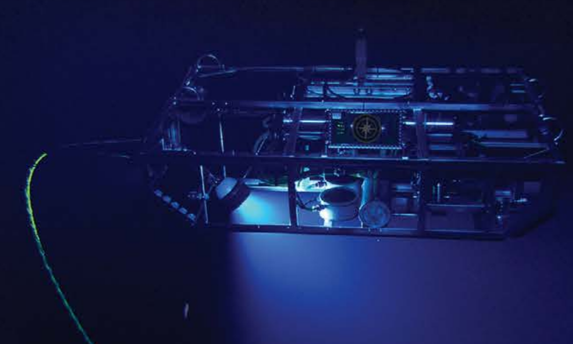
SUB-BOTTOM PROFILING SONAR. TriTech SeaKing Parametric Sub-bottom Profiler (10–30 kHz)

SIDE-SCAN SONAR. EdgeTech 4200 MP (300/600 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. A suite of high-resolution mapping tools 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)

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 DeepSea Power & Light Wide-i-SeaCam to view starboard side sample box, NTSC format

LIGHTING

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

SCALING. Two green DeepSea 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 or a Norbit WBMS 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)

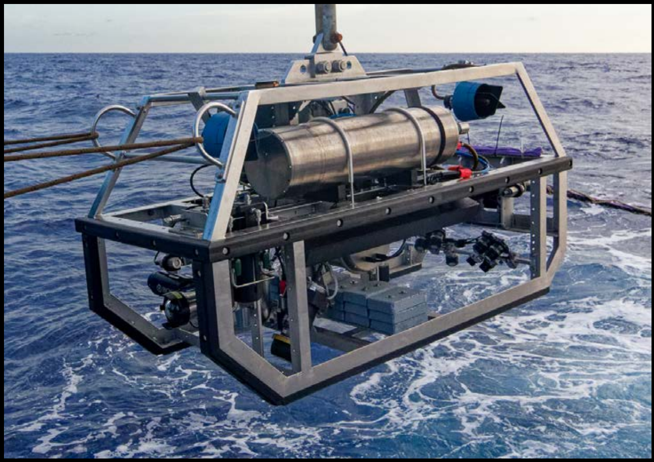
EXAMPLES OF USER-INSTALLED TECHNOLOGY

Advance notice is required for custom solutions to engineering integration of user-provided sensors and equipment.

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

Remotely Operated Vehicle (Towsled) *Atalanta*

Atalanta was first launched in 2019 and is a smaller version of *Argus*. It is used in tandem with ROVs *Little Hercules* or *Hercules*, hovering several meters above in order to provide a bird's-eye view of the ROV working on the seafloor. *Atalanta* is also capable of operating as a stand-alone system for wider-scale deepwater survey missions.



GENERAL

DEPTH CAPABILITY. 6,000 meters (19,685 feet)

SIZE. 2.16 meters long × 1.0 meters wide × 1.2 meters tall

WEIGHT. 1,000 kg (2,200 pounds) in air;
1,700 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 1 HP thrusters for heading control

IMAGING & LIGHTING

CAMERAS

- One Insite Pacific Mini Zeus high-definition camera
- Two mini utility cameras (fixed mounted) 480 line NTSC format

LIGHTING

- Eight DeepSea Power & Light (LED) LSL-1000 SeaLite Sphere lights

VEHICLE SENSORS & NAVIGATION

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

ALTIMETER. Valeport VA500 500Khz Altimeter

FORWARD-LOOKING SONAR. Mesotech 1071, 675 kHz, 0.5–100 meter range typical

SIDE-SCAN SONAR. Edgetech 2205, 75/410 kHz

SCIENTIFIC INSTRUMENT SUPPORT

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

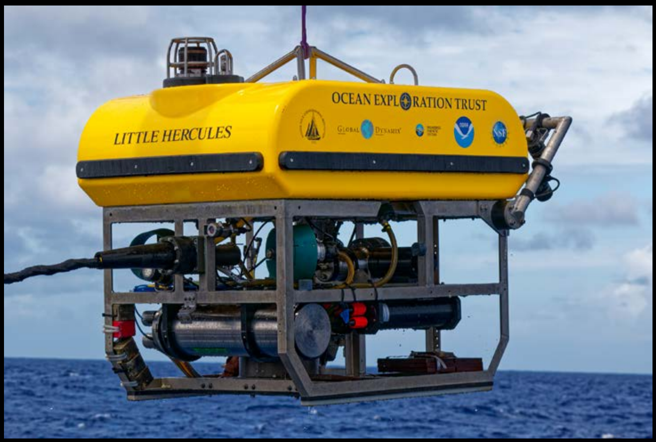
DIGITAL DATA CHANNELS. Ethernet, RS-232

2019 TECHNOLOGY COLLABORATIONS

- Applied Marine Sciences: PCB pump
- Coda Octopus Group: Echoscope sonar
- National Geographic Society: Deep Ocean Drop Cameras
- CORDC, Scripps Institution of Oceanography: Miniature wave buoys
- NOAA Pacific Marine Environmental Lab: Miniature Autonomous Plume Recorders (MAPRs)
- SoFar Ocean Technologies: Spotter buoys
- University of New Hampshire CCOM: Autonomous surface vehicle and aerial drones
- University of Rhode Island: Laser mapping system, Norbit multibeam sonar
- University of Texas Rio Grande Valley. Suspended particulate rosette (SUPR)
- Woods Hole Oceanographic Institution. MISO GoPro Camera & Housing, Isobaric Gas Tight (IGT)

Remotely Operated Vehicle *Little Hercules*

ROV *Little Hercules* is a smaller sister to *Hercules,* designed to function similarly with *Argus* or *Atalanta* but with a focus on gathering high-quality video imagery. *Little Hercules* is equipped with a high-definition or 4K video camera, LED lights, and basic sensors for navigation and situational awareness. *Little Hercules* was originally built in 2000, and was extensively refurbished and upgraded to 6,000-meter capability in 2019.



GENERAL

DEPTH CAPABILITY. 6,000 meters (19,685 feet)

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

SIZE. 1.4 meters long × 1.0 meters wide × 1.2 meters tall

WEIGHT. 400 kilograms (900 pounds) in air;
100 lbs payload

MAXIMUM TRANSIT SPEED. 2 knots

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

PROPULSION. Four Tecnadyne Model 1020 thrusters for heading control

IMAGING & LIGHTING

CAMERAS

- High definition: 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
- Ultra high definition: DeepSea Power & Light, 6,000 msw rated, 4K iDSPL Apex Cam
- Two mini utility cameras (fixed mounted) 480 line NTSC format

LIGHTING

- Seven Deepsea Power & Light LED Sphere lights

VEHICLE SENSORS & NAVIGATION

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

ALTIMETER. Valeport VA500 500Khz Altimeter

FORWARD-LOOKING SONAR. TriTech Super SeaPrince 675 kHz, 50 meter (164 feet) range

SCIENTIFIC INSTRUMENT SUPPORT

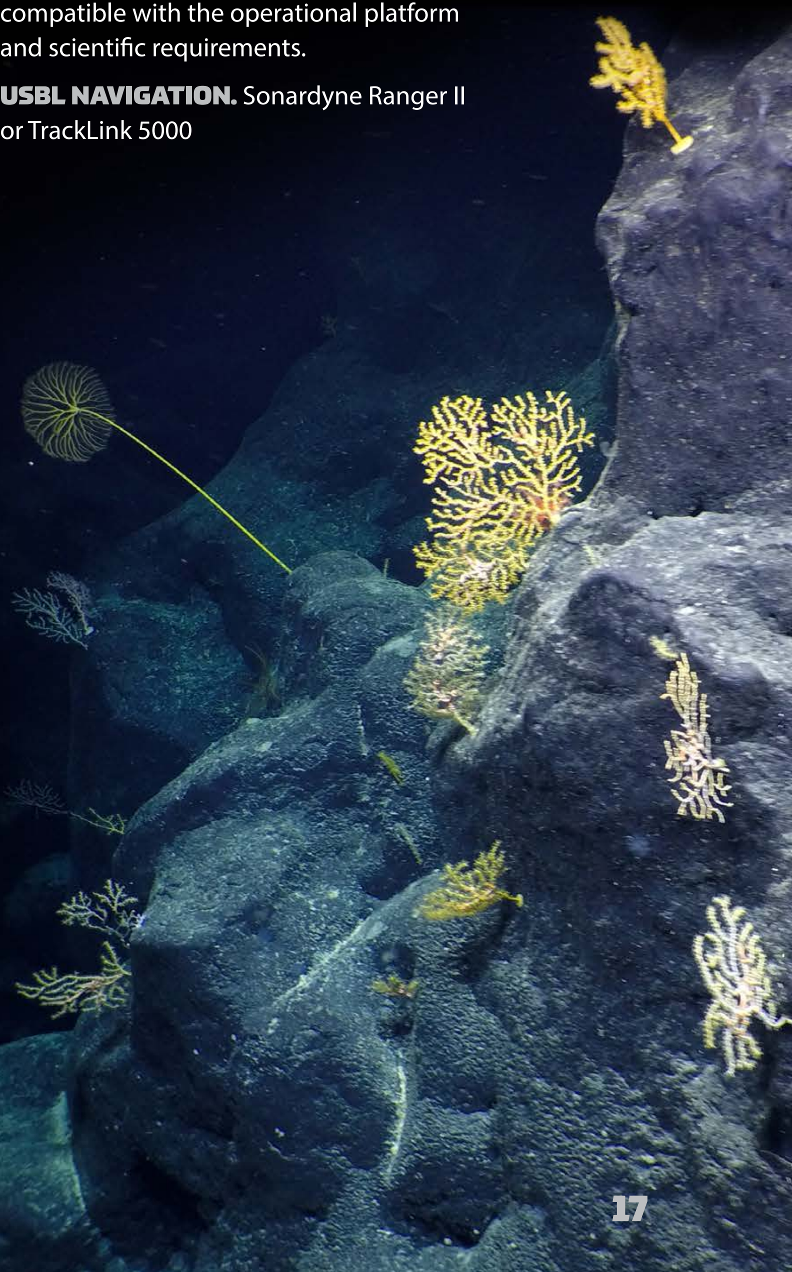
POWER. 110 V 60 Hz AC, 24 VDC and 12 VDC power options

DIGITAL DATA CHANNELS. RS-232 serial

ROV POSITIONING

The ROV systems are outfitted with an ultrashort baseline (USBL) navigation system compatible with the operational platform and scientific requirements.

USBL NAVIGATION. Sonardyne Ranger II or TrackLink 5000



Wet Lab Renovations and Selected 2019 Specimen Highlights

By Nicole A. Raineault, Roxanne Beinart, Amanda Kahn, and Kevin Konrad

In 2019, E/V *Nautilus* explored remote areas of the Pacific Ocean that, to date, few scientists have had the opportunity to study. An important aspect of our exploration program involved collecting representative specimens that scientists could examine to characterize the deep-sea environment in these areas. To that end, ROV *Hercules* collected 639 biological, geological, and water samples, resulting in over 1,250 subsamples. Samples from these collections can be requested for research by contacting partnering repositories: Harvard University's Museum of Comparative Zoology for biological samples and the University of Rhode Island Graduate School of Oceanography's Marine Geological Samples Lab for rock samples. In addition, we continued our collaborations to extract environmental DNA (eDNA) from water samples, including with the NOAA Northwest Fisheries Science Center for deep-sea coral, sponges, and fish, and with the NOAA Pacific Marine Environmental Laboratory for hydrothermal vent biota.

WET LAB RENOVATION

The wet lab is the hub of scientific activity after the ROVs are on deck. Following a successful dive, the ROV's boxes, Niskin water samplers, slurp chambers, and push cores are often full of unknown or strange specimens from the deep sea—each precious for providing new information on a remote environment. The lab is packed with scientists, students, and others who prepare the specimens for future use by researchers on land. In addition, researchers increasingly bring on board specialized tools and analytical equipment that require bench space and access to power, water, and/or gas lines, or they require additional cold space for sample preservation. As such, the lab needs to be a space that permits efficient and flexible use. The old lab space was sufficient for small numbers of samples and scientists and simple methodologies, but it became chaotic and cramped with the growing need to host more gear, people, and samples (Figure 1a).

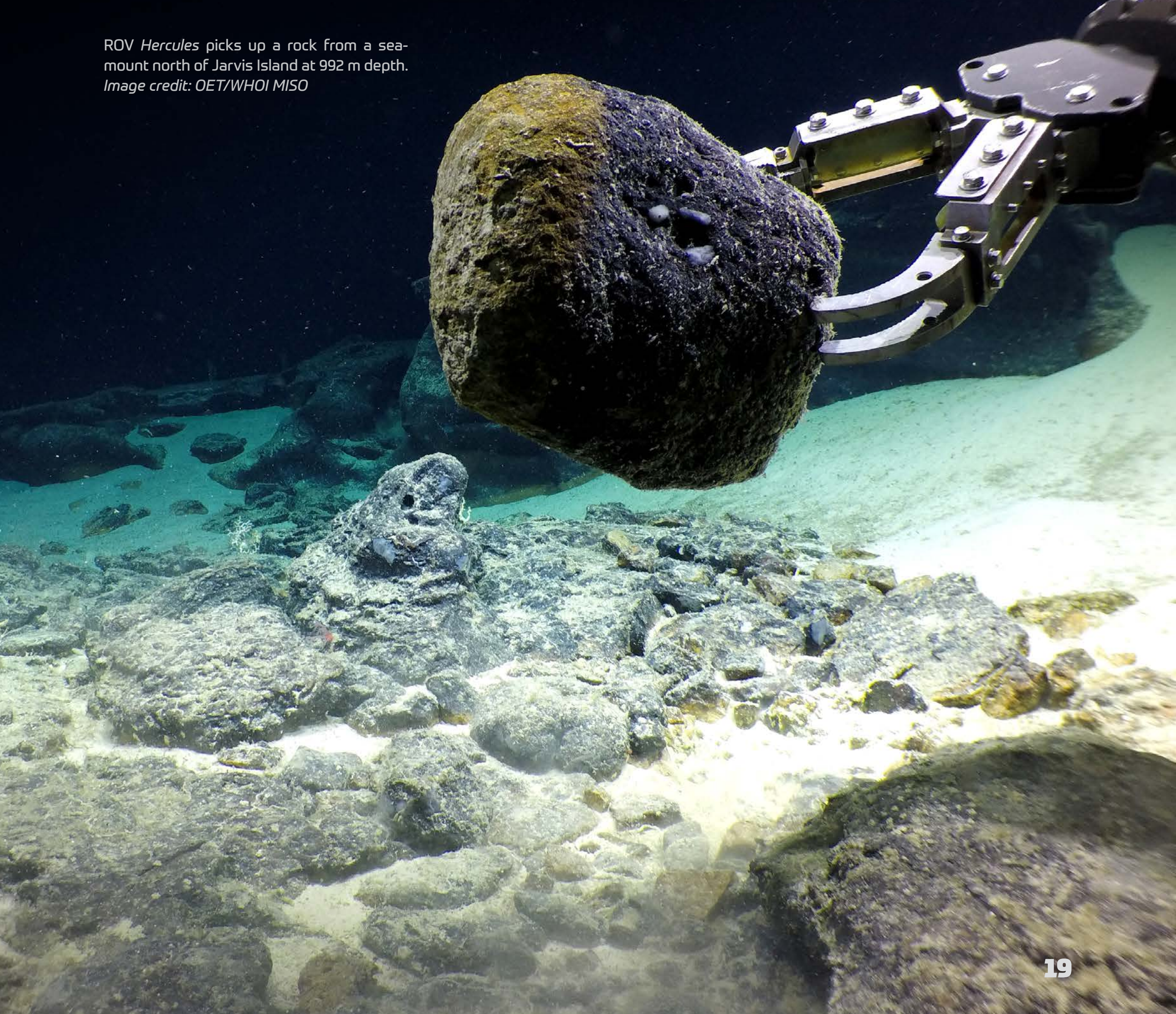
In 2018, OET began a lab renovation process, working with Anthony Paprocki, a Boston-area architect and designer. Space limitations were alleviated by increasing benchtop and standing capacity, as well as by doubling refrigerated space and adding a small freezer (Figure 1b). Raising the ceiling height, adding light fixtures, and brightening the lab with light colors on the bulkheads and floor improved the lab ambiance. Relocating the fume hood to the interior corner of the lab, increasing electrical outlet locations, and installing non-slip epoxy floor coating improved lab safety. The addition of a new, deeper sink provides both fresh and salt water access for sample processing or rinsing of instruments or sample trays.

FIGURE 1. The updated wet lab (b) uses space more efficiently than the previous configuration (a). (c) Scientists prepare samples post-dive in the new wet lab. *Image credits: (b) A. Paprocki, (c) M.L. Parker*

DEEP-SEA ROCKS – Kevin Konrad

Nautilus expedition NA110 explored seamounts in the Kingman Reef, Palmyra Atoll, and Jarvis Island regions of the Pacific Basin and provided geologists with an unprecedented opportunity to study the dynamics of submarine post-erosional volcanism. Dives during this expedition typically started on the deep flanks of guyots (flat-topped seamounts) and traversed up toward the summit where volcanic cones rise above the otherwise flat surface. Basalt samples were taken from the various depths and features on the guyots/volcanic cones. Through $^{40}Ar/^{39}Ar$ age determinations and geochemical analyses, geologists will determine if these volcanic cones represent episodes of rejuvenated volcanism that occurred within a few million years after the ocean island subsided or reactivated volcanism driven by local tectonic stress long after the island subsided. These results will speak to the underlying geodynamics governing the origin of the Line Islands volcanic lineament. In addition, this expedition recovered basaltic samples from the Jarvis Island region—providing an opportunity to place these islands and seamounts within the broader tectonomagmatic framework of the Pacific basin.

ROV *Hercules* picks up a rock from a seamount north of Jarvis Island at 992 m depth. *Image credit: OET/WHOI MISO*



CARNIVOROUS SPONGE – Amanda Kahn

The distance from the deep seafloor to the ocean's surface means that benthic communities rely on food imports alone, and the many adaptations of its inhabitants reflect that large separation. Sponges as a group are filter feeders that concentrate minute particles from the water to obtain nutrition. In the food-poor deep ocean, however, any edge to acquire more food would give sponges an advantage. To this end, one group of sponges has eschewed a filter-feeding lifestyle and has become predatory. Carnivorous sponges ensnare small prey on glass barbs and hooks that stick out of the sponge's body. Once ensnared, the body of the captured prey is slowly engulfed by cells and digested.

A small, leaf-like sponge was spotted during the NA116 cruise to Cordell Bank/Greater Farallones National Marine Sanctuary (Figure 2a). This sponge resembled a thin white leaf connected to the seafloor by a stalk, with veins of reinforcing skeleton running down the center of the leaf. By comparing it to similar specimens collected between California and British Columbia, Canada, researchers identified the glass skeletal elements that typify a carnivorous sponge. This species is especially interesting because it has a very different morphology than other known carnivorous sponges, and either represents a new species or possibly a new genus. The specimen collected on this cruise was also particularly interesting because it had several prey items visibly pinned against the sponge body wall, so researchers will also be able to understand something about the sponge's ecology: the size ranges of prey items captured, their diversity, and the degree of digestion/decomposition (Figure 2b). The specimen is currently housed at the California Academy of Sciences and will be used along with several others to create a formal species description (and name), which will be done as a collaboration between Henry Reiswig (University of Victoria/Royal British Columbia Museum), Lonny Lundsten (Monterey Bay Aquarium Research Institute), and Amanda Kahn (Moss Landing Marine Laboratories).

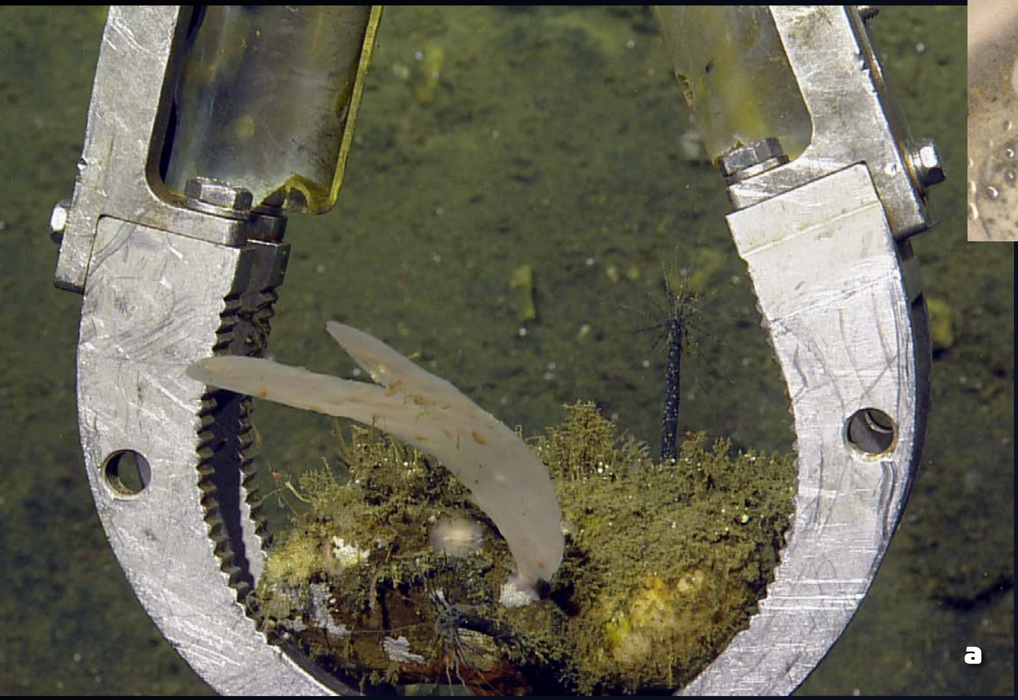


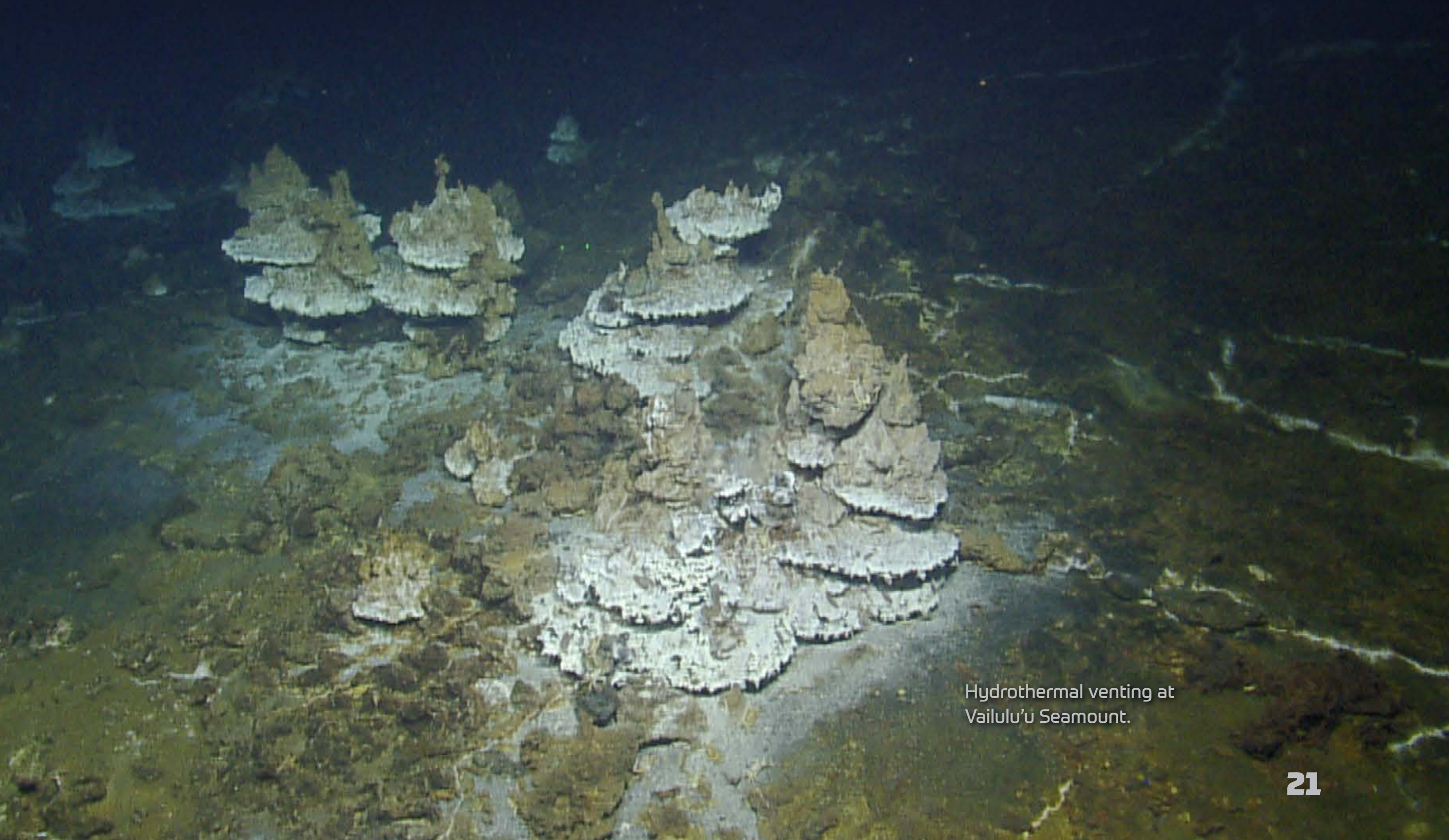
FIGURE 2. New species of carnivorous sponge discovered on the Point Arena south ROV dive in Greater Farallones National Marine Sanctuary (a) in situ, and (b) in the lab.

FIGURE 3. Hydrothermal vent snails (*Alviniconcha*) discovered at the Vailulu'u seamount (a) in situ, and (b) in the lab.

HYDROTHERMAL VENT GASTROPODS

– Roxanne Beinart

Alviniconcha snails were found around areas of hydrothermal venting (678 m depth) at Vailulu'u Seamount for the first time (Figure 3). *Alviniconcha* species are endemic to vents across the western Pacific and Indian Oceans and are one of the predominant taxa in these ecosystems. Recently completed genotyping of these Vailulu'u specimens indicates that they are *Alviniconcha boucheti*, a species that is also found at hydrothermal vents in the relatively nearby Lau, North Fiji, and Manus Basins (Johnson et al., 2015). Further work will be necessary to understand whether the Vailulu'u population is genetically connected to populations elsewhere.



Hydrothermal venting at Vailulu'u Seamount.

Illuminating STEM Career Pathways and Deep-Sea Discoveries Through *Nautilus* Exploration and Outreach

By Megan Cook, Samantha Wishnak, Kelly Moran, Timothy Burbank,
Jessica Kaelbein, Michael Viveiros, Madison Dapcevich, and Allison Fundis

In our mission to inspire the next generation of explorers and to connect learners to physically and conceptually distant reaches of our planet, the Ocean Exploration Trust conducts a suite of outreach and education programs. The keystone of these programs is centered around a universally recognizable element of our work—the curiosity, passion, and diversity of STEM career pathways within our team. Each year, the Nautilus Exploration Program's Corps of Exploration is made up of more than 200 professional engineers, scientists, technologists, educators, students, and mariners who work together to undertake expeditions that reveal new phenomena in the deep sea and generate more questions about it. Featuring these professionals with their varied skill sets, backgrounds, and career and education pathways creates authentic opportunities for our audiences to find more personal connections to the deep sea. As featured participants in our live streams and ship-to-shore interactions while aboard E/V *Nautilus*, members of the Corps of Exploration return to their home communities as ambassadors for ocean exploration, amplifying our ability to connect with diverse audiences. During the 2019 *Nautilus* expedition, OET continued to expand the ways learners can connect with our mission and to broaden our real-time outreach capabilities and role modeling resources to illuminate pathways to deep ocean exploration and STEM workforce careers.

Ocean Science Intern Taylorann Smith processes a deepwater coral sample in the *Nautilus* wet lab. *Image credit: Erin Ranney*

As we conducted visual surveys of the whale fall discovered at Davidson Seamount in Monterey Bay National Marine Sanctuary, thousands of viewers around the world tuned in to explore alongside our team in the control van. *Image credit: Erin Ranney*

DIGITAL OUTREACH

Bringing an over-the-shoulder view to ocean exploration, the Nautilus Live website and social media pages encourage viewers to participate and become explorers. As the central portal into our expeditions, NautilusLive.org scaffolds our underwater live streams with rich educational context, integrating data streams, highlighting unusual sightings, and showcasing our interdisciplinary team. Our social media platforms offer shore-based explorers real-time glimpses behind the scenes of shipboard operations and help share new discoveries with the public and press around the world.

Over our six-month 2019 expedition season, the Nautilus Live website gained over 1.5 million views, on par with previous years while accommodating a "closed set" during a month of National Geographic filming. Viewers in over 100 countries across the globe watched more than 6.7 million minutes of our live streams, as this resource continues to serve as an introductory portal into ocean exploration, attracting students, educators, scientists, and the general public. Amplifying the reach of our live streams, engagement with short video highlights of our sightings on YouTube and the Nautilus Live website doubled this year, gaining over 10 million views.

The power of providing a real-time ocean exploration experience to a global audience becomes most apparent when our sightings goes viral. During one dive in October 2019, views on the Nautilus Live website increased by 1,200% as our team happened upon a whale fall feeding bonanza in Monterey Bay National Marine Sanctuary. Twitter was the major driver of traffic to the live stream as several popular science outlets and influencers tweeted about our live stream, resulting in 55,000 interactions with our content. By hooking the curiosity of the general public, scientists, and students, thousands of new viewers followed the exploration and continued the conversation across social media platforms for days afterward.

Instagram continues to attract new audiences to Nautilus Live—a 165% increase in followers this year demonstrates some of the highest levels of engagement across our social platforms, most frequently from followers tagging friends to share our posts. Top video views on Instagram are often comparable to our YouTube video views, and Instagram Stories often receive higher levels of engagement than traditional posts on Facebook or Twitter. Instagram Story takeovers continue to shine as an opportunity to spotlight members of the at-sea team, behind the scenes activities, and expedition partners, with these takeovers saved as browsable highlights. Expedition team members, from visiting scientists to first-timers at sea, enjoy the opportunity to share their perspectives, and followers frequently comment on how powerful it is to meet some of the interns, educators, and other STEM professionals heard on Nautilus Live.

Continuing to innovate to provide cutting-edge public access to ocean exploration, we are undertaking a major redesign of the Nautilus Live website. Features will be expanded to include more real-time expedition content, data visualization, resources for K–12 learners, and new ways to feature partnerships and our expeditions deployed from other vessels in order to offer a more dynamic and interactive experience. The new fully responsive design will support and promote our multiple audiences, including educators, students, scientists, current and potential partners and funders, and the general public.

Instagram Story takeovers provide behind-the-scenes insight into research and life at sea, like this feature with WHOI microbiologist Sarah Hu.

New career pages on the Nautilus Live website offer in-depth profiles and overview videos of expedition roles by featuring members of the Corps of Exploration.

PRESS

As an extension of the Nautilus Live website and social media platforms, coordinated media efforts among the OET team and partners expand our most viral stories to include narratives of the people and technology behind the discoveries. Over the 2019 season, more than 1,095 *Nautilus*-related news reports were featured in print, radio, television, and online media outlets with an estimated reach of 65 million. Positioning our team and resources to be able to turn around same-day press kits for surprising or unique sightings resulted in our stories hitting viral status both on social media and in news outlets, with subjects including a translucent *Deepstaria* jelly with a resident isopod, a rarely seen *Asperoteuthis* squid, and two billowing *Cirroteuthid* octopuses—all in the Pacific Remote Islands Marine National Monument and shared alongside US Fish and Wildlife and NOAA Office of Ocean Exploration and Research partners. The whale fall was seen around the world in classrooms, museums, and offices as viewers tuned in to watch the live exploration from Monterey Bay National Marine Sanctuary, and it was extensively covered by national and local media outlets, supported by our partners at the NOAA Office of National Marine Sanctuaries.

Across our six-month field season, news outlets featuring articles about *Nautilus* team members, expeditions, and partnerships, included *The New York Times*, *The Washington Post*, NPR, *Smithsonian Magazine*, *Air & Space Magazine*, National Geographic, NASA, *Worth*, *Forbes*, CNN, CBS, ABC, Marine Technology News, LiveScience, Slate, Huffington Post, IFLScience, *Wired*, and *Popular Science*. In addition to standard press requests, Ocean Exploration Trust licensed expedition footage for use in over a dozen documentary productions with distribution across National Geographic, BBC, Discovery, and Science Channel networks, and museum exhibitions around the world. Complementing our standard press and media support during research expeditions, the Ocean Exploration Trust team also supported a three-week-long "closed set" and assisted with press relations as *Nautilus* and Ocean Exploration Trust team members were featured in the National Geographic documentary "Expedition Amelia." The two-hour special premiered on the National Geographic Channel in October 2019 with 212,000 viewers across the United States and over 170 news stories in print, radio, television, and online media outlets.


42 CIENCIA

EDUCADORA DE JUNCOS

Exploran las profundidades del Pacífico

Yashira Cruz Rodríguez colabora en el estudio de la vida marina y la creación de mapas del suelo oceánico

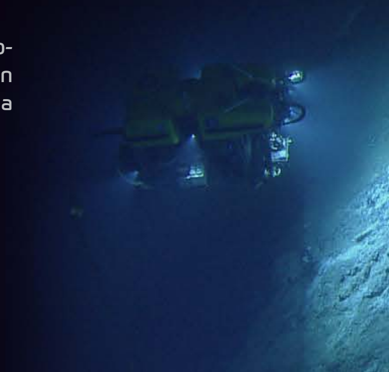
Members of the Corps of Exploration were featured in online and print news around the world, including this article about Science Communication Fellow Yashira Cruz Rodriguez connecting with her home community in Puerto Rico via a ship-to-shore interaction.

For Students

In addition to data logging and sample processing duties, Ocean Science intern Peyton Lee documented his at-sea experience in a beautiful graphic travelogue.

SHIP-TO-SHORE CONNECTIONS

Telepresence technology installed on board *Nautilus* allows onshore audiences to engage in a two-way dialogue with shipboard team members. Live ship-to-shore interactions give K–12 classrooms, universities, museums, science centers, and out-of-school programs the opportunity to learn and ask questions about *Nautilus* expeditions and ocean exploration directly from the at-sea team. These connections are a popular way to showcase the many professions essential within an expedition and, as such, are a key component of the role modeling aspects of OET's program.



Once samples have been recovered from the vehicles, Ocean Science intern Peyton Lee learns processing techniques from Science Manager-in-Training Rebecca Wipfler.

One of 21 Science & Engineering interns during the 2019 season, ROV Engineering intern Avery Malachi works alongside the ROV team to conduct pre-dive checks on the vehicles. *Image credit: Marley Parker*

OET continues to experiment with different technologies to provide dynamic experiences that connect audiences to exploration. New in 2019, an onboard production switcher in the ship's studio allowed presenters to produce customizable interactions featuring expedition and technology imagery as well as live feeds from the ROVs and topside shipboard cameras. A mobile interaction kit also allowed presenters to speak with students from unique STEM workplaces like the ship's wet lab and the ROV hangar.

Interest in these real-time opportunities to connect with STEM role models continues to grow. Surpassing the reach of the 2018 *Nautilus* season, the Corps of Exploration conducted 257 live ship-to-shore interactions reaching over 12,410 students and community members in 30 states and US territories and nine countries in 2019. This year, 131 ship-to-shore interactions went directly into K–12 schools, offering students an engaging outlet for their curiosity about the ocean and a direct connection with scientists, interns, educators, and engineers aboard *Nautilus*. OET continues to partner with the NOAA Office of National Marine Sanctuaries to connect NOAA scientists on *Nautilus* to learners around the world and those local to their sanctuaries. In 2019, OET conducted 32 ship-to-shore interactions in partnership with the National Marine Sanctuaries (NMS) in Cordell Bank NMS, Greater Farallones NMS, and Monterey Bay NMS, as well as the Pacific Islands Marine National Monument.

SCIENCE & ENGINEERING INTERNSHIP PROGRAM

For students in community colleges through graduate programs, as well as those beginning their professional careers after earning a recent degree, OET offers the Science & Engineering Internship Program (SEIP). SEIP provides training and real-world experiences in the ocean and nautical sciences, seafloor surveying, engineering, and video through positions that entail two to four weeks working aboard *Nautilus*. The program fosters teamwork and helps the interns develop hands-on skills and apply their growing knowledge to real-world problems.

The five internship tracks—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. Interns spend their time at sea working alongside a wide array of scientists, engineers, students, and educators and gain communication and leadership experience, as well as participate in educational outreach activities. The navigation internship, offered in partnership with the United States Naval Academy and the United States Coast Guard Academy, provides operational experience for cadets and midshipmen to use course instruction, critical thinking, and problem-solving skills to support deep-sea exploration.

OET is committed to leveraging at-sea programs to provide learning experiences and role modeling opportunities for a broad representation of students. This year, 21 participants from 15 US states and one Canadian province joined the Corps of Exploration through the internship program. The internship pool included 33% of applicants who self-identified as non-Caucasian or multiracial and 37% of the internships were awarded to students of color. OET has also worked to ensure women are equally represented in our internship program. In 2019, more than 65% of Science & Engineering Internship Program applicants were women and 60% of internships were awarded to female students.

EDUCATION RESOURCES AND PROFESSIONAL DEVELOPMENT

OET offers a suite of educational resources designed to link classroom STEM content and twenty-first century skills with real-world applications of concepts fundamental to deep-sea exploration. OET has a collection of inquiry-driven STEM Learning Modules aligned to and guided by the performance expectations of the Next Generation Science Standards, Common Core State Standards, and Ocean Literacy Principles. The STEM Learning Module collection has grown since 2015 and now includes 28 stand-alone and freely available lessons. OET has also built a Digital Resource Library of over 65 unique resources to equip educators with introductory and instruction-enhancing material to bring exploration and discovery to students of all ages. Enhancing the ability of students and educators to explore STEM careers on our website, this year OET introduced a series of career profile pages with video introductions featuring various careers and team members aboard *Nautilus*.

Science Communication Fellow Brandon Rodriguez conducts a ship-to-shore interaction with educators in a professional development event he coordinated with NASA's Jet Propulsion Laboratory.

Education resources are all freely available online via https://nautiluslive.org/education and were accessed by 563 educators from 40 countries in 2019. OET staff provides coaching for educators to encourage implementation of these resources in classrooms and works with educators to differentiate lessons for various grade levels and classroom styles like 1:1 technology access, homeschool, free choice, or after-school activities.

Developed alongside OET's education resources, professional development workshops provide formal training and collaboration time for educators to brainstorm and build connections from their classroom content to real-world exploration. This year's workshops and local STEM events reached more than 600 educators, students, and community members in California, Illinois, and Texas.

SCIENCE COMMUNICATION FELLOWSHIP

The Science Communication Fellowship (SCF) invites formal and informal educators to participate in the Nautilus Exploration Program as communicators for ocean exploration, sharing the excitement of exploration and research with students and public audiences in their communities and around the world. The SCF includes participation in a science communication training workshop alongside the OET team; experience sailing for one to three weeks as expedition interpreters aboard E/V *Nautilus*; a one-year commitment to collaborate with OET, STEM professionals, and fellow educators; and the development of STEM lessons or outreach materials for their learners as a summative deliverable.

Participation in the fellowship provides not only authentic experience within a research expedition setting, but also develops key communication capacities such as on-camera presenting and strengthens Fellows' 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 their understanding of STEM concepts as they relate to ocean exploration. All of these experiences combine to support an essential goal of the SCF program: to impart the significance of STEM fields and ocean exploration, as well as the various career options in STEM, to the students of participating educators.

The application pool for the 2019 SCF was the most diverse, as measured by self-reported ethnicity, of any program year to date. The resulting cohort (16 Fellows from 10 US states and Canada) was the most inclusive of underrepresented communities in OET's eight-year

The 2019 Science Communication Fellow cohort included 16 classroom teachers, museum educators, and communicators representing communities across the United States and Canada.

program history, including five educators of color and four educators who teach at Title-1 or majority low-income K–12 schools. We continue to seek applicants for this program who reach learners from inland communities and underrepresented and underserved backgrounds and who can serve as role models of excellence in STEM education. One Fellow shared, "This is an amazing opportunity to get inspired, to be creative, to expand your ideas and network, to realize the importance of spreading the word about exploring our planet."

NAUTILUS AMBASSADOR PROGRAM

The Nautilus Ambassador Program is designed for educators interested in bringing real-world science into their classrooms. This introductory program fosters a foundation in ocean literacy and exposure to career pathways in STEM and maritime industries for educators with limited previous experience. The Ambassador Program brings educators to sea for a four-day expedition. Ambassadors are involved in all aspects of the Nautilus Exploration Program while on board, gaining familiarity with ocean science, technology, engineering, and science communication. This year, four Nautilus Ambassadors from Louisiana, Texas, and Illinois sailed on an expedition, conducting visual surveys and testing a new mapping tool in the Channel Islands and around Osborn Bank off the coast of California. Ambassadors took an oceanography short course focused on phenomena under investigation on this expedition that included plate tectonics, regional ocean chemistry and structure, and sea level variation. Ambassadors shared these learning experiences while on board *Nautilus* with students in their classrooms through live ship-to-shore interactions.

After their at-sea experience, Ambassadors return home as strong role models for students and education peers ready to share the excitement of ocean exploration with their schools and communities. The collaborative format and teaching/learning style of this program profoundly impacts educators' teaching practices, and ambassadors remain active in the OET community outreach as advisors to and participants in local programs.

One of the signatures of success for OET's at-sea programs can be observed in how participants become empowered as ambassadors for exploration. This confidence and quality of experience displays itself as participants lead outreach within their own communities. Program participants from interns, to ambassadors, to fellows became active role models for STEM learning after sailing on *Nautilus,* hosting community talks and professional development workshops using OET materials nationwide. The authenticity of sharing the mission of *Nautilus* through local students and educators opens up new audiences to learning about ocean exploration. These events also broaden the impact of OET programs and further develop professional skills such as public speaking and crafting the story within technical information for varied audiences. Participants led public talks, outreach events, and live ship-to-shore connections; spoke at conferences; and organized professional development workshops for educators in California, Florida, Illinois, Maryland, New York, Pennsylvania, Texas, and Puerto Rico, reaching thousands.

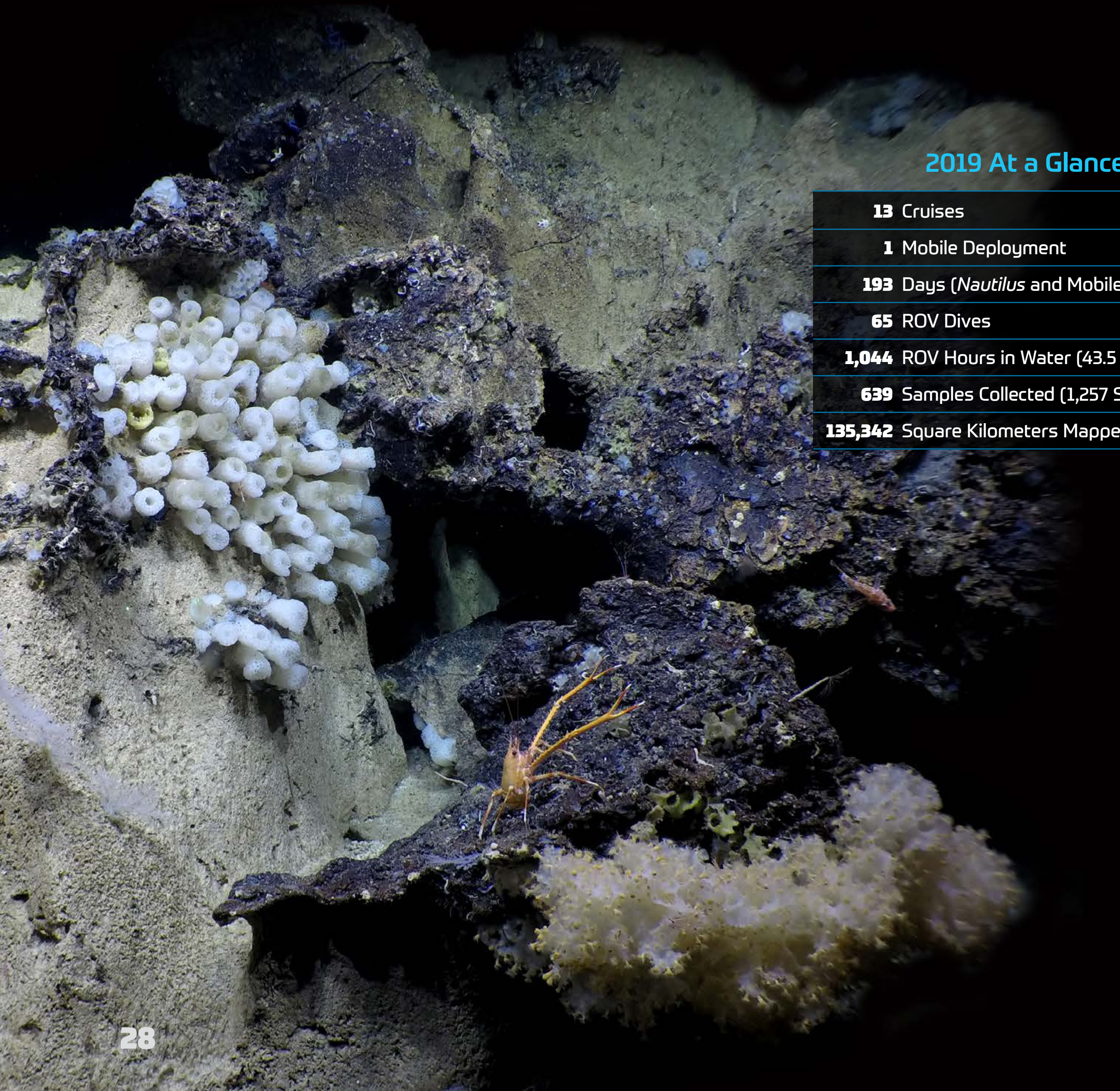
OET looks forward to 2020, the twelfth year of the Nautilus Exploration Program, with renewed commitment to bringing the excitement of discovery and inspiration of STEM-focused careers to global audiences. We celebrate the opportunity to connect the deep ocean with the professional science community and also those just beginning to become familiar with marine science and technology. As our programs continue to grow, new opportunities for scaling will develop from OET's involvement in NOAA's Ocean Exploration Cooperative Institute, working alongside other technology, research, and education partners.

Nautilus Field Season Overview

By Nicole A. Raineault

In 2019, E/V *Nautilus* and its Corps of Exploration ventured further west and south than ever before. The nearly 200-day expedition season included research with new partners at the National Marine Sanctuary of American Samoa and the US Fish and Wildlife Service within the Pacific Remote Islands Marine National Monument (PRIMNM). Comparatively little is known about both of these expansive protected areas, in large part due to their remote locations. Continuing partnerships with groups, including the National Geographic Society, also allowed comprehensive mapping and exploration within the Phoenix Islands Protected Area, particularly around Nikumaroro. Working in these remote areas brought new opportunities for collaborations with physical oceanographers: as we mapped long distances between survey and remotely operated (ROV) dive locations, we deployed wave buoys for Scripps Institution of Oceanography, Sofar Ocean Spotter buoys, and an Educational Passages sailboat, allowing researchers and students to learn more about central Pacific Ocean surface dynamics.

This year also marks the first deployment of our mobile capabilities. OET and the University of New Hampshire's Center for Coastal and Ocean Mapping worked with the Thunder Bay National Marine Sanctuary in northwestern Lake Huron (pages 32–33). Dual survey efforts with the autonomous surface vehicle (ASV) *BEN* and a mapping



2019 At a Glance

13	Cruises
1	Mobile Deployment
193	Days (*Nautilus* and Mobile Deployment)
65	ROV Dives
1,044	ROV Hours in Water (43.5 Days)
639	Samples Collected (1,257 Subsamples)
135,342	Square Kilometers Mapped

system on R/V *Storm* resulted in the discovery of new targets, which will be characterized by ROV in the future. We mapped more seafloor this year than any on record, over 135,340 km^2 (pages 30–31). This activity was a major contribution to the Seabed 2030 effort to map the entire world's ocean floor by 2030, particularly because *Nautilus* surveyed remote US territories, areas that were otherwise unlikely to be mapped.

Nautilus operated 174 days between late April and mid-October 2019 and conducted a total of 65 ROV dives. In addition to ROVs *Hercules* and *Argus*, we tested the newly refitted *Little Hercules* on two expeditions and the new *Atalanta* ROV (pages 30–31). ASV *BEN*, aerial drones, and National Geographic Drop-Cams added to our exploration capabilities on expeditions this year. Over 180 people participated on board, and dozens of researchers joined in from shore, adding their expertise to the exploration.

Winter improvements to E/V *Nautilus* included installation of the traction winch in the main hold, wet lab renovations, and a new dynamic positioning system, as well as upgrades to computing, video, and vehicle systems. The annual shakedown cruise tested standard systems as well as ROV *Little Hercules* off the coast of San Pedro, California. A new high-resolution mapping system on *Hercules* was tested during a brief expedition at the Osborn Bank caves south of Santa Barbara Island (pages 34–35), which also hosted educational Ambassadors. A mapping expedition from San Pedro to San Francisco, California, focused on mapping areas in advance of the October expeditions to the Greater Farallones and Cordell Bank National Marine Sanctuaries.

Our second expedition of the NASA SUBSEA program was located at Gorda Ridge, off the Oregon coast. Scientists generated dive plans and led dives from the Inner Space Center at the University of Rhode Island using new software to aid in dive planning and data review, resulting in the discovery of the Apollo hydrothermal vent site (pages 36–37).

Nautilus crossed the Pacific to Hawai'i, adding mapping coverage adjacent to last year's track near the Murray Fracture Zone and deploying the National Geographic Drop-Camera to catch glimpses of the benthos (pages 30–31). From Hawai'i, the team set off on an expedition around the US territories within the Line Islands: Kingman Reef, Palmyra Atoll, and Jarvis Island (pages 38–39) to American Samoa. The Corps of Exploration conducted nearly a week of side-scan sonar surveys and targeted reconnaissance with *Argus* to search for the *Samoan Clipper*, a Pan Am plane lost January 11, 1938, near American Samoa (pages 40–41).

Our first expedition with the National Marine Sanctuary of American Samoa added new information about habitat diversity, including at the active hotspot volcano Vailulu'u, which lies within this southernmost US Territory (pages 42–43). A team of scientists is analyzing high-resolution photomosaics, oceanographic data, and samples to plan a return in the next few years.

Dr. Ballard led a team of explorers in search of Amelia Earhart's plane around Nikumaroro, a Kiribati atoll (pages 44–45). Extensive seafloor mapping by *Nautilus* and ASV *BEN*, aerial drones, and ROV dives gathered enormous quantities of data and were featured in a National Geographic Society television special.

The 22-day expedition from Samoa to Honolulu featured seven ROV dives and extensive mapping in the Pacific Islands Remote Marine National Monument focused around Baker and Howland Islands and Johnston Atoll, and included crossing both the International Date Line and the equator (pages 46–47). The team also delivered supplies to Kanton Island, the only populated Phoenix Island.

Dual goals of charting unmapped areas of seafloor and conducting the first tandem *Little Hercules* and *Atalanta* ROV dives were met on the return crossing from Honolulu to San Francisco. Extensive trials with engineers and computer programmers further developed the systems and tools for future scientific expeditions.

We conducted a joint expedition with the NOAA Office of National Marine Sanctuaries to the Cordell Bank and Greater Farallones National Marine Sanctuaries in early October. This expedition utilized mapping data gathered by *Nautilus* in May to help select ROV dive locations in changing fisheries management zones and also continued the ROV exploration of Bodega Canyon, resulting in dives that showcased deep-sea coral and sponge habitat (pages 48–49). The final and much-anticipated expedition to Monterey Bay National Marine Sanctuary was a return to the site of brooding cephalopods (*Muusoctopus robustus),* where we deployed long-term monitoring instruments to better understand the low-temperature hydrothermal system. However, the whale fall we encountered on our second exploratory dive stole the show (pages 50–51).

During the winter of 2019–2020, *Nautilus* underwent major upgrades. The heart of the ship—the engine—and the brain of the ship—the control vans—were removed and replaced. Due to the large scale of these projects, we anticipate a later start date for the E/V *Nautilus* season in the summer of 2020, which will begin with extensive system tests. We also anticipate a return to Lake Huron to continue seafloor mapping and possibly conduct target identification with ROVs in partnership with the Thunder Bay National Marine Sanctuary. The E/V *Nautilus* field season will include mapping large areas of the US EEZ off of the West Coast, work with Ocean Networks Canada at their cabled observatories, and ROV exploration of methane seeps along the Cascadia Margin, within the West Coast National Marine Sanctuaries and offshore of southern California.

E/V *Nautilus* 2019 Mapping

FILLING THE GAPS IN SEAFLOOR COVERAGE OF THE REMOTE PACIFIC AND CONTRIBUTING TO GLOBAL SEABED MAPPING INITIATIVES

By Lindsay Gee, Erin Heffron, Renato Kane, Colleen Peters, and Nicole A. Raineault

In 2019, E/V *Nautilus* expeditions covered wide areas of the North and Central Pacific, with transits from San Francisco to Honolulu in June and a return to the West Coast in early October (Figure 1). In between, *Nautilus* operated as far south as Samoa. During both exploration cruises and transits in the Central Pacific, *Nautilus* mapped the seafloor with the multibeam sonar and a sub-bottom profiler. Transits were planned to follow tracks away from direct routes between ports, filling in some of the major gaps in seabed mapping coverage of this remote region.

The more than 135,000 km^2 mapped this field season contributed to the Nippon Foundation-GEBCO Seabed 2030 project and added over 45,900 km^2 of new seafloor maps for the US Exclusive Economic Zones (EEZs) of Hawaiʻi, American Samoa, and the Pacific Remote Islands Marine National Monument (PRIMNM). The seabed mapping also provided a foundational data set for all 2019 *Nautilus* cruises, supporting the planning and successful completion of 65 ROV dives that collected an array of ocean observations.

Discovering and identifying suitable quality multibeam data during 2019 expedition planning highlighted part of the challenge for the GEBCO Seabed 2030 project, an international effort to map the world's seafloor by 2030. Currently, there is no single source for identifying all mapped areas of the seafloor. Instead, there are numerous data archives globally, and the flow of data from acquisition by ships to bathymetric map varies depending on the data source, archive, and model. The importance of not only publicly archiving raw data but also optimizing the data flow to support the global models cannot be overemphasized. *Nautilus* data are archived publicly via the Rolling Deck to Repository (R2R) program, which provides data to the NOAA National Centers for Environmental Information. In addition, since 2018, OET has provided processed grids of the multibeam data collected to the Seabed 2030 North Pacific Ocean Regional Data Center to ensure timely inclusion in the GEBCO grid.

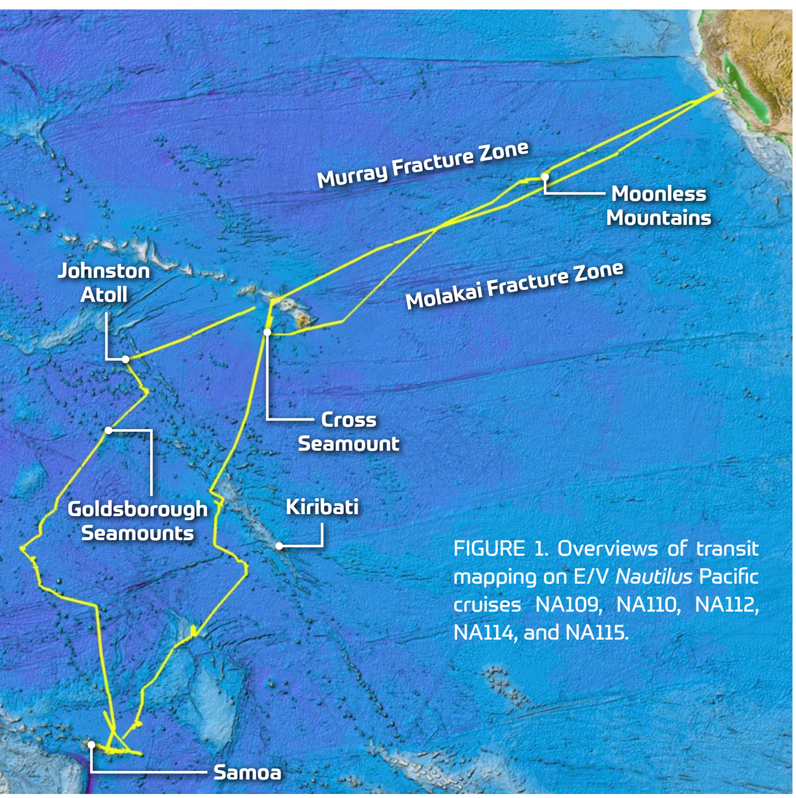


FIGURE 1. Overviews of transit mapping on E/V *Nautilus* Pacific cruises NA109, NA110, NA112, NA114, and NA115.

During the two transits between San Francisco and Honolulu (NA109 and NA115), *Nautilus* mapped over 48,450 km^2 of seafloor along more than 8,400 km of trackline (Figure 1). The depths ranged from just under 360 m on Cross Seamount to over 6,050 m crossing the Molokai Fracture Zone. There were only a few days available for dedicated mapping during the NA109 transit, so an important consideration was maximizing the value of the short time available to ensure it added, and complemented, available data. In 2018, we mapped seamounts from a linear chain south of the Murray Fracture Zone called the Moonless Mountains, and this year mapping extended to a series of adjacent ridges to the east (31°0'N 136°30'W). These data continue to add to the overall knowledge about the structure of the features adjacent to the fracture zone (Figure 2).

The return mapping transit from Honolulu to the West Coast was combined with testing of the new OET/Woods Hole Oceanographic Institution mobile ROV system funded by NOAA OER. The transit began by proceeding south to Cross Seamount where the first engineering tests were conducted with ROV *Atalanta* and supporting equipment. After departing the EEZ south of Hawaiʻi, the track was diverted slightly further north than planned to avoid the effects of a tropical depression to the southeast. However, it did allow some further mapping of an unexplored seamount located on the outbound transit, before the first two combined engineering dives of ROVs *Little Hercules*

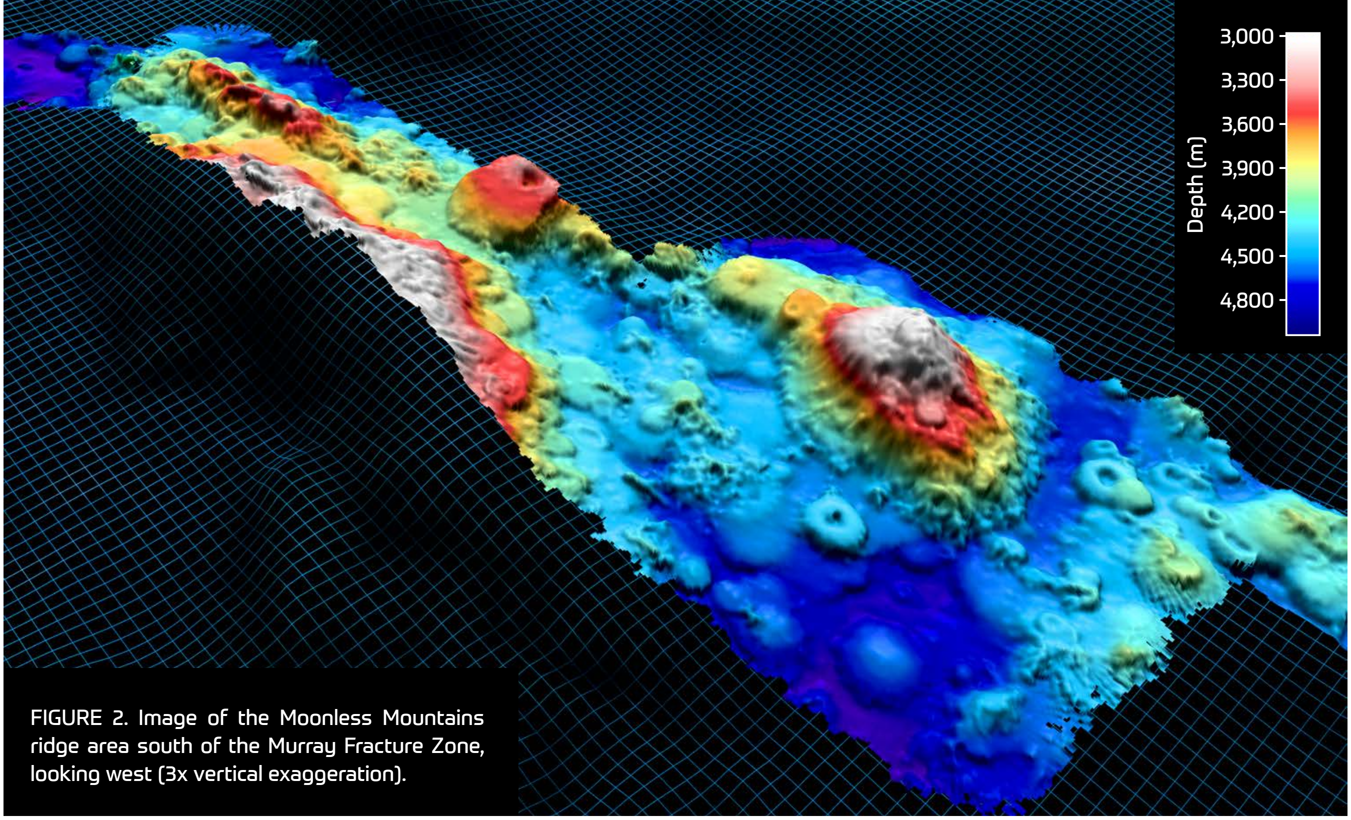


FIGURE 2. Image of the Moonless Mountains ridge area south of the Murray Fracture Zone, looking west (3x vertical exaggeration).

and *Atalanta*. A final dive with ROVs *Hercules* and *Atalanta* was conducted on another unexplored seamount that was originally mapped during the NA102 transit in 2018. After the dive, we also took the opportunity to complete mapping of the seamount to define its full extent.

In addition to specific mapping during explorations, the large distances between the PRIMNM and further south to American Samoa permitted extensive transit mapping where there were gaps in data. Combined, *Nautilus* mapped 67,700 km^2 from over 11,670 km of trackline in this large region of the Pacific. Over 25 seamounts were completely or partially mapped, as well as numerous other significant previously unmapped seafloor features, and the location of a new plume on the hydrothermally active Vailulu'u Seamount was identified.

Mapping during NA114 also led to the discovery of some inaccuracies in sections of the global bathymetric models, which were reported to hydrographic agencies. *Nautilus* mapped a large guyot in the Goldsborough seamount chain (11°00'N, 170°50'W) with a reported minimum depth of 22 m that was based on one trackline of single-beam echosounder data from a 1979 survey and estimated bathymetry from radar altimetry. Multibeam mapping revealed a feature with a flat summit approximately 11 km wide, with a minimum depth of approximately 1,300 m (Figure 3). In addition, *Nautilus* mapping filled gaps in coverage when transiting international waters and in the EEZs of Kiribati, the Cook Islands, and Samoa, and in the high seas outside national EEZs. The data will be provided to those countries and also provided for inclusion in the GEBCO grid.

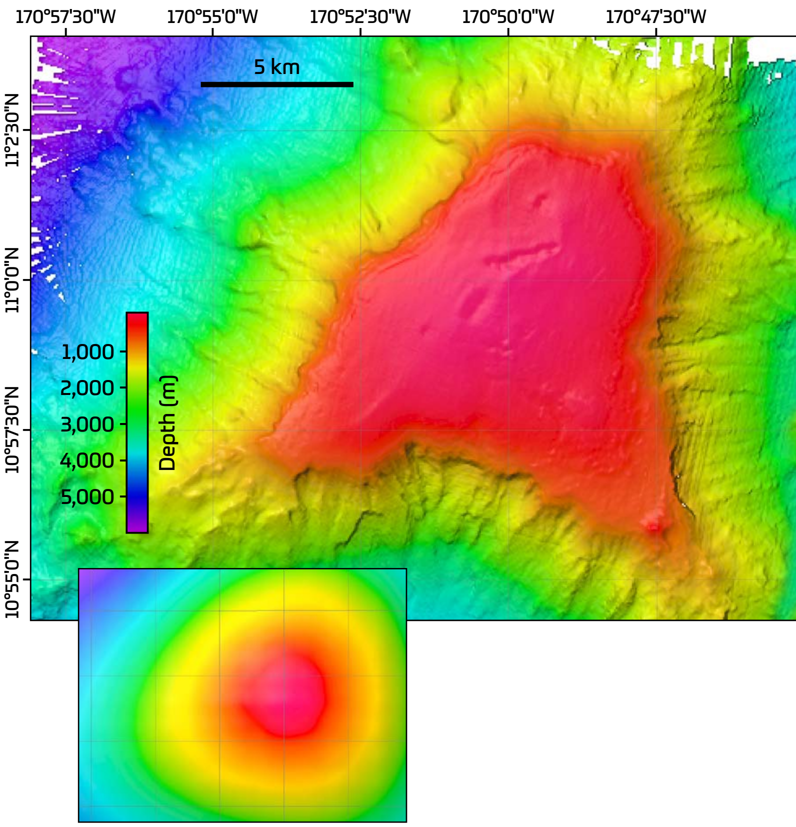


FIGURE 3. Image of a large guyot in the Goldsborough seamount chain from E/V *Nautilus* mapping on NA114. The inset shows previously available data. *Nautilus* multibeam mapping revealed a 11 km wide flat summit, with a minimum depth of approximately 1,300 m.

Searching for Shipwrecks in Thunder Bay National Marine Sanctuary

By Stephanie Gandulla, Sarah Waters, Val Schmidt, Clint Marcus, Erin Heffron, and Lindsay Gee

Located in the heart of the Great Lakes, NOAA's Thunder Bay National Marine Sanctuary (TBNMS) protects one of the most historically significant collections of shipwrecks in the United States. Encompassing 11,140 km² of northern Lake Huron waters, TBNMS is the nation's largest marine protected area focused on underwater cultural heritage sites (Figure 1). There are 99 known shipwrecks in the sanctuary, and research indicates as many 100 additional sites remain undiscovered (Figure 2). These submerged archaeological sites are a nearly complete collection of Great Lakes vessel types, from small schooners and pioneer steamboats of the 1830s to massive bulk carriers that supported America's heavy industries during the twentieth century.

In May 2019, a first-of-its-kind partnership was launched between TBNMS and the Ocean Exploration Trust with a mission to map unexplored areas of the sanctuary. Working with a team from the University of New Hampshire's Center for Coastal and Ocean Mapping (CCOM), the partners searched for undiscovered shipwrecks. The mapping mission also had the potential to identify a variety of natural features and important fish habitat on the lake bed.

The shipping lanes in northern Lake Huron, notorious for heavy vessel traffic and intense weather patterns, are known as "Shipwreck Alley." With only approximately 16% of sanctuary bottomlands mapped at high resolution, researchers prioritized target areas, including one that represented the highest potential for the discovery of intact shipwrecks. In 2017, the sanctuary and its partners discovered and identified the wooden freighter *Ohio* within the historic shipping lanes. *Ohio* suffered a fatal collision with the schooner *Ironton* in 1894. *Ironton* was not found in 2017, and its discovery remained an objective of this expedition.

During the sanctuary mapping expedition, the 4 m long autonomous surface vehicle *BEN* (for Bathymetric Explorer and Navigator; see photo on page 16) was operated for the first time from a shore-based mobile control van using a long-range telemetry system that extended connectivity to about 20 km from shore. Surveying in the shipping lanes of Lake Huron many kilometers from the control van presented challenges for ASV operations and provided a good evaluation of the ASV camera and radar systems used to detect traffic that might interfere with the survey. It also allowed the team to evaluate the ability of other vessels to detect the ASV both visually and on radar.

Throughout the mission, R/V *Storm*, a 15 m research vessel from NOAA's Great Lakes Environmental Research Laboratory, supported ASV *BEN* mapping operations by

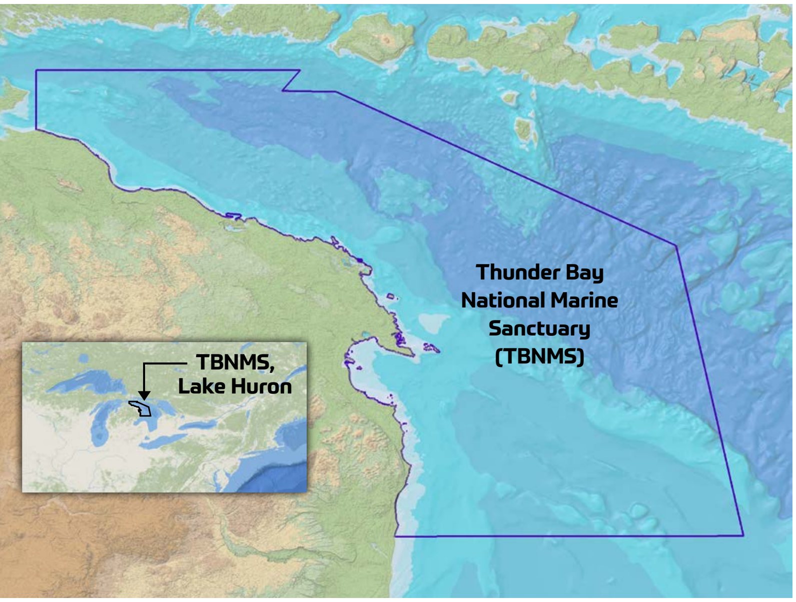


FIGURE 1. Map of NOAA's 11,140 km² Thunder Bay National Marine Sanctuary (TBNMS), in northern Lake Huron. *Image credit: NOAA, TBNMS*

FIGURE 2. The schooner *Northwestern*, sunk in 1850 in what is now Thunder Bay National Marine Sanctuary. Researchers estimate there are at least another 100 shipwrecks still to be discovered in sanctuary waters. *Image credit: NOAA, TBNMS*

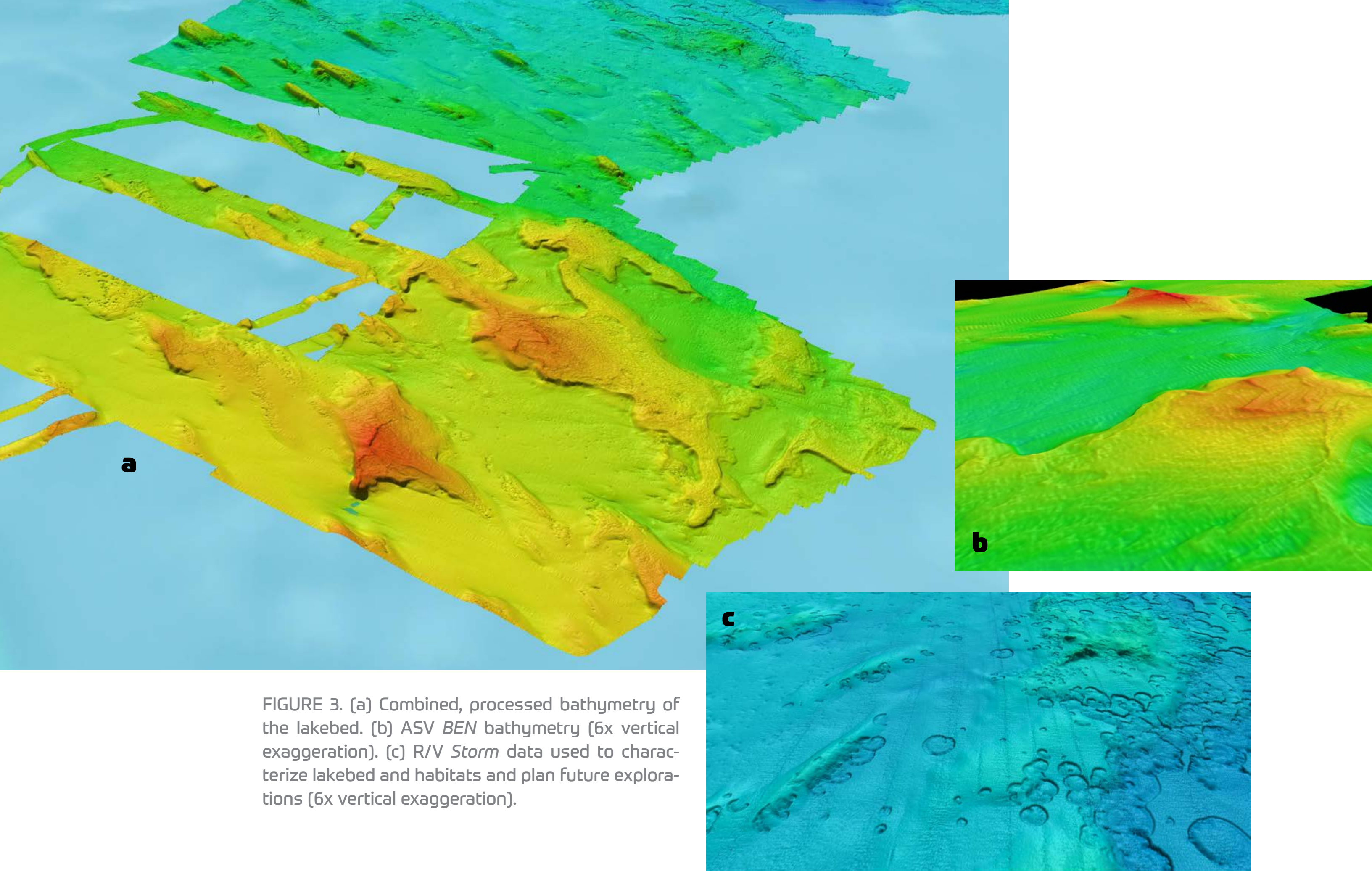


FIGURE 3. (a) Combined, processed bathymetry of the lakebed. (b) ASV *BEN* bathymetry (6x vertical exaggeration). (c) R/V *Storm* data used to characterize lakebed and habitats and plan future explorations (6x vertical exaggeration).

taking regular sound velocity profiles; the ship was also available in case the ASV had to be rescued. Led by a physical scientist from NOAA's Office of Coast Survey, *Storm* also conducted surveying operations in adjacent areas, more than doubling the ground covered. Both ASV *BEN* and R/V *Storm* were equipped with Kongsberg multibeam sonar systems. With mostly fair seas and cold winds, ASV *BEN* mapped a total of 73.3 km^2 and R/V *Storm* 79.6 km^2. The mapping was tailored to meet the marine archaeology goals of the sanctuary in locating and mapping wrecks. However, this goal was balanced by acquisition of data that was suitable for characterizing the lake's benthic habitat and also of sufficient quality for updating NOAA navigation charts. Both survey vessels identified interesting features, including glacial scours, sinkholes, and potential cultural resources (Figure 3).

Throughout the two-week survey mission, team members shared their explorations through social media, reaching nearly 15,000 general public viewers. Through telepresence, the research team interacted with middle and high school students (ages 10–18). Expedition team members mobilized operations to NOAA's Great Lakes Maritime Heritage Center in Alpena, Michigan, during the sanctuary's underwater robotics competition. This annual STEM event, sponsored by the Marine Advanced Technology Education (MATE) Center, was a perfect backdrop to showcase mapping technologies, and it allowed students to interact in person with scientists. Fifty eighth-graders from Rogers City, Michigan, also visited ASV *BEN*'s mobile control van in person, experiencing mapping operations in real time. This expedition's telepresence and outreach events provided an extraordinary opportunity for classrooms, other online viewers, and community members to go behind the scenes and find out what it is like to be part of the hunt for lost shipwrecks in the Great Lakes.

With thousands of square kilometers of sanctuary waters yet to explore, ASV-aided mapping efforts demonstrated the value of using an unmanned platform to supplement traditional vessel survey operations. The data collected with ASV *BEN* will also be used to support ongoing CCOM research as the team seeks to improve survey efficiency through applied autonomy. Not only can sanctuary researchers use these data to document and protect cultural resources, they can also employ them to characterize the lakebed, map important biological habitat, and update nautical charts. Stay tuned for mapping and groundtruthing efforts in 2020. Plans include deploying ROVs to further explore interesting lakebed features identified in the 2019 mission.

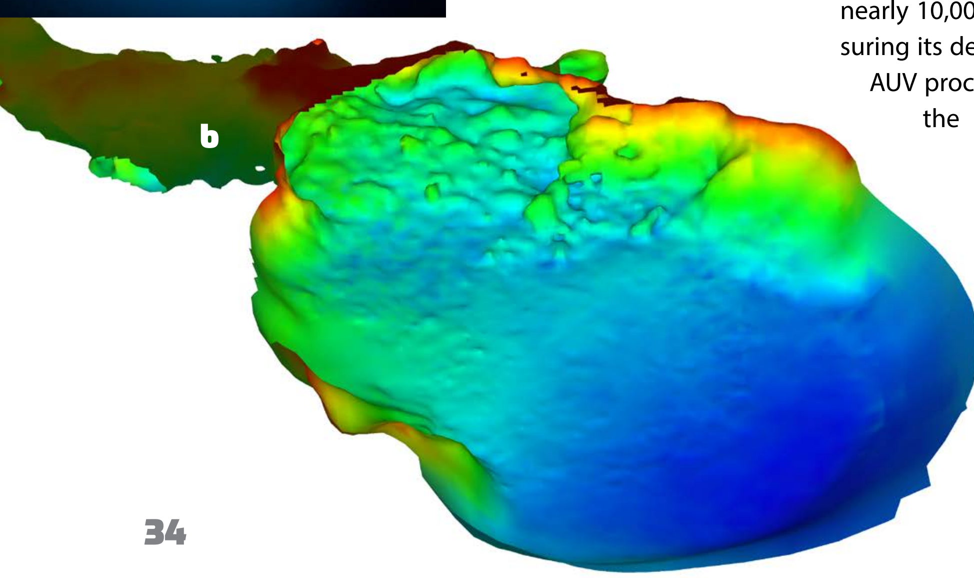
Sea Caves of the Channel Islands

By Robert D. Ballard, Larry Mayer, Kenneth Broad, Kristof Richmond, and Beth Shapiro

Exploration of sea caves off the Channel Islands of southern California continued in 2019 with three expeditions: one conducted aboard E/V *Nautilus* and two aboard the diver support boat M/V *Peace*.

In previous years, we used the multibeam sonar on *Nautilus*, the University of New Hampshire's Center for Coastal and Ocean Mapping's ASV *BEN*, and ROVs *Argus* and *Hercules*, as well as a team of divers to locate sea caves in the continental borderland of southern California (Ballard et al., 2018, 2019). These efforts focused around Santa Cruz Island, Santa Barbara Island, Pilgrim Bank, and Osborn Bank, where several caves were created over a period of 22,000 years as sea level rose 120 m after the Last Glacial Maximum. During that period, sea level rise halted six times, with each "still stand" lasting 1,000 to 3,000 years (see Figure 2 in Ballard et al., 2018). During these still stands, winter storms carved caves along the high-energy shorelines typical of the Channel Islands. Rising seas subsequently destroyed or buried many of those caves, except (in our observations) those in faulted igneous terrain, where wave action removed fractured rock to form a cave maintained within the host rock. Sea caves were only found along these six paleo-shorelines and not at other depths, which were also extensively investigated (Ballard et al., 2018, 2019).

FIGURE 1. (a) *Sunfish* entering Seal Cove Cave. *Image credit: Jill Heinerth.* (b) Frame grab taken from the three-dimensional map constructed by the *Sunfish* sonar system within the cave.



The goal of the 2019 program was to develop and test the technology needed to map the interior of these caves. We focused our efforts on Seal Cove Cave off Santa Cruz Island and two caves on Osborn Bank.

Seal Cove Cave is located on the northern coast of Santa Cruz Island, east of Painted Cave, with an entrance located just below sea level. In 2018, a team of divers supported by M/V *Conception* used a MNEMO hand-held mapping system to create a three-dimensional map of the cave's interior and found a series of passages collectively totaling some 150 m in length (Ballard et al., 2019). It was selected to serve as the cave to test the autonomous underwater vehicle (AUV) *Sunfish*, developed by Stone Aerospace, which will ultimately be used to map and visually explore deeper caves.

From July 1 to July 6, 2019, joint scuba and AUV exploration was conducted at five different locations from M/V *Peace*. Thirty dives, involving seven divers using back-mounted and side-mounted rebreathers and open circuit diving systems, were successfully executed under sea conditions ranging from calm to moderate. The initial dives rigged the cave with perimeter lines for safety and navigational purposes. Subsequent dive missions focused on assisting with deployment, handling, and retrieval of AUV *Sunfish*. Surveys using the diver-held MNEMO device were also conducted to enable comparison with the *Sunfish* data when possible and to examine one previously unexplored cave that was deemed too narrow for *Sunfish*. Additionally, a single dive testing the Project Prometheus lidar-based imaging system was conducted in open water. Still and video footage of all aspects of the mission were also collected.

AUV *Sunfish* weighs 37 kg in air, is neutrally buoyant in water, and can hover motionless (Figure 1a). It houses a three-dimensional acoustic mapping system that captures nearly 10,000 data points per second, in addition to measuring its depth, position, and orientation (Figure 1b). The AUV processes the data to find the direction that offers the most new volumetric information and then moves in that direction as far as it can without violating obstacle-avoidance criteria. An inertial guidance system measures the vehicle's velocity to reduce navigation error buildup. *Sunfish* then repeats the process to exit the cave. In 2019, *Sunfish* initially used its normal tether to map the interior of Seal Cove Cave. Following that successful dive, it was redeployed using a 4 km expendable fiber.

During the course of this multiyear effort, several caves have been located further offshore, on Osborn Bank. Shells dated from caves at 100–110 m depth are estimated to have formed 11,000–12,000 years ago. A *Coda Octopus* three-dimensional imaging system was mounted on ROV *Hercules* with a goal of accurately determining, in real time, the context and dimensions of the cave openings. The sonar generated a complete three-dimensional model composed of over 16,000 soundings for each acoustic transmission at rates up to 20 times per second. As a result, targets could be visualized many times in a single pass, allowing for real-time viewing from many different angles. The results exceeded our expectations: in real time we were able to determine the geospatial context of the caves as well as measure the dimensions of the cave openings. Most remarkably, we were able to image >20 m into several of the caves (Figure 2a,b).

The final 2019 effort was a return trip to two caves at 70 m depth on Osborn Bank with a dive team supported by M/V *Peace*. Cave A turned out to be the largest of the two caves, running for a distance of approximately 65 m, with entrances at both ends. The team mapped the interior of both caves using the MNEMO device and collected sediment core samples for post-cruise eDNA analysis (Figure 3).

In 2020, we plan to return to Osborn Bank Cave A with E/V *Nautilus* and M/V *Peace* to test the deployment of AUV *Sunfish* from the bottom of ROV *Hercules* to both map and visually inspect the interior of the cave.

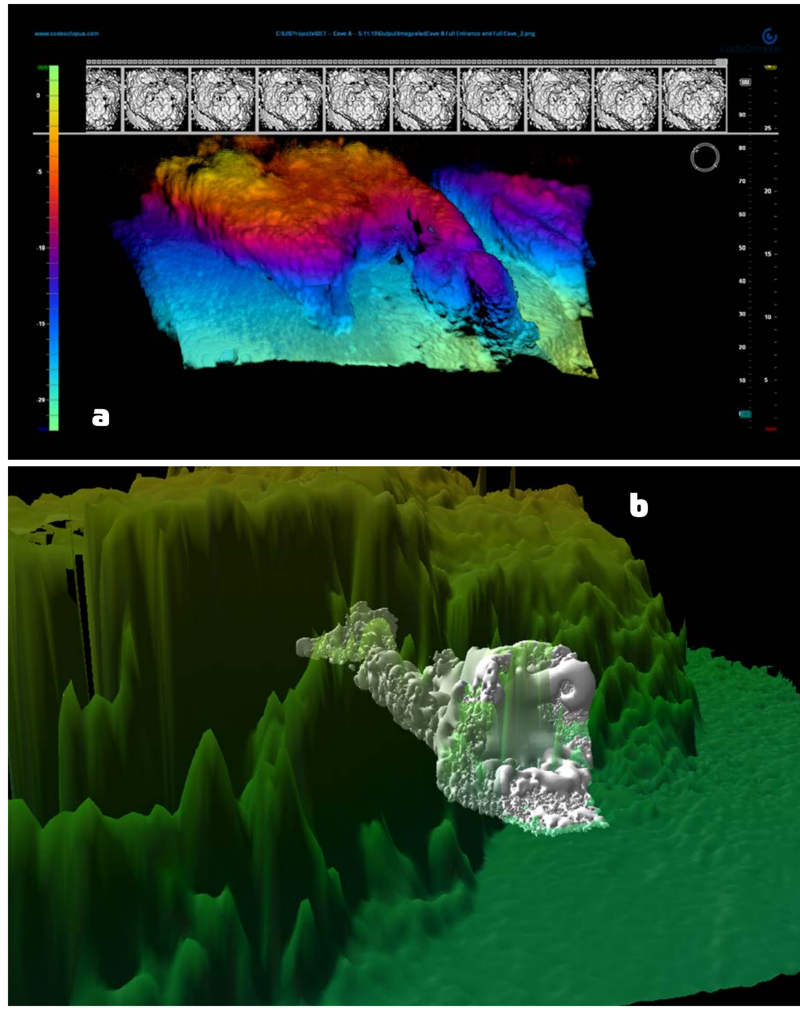
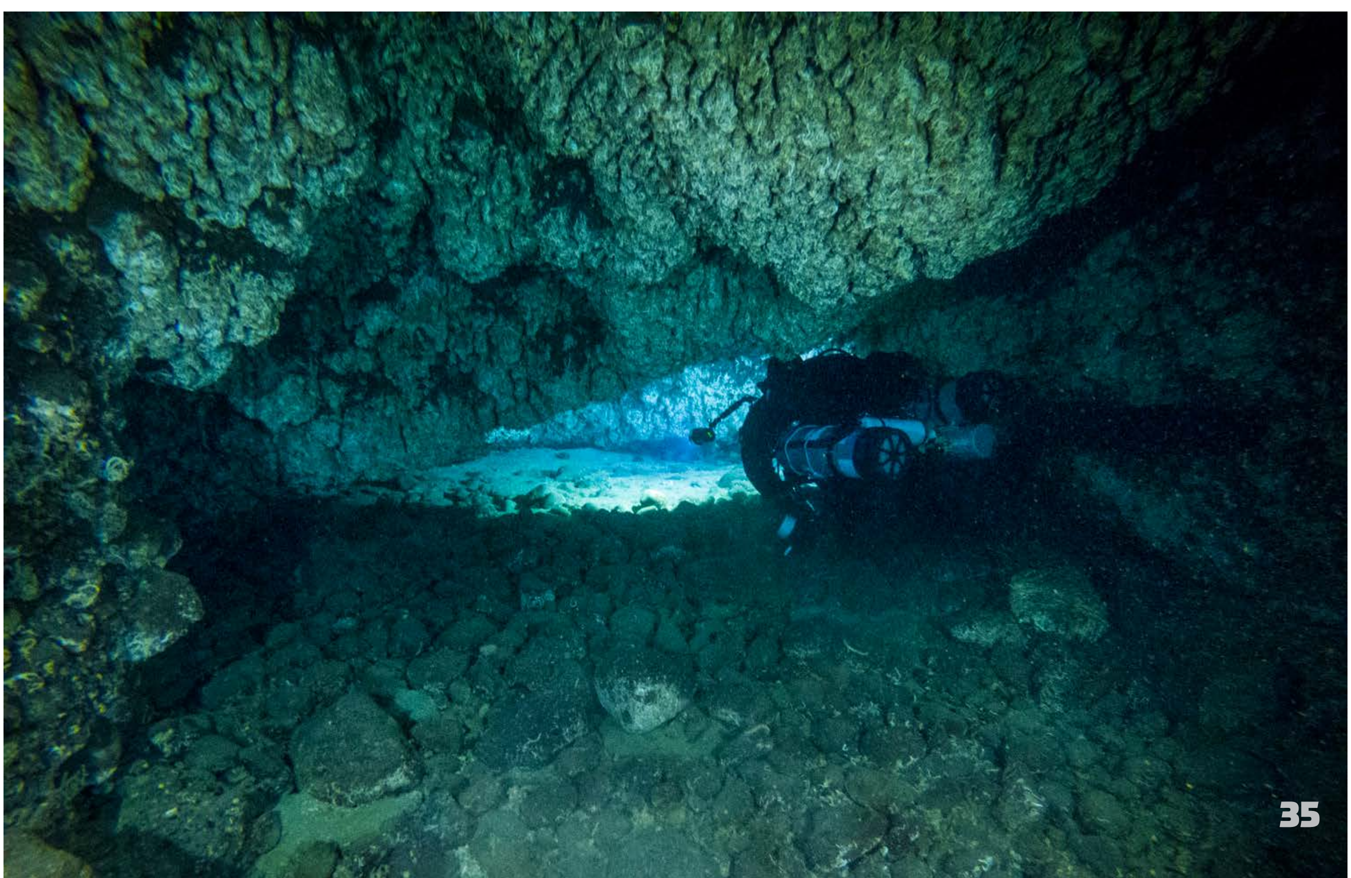


FIGURE 2. Coda Octopus Ethoscope real-time overview image of Cave A (a) and post-processed imagery looking into Cave E (b).

FIGURE 3. A diver surveying Osborn Bank Cave E.
Image credit: Mike Wynd



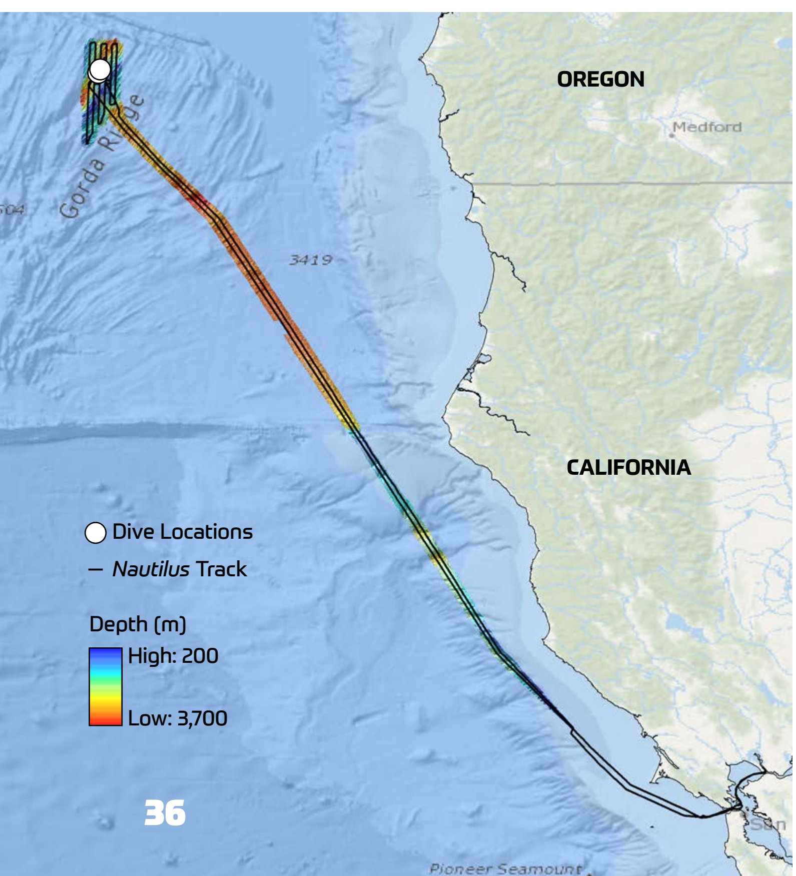
SUBSEA 2019 Expedition to the Gorda Ridge

By Darlene S.S. Lim, Nicole A. Raineault, John A. Breier, Eric Chan, Josh Chernov, Tamar Cohen, Matthew Deans, Angela Garcia, Christopher R. German, Michelle Hauer, Sarah Hu, Julie A. Huber, Renato Kane, Shannon Kobs Nawotniak, David Lees, Justin Lowe, Megan Lubetkin, Leigh Marsh, Vincent Milesi, Matthew J. Miller, Zara Mirmalek, Miles Saunders, Khaled Sharif, Ashley Shields, Everett Shock, Amy Smith, and Sean Sylva

The SUBSEA (Systematic Underwater Biogeochemical Science and Exploration Analog) program blends ocean exploration with "ocean worlds" research, along with NASA analog and work studies research, to address science, science operations, and technology knowledge gaps related to the exploration of our solar system. The science group researches venting fluids at isolated seamounts and spreading ridges in the Pacific Ocean as analog environments to putative volcanically hosted hydrothermal systems on other "ocean worlds" (defined as places in the outer solar system that could possess subsurface oceans). The science operations research group studies E/V *Nautilus* architecture, distributed teams, communication, and low-latency telerobotics. The technology research group provided Exploration Ground Data Systems (xGDS) software to the shore team to support the integration and visualization of diverse data products during the cruise.

From May 22 to June 9, 2019, the SUBSEA team explored the SeaCliff hydrothermal field, an off-axis submarine vent system located in the northernmost segment of Gorda Ridge, a section of the globe-circling mid-ocean ridge that lies ~200 km off the coast of Oregon and California (Figure 1). Von Damm et al. (2006) reported that SeaCliff emitted clear fluids from barite and anhydrite chimneys at temperatures no greater than 300°C. The 2019 deployment at Gorda Ridge was the second for SUBSEA; the first was to Lō`ihi Seamount off the Big Island of Hawai'i in August 2018 (Lim et al., 2019).

FIGURE 1. A cruise summary map showing the shiptrack (black line), multibeam depth data, and ROV dive locations.



The Gorda Ridge operational environment was significantly different from the first SUBSEA cruise. This year, researchers tested whether telepresence could be used as an analog for developing human space exploration. After the 2018 cruise, members of the operations research group examined the feasibility of implementing flight-like parameters for the Gorda Ridge deployment. They assessed the SUBSEA teams' workflow and decision-making elements in order to develop plans to alter the two-way communication between ship and shore. A planned work schedule and communication protocols were circulated for feedback and adjustments months prior to the cruise. A week-long operational readiness test prior to the cruise allowed the team to enact their workflow within study conditions.

Team members were distributed across two worksites: (1) the University of Rhode Island's Inner Space Center, which included members of the science and technology groups, and (2) on board *Nautilus,* which included members of science (natural and social/operations) groups; experts in navigation, robotics, and mapping; and the ship's crew. Communication across distributed teams was subject to protocols for ship-to-shore and shore-to-ship communications and data sharing. The Mode 1 protocol emphasized the use of written exchanges for communicating between ship and shore workgroups via specific documents sent daily. This was a radical departure from the use of typical *Nautilus* telepresence architecture that uses real-time oral and chat-style text communications. The Mode 2 protocol lifted all restrictions. This experiment was a success. The target number of days for each mode was reached and both natural and social science objectives were achieved.

The technology group enhanced the telepresence architecture by integrating its web-based xGDS open-source software into the shore-side science activities. xGDS supported planning, situational awareness, and data visualization for the ISC team and was tailored specifically to support *Nautilus* data sets. xGDS leveraged OET's data

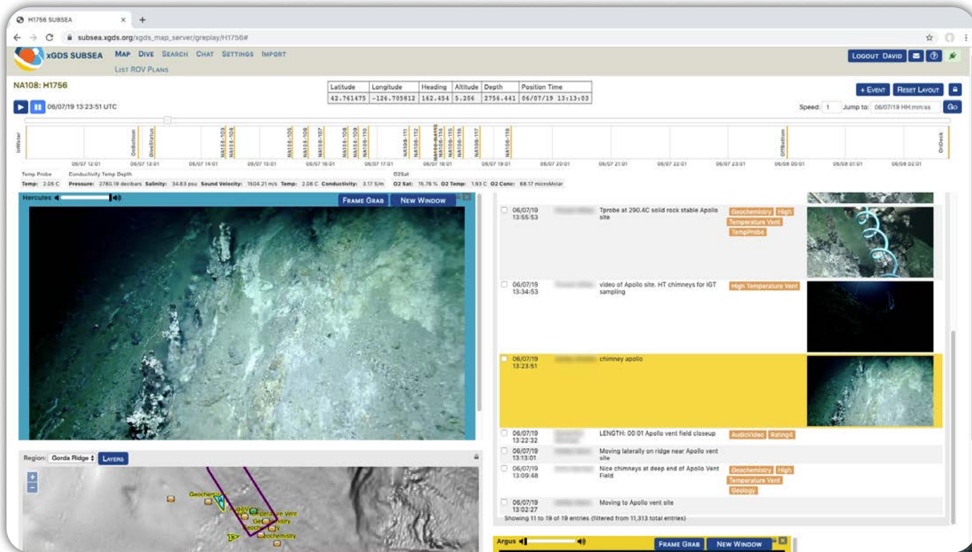


FIGURE 2. The xGDS live, interactive interface with (counterclockwise from top left): streaming video from ROV *Hercules*, navigation/positioning from E/V *Nautilus* and ROVs *Hercules* and *Argus*, collaborative note-taking, and still capture of video frames at the University of Rhode Island's Inner Space Center (yellow row).

broadcast infrastructure (from *Nautilus* to shore) to record and display real-time positioning of the ROVs and *Nautilus*, oceanographic data (e.g., CTD, O_2), and observations logs within the xGDS interface (Figure 2). These data were synchronized with a copy of the satellite video. The onshore team used xGDS to search and replay dives with a unified context comprising a site map, video, telemetry, and event data. xGDS was also used to simulate the distance and duration of upcoming dives, including specific activities (e.g., sampling), to generate a human-readable dive plan and to export the plan in formats for delivery to various navigation and mapping software.

Science activities for volcanology, geochemistry, microbiology, and chemical engineering groups were conducted within Mode 1 and Mode 2. During the pre-cruise period, the group developed a tool that would maximize scientific return. Geochemists modeled thousands of prospective water-rock interactions at the origin of hydrothermal fluids venting at the SeaCliff site to identify shipboard chemical measurements that would allow them to learn in real time about the hydrothermal system. The comparison between daily sample measurements and modeled fluid compositions provided answers and posed new questions about the functioning of the system, which were used to define subsequent dive and sampling objectives.

Researchers explored the broader morphologic context of the rift valley, measuring how sediment infill impacts apparent surface roughness over time and used apparent textural anomalies to identify and discover the Apollo hydrothermal field. Basalt substrate was collected from the targeted areas to better constrain the chemical evolution of surface rocks that are in contact with both hydrothermal fluids and ambient seawater. Fluid, rock, and eukaryotic mat samples were collected in order to understand how the geochemistry and energetics of the vent fluids affect the abundance, distribution, and metabolic function of microbial communities. These samples are currently being studied using a variety of techniques, including stable isotope probing, culturing, grazing experiments, cell counts, and DNA-based analyses. Colonization devices that contained rock and mineral grains as prospective colonization substrates for vent microbes were deployed and recovered during the 2019 expedition (Figure 3). These devices were deployed for up to one week to examine the identity and function of the microbial community associated with mineral surfaces as compared to the free-living planktonic community present in venting fluids. The addition of colonization experiments at vent sites on Gorda Ridge allowed the team to gain a more complete picture of microbial processes occurring in the subsurface at hydrothermal vents.

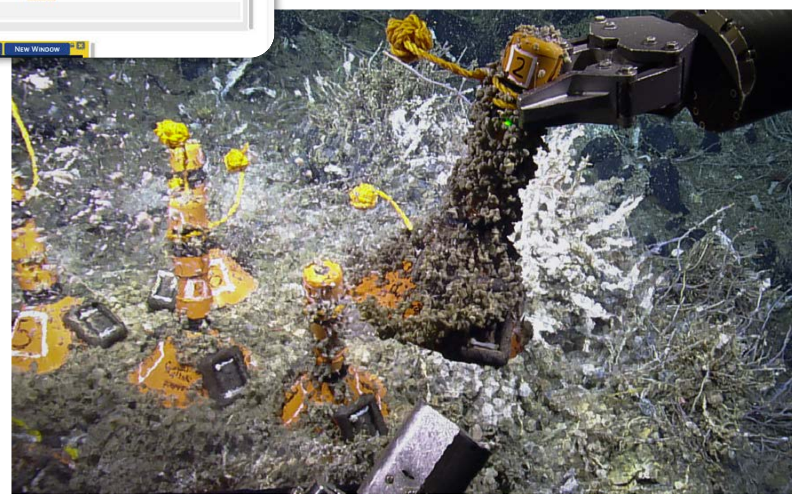


FIGURE 3. An ROV manipulator retrieves a colonization experiment from a vent system on Gorda Ridge.

Gorda Ridge was the final cruise for the SUBSEA research program. We anticipate that our partnership between the ocean and space science research communities will broadly impact and contribute to the state of knowledge in (1) the habitability and energetics of an expanded range of analog vent systems for ocean worlds, (2) methods for conducting science-driven exploration in representative deep space environments such as Mars, and (3) the capability to support mission science teams as they conduct telerobotic missions.

Deepwater Exploration of Kingman Reef, Palmyra Atoll, and Jarvis Island

GEOLOGICAL AND BIOLOGICAL DISCOVERIES FROM THE US LINE ISLANDS

By Steven Auscavitch, Robert Pockalny, Kevin Konrad, Jennifer Humphreys, Timothy B. Clark, Erin Heffron, and Allison Fundis

In June and July 2019, E/V *Nautilus* explored the two easternmost units of the Pacific Remote Islands Marine National Monument (PRIMNM), the Kingman Reef and Palmyra Atoll unit, and the Jarvis Island unit. This expedition followed an initial survey in 2017 (Bohnenstiehl et al., 2018) as a part of the NOAA CAPSTONE program (Kennedy et al., 2019). While previous expeditions provided brief glimpses into the nature of geological and biological aspects of the deep-sea environment, this expedition leveraged previous mapping and exploration dives in order to maximize bottom time and sampling effort at specific sites within the units. In total, 28,340 km^2 of seafloor were mapped. During high-seas transits, six ocean wave buoys and one small sailboat drifter (part of the Educational Passages program) were deployed (Figure 1).

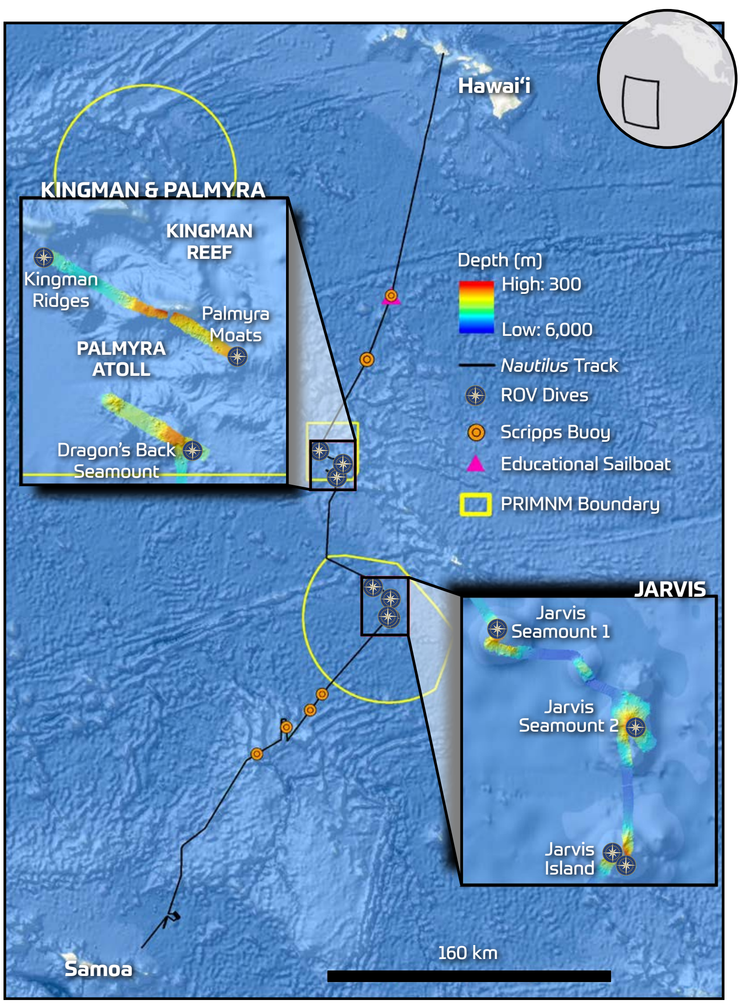


FIGURE 1. Overview map of the NA110 cruise track. Insets show dive site locations and new detailed multibeam bathymetry gathered in the Kingman and Palmyra and Jarvis units.

Across seven ROV dives, this expedition accumulated 117 hours of bottom time and traversed approximately 23 km of seafloor within PRIMNM's boundaries (Figure 1). In order to better characterize biodiversity and the geological setting, intensive sampling was a priority. Seventy-six primary biological specimens were collected, including 64 deepwater corals and sponges. Sampling targeted individuals that represented characteristic fauna for the area, new records for the Line Islands, or potential new species requiring further examination by taxonomic experts. To evaluate new tools for exploring biodiversity on seamounts, eDNA samples were also taken in high-density or high-diversity benthic communities (Everett and Park, 2018).

Thirty-nine rock samples were collected for age dating as well as for analysis of regional ferromanganese crust composition. Within the Line Islands region, geologic sampling focused on recovering volcanic rocks from the deep flanks of guyots (flat-topped seamounts) as well as from younger volcanic cones that sit atop the guyots and that erupted through the guyot platform. Sample analyses will test whether these volcanic cones represent episodes of rejuvenated volcanism that occurred within a few million years after the ocean island subsided, reactivated volcanism driven by local tectonic stress long after the island subsided, or reoccupation of the volcanic conduits by a separate mantle hotspot (e.g., Davis et al., 2002). Age determinations of the recovered lava samples will aid in placing the seamounts surrounding Jarvis Island within the broader tectonomagmatic framework of the Pacific basin.

Three dives with ROV *Hercules* were conducted within the Kingman and Palmyra unit of PRIMNM between 1,417 m and 3,225 m depth. The three features explored included a prominent ridge exposed by mass wasting west of Kingman Reef, a series of enigmatic moat-ringed seamounts southeast of Palmyra Atoll, and a ridge named Dragon's Back Seamount, based on its undulating bathymetric profile. Biological communities at these depths were

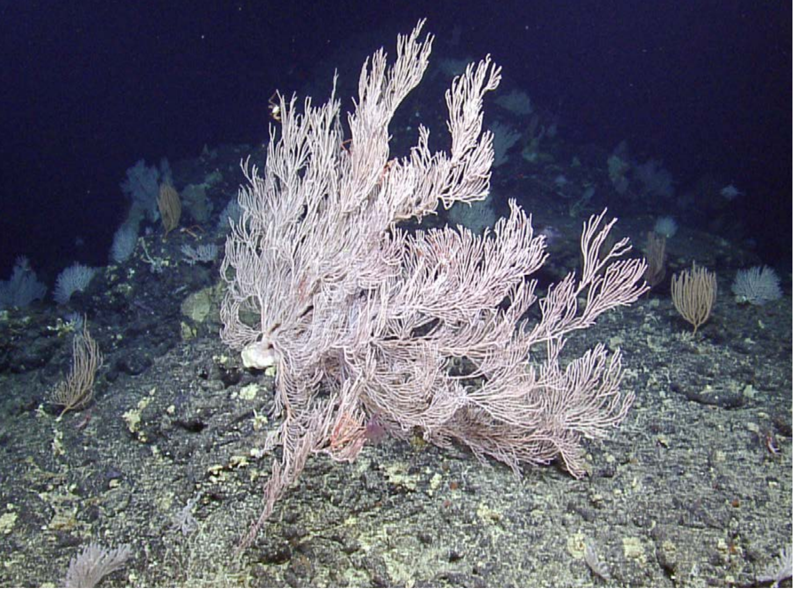


FIGURE 2. A mixed assemblage of stony corals (*Enallopsammia* sp.) and sea fans (mainly *Calyptrophora* and *Paracalyptrophora* spp.) capped the summit of Cone 2 at Jarvis Seamount 1 at 920 m depth.

sparsely populated. Deepwater corals from the families Chrysogorgiidae and Plexauridae, as well as precious corals and stony corals (*Enallopsammia* sp., at depths shallower than ~1,500 m), were most common.

A series of small, late-stage volcanoes on top of Kingman Ridge were also characterized by lightly sedimented lobate flows and pillow basalts along their flanks. Shallow depressions (i.e., moats) surrounding the volcanoes were characterized by ripples of carbonate sands that changed orientation approaching the volcanoes. The orientation and asymmetry of the ripples suggest transport toward and around the moats at the bases of the volcanoes.

Four dives were conducted within the Jarvis Island unit between 255 m and 1,828 m depth: two on Jarvis Island proper and two on unexplored guyots north of Jarvis. Both guyots were found to host sparse biological communities on their flanks and summits. However, smaller parasitic volcanic cones shallower than the main guyot plateau at Jarvis Seamount 1 were occupied by dense octocoral and stony coral assemblages at around 900 m depth (Figure 2).

The surficial geology of the seamounts in the Jarvis Island region was very similar, but significantly different, than Jarvis Island proper along the upper reaches of the seamounts. The lower sections were covered by lightly sedimented lobate and pillow flows; however, the upper 800 m of Jarvis Island was composed of carbonate reef material. The Jarvis seamounts were primarily composed of lava flows all the way to their summits, where relatively thin layers of carbonate were covered by carbonate ooze with evidence of ripples and scoured bed forms. The lack of significant carbonate cliffs on the Jarvis seamounts suggests that these guyots, with small parasitic cones, may never have been subaerially exposed.

FIGURE 3. A striking and enigmatic blue octocoral (cf. *Muriceides* sp.) was observed at high densities along the western carbonate slope of Jarvis Island at 386 m depth.

Dive observations at Jarvis Island suggested that it has both dense and diverse biological communities. A continuous transect from 1,700 m to 255 m depth conducted on the southeastern side of the island identified a prominent zone of stony coral reef structures between 600 m and 1,000 m depth. Primarily composed of *Enallopsammia rostrata* and *Madrepora oculata*, these reef structures are ecologically significant, as they have likely been in place for several hundred years or longer given their size, extensive debris fields, and slow growth rates (Houlbrèque et al., 2010). On the shallower carbonate platform, between 300 m and 600 m depth, often nested among the carbonate cliffs and overhangs, dense deepwater coral and sponge communities were observed that differed in species composition from those on the southeastern side (Figure 3).

In light of these biological observations, immediate follow-up work to this expedition will focus on establishing baseline deepwater benthic species inventories from DNA barcoding and morphological identification of collected specimens, as well as annotation of ROV video. These data are valuable additions to management efforts that seek to identify and characterize high-density and diverse communities within monument boundaries.

The Search for *Samoan Clipper*

By Russ Matthews, Michael L. Brennan, Allison Fundis, Lonnie Schorer, Megan Lickliter-Mundon, Deborah Marx, Miles Saunders, Renato Kane, Samantha Wishnak, James P. Delgado, Edward Trippe, Robert D. Ballard, John H. Hill, Doug Miller, and Christopher Jacques

In July 2019, more than 81 years after Pan American Airways' *Samoan Clipper* went missing, the search for the lost plane resumed in American Samoan waters. Scientists and crew aboard E/V *Nautilus* conducted six days of intensive underwater sonar survey operations in the immediate vicinity of the reported crash position. The project, launched by the Air/Sea Heritage Foundation in partnership with SEARCH Inc. and the Ocean Exploration Trust, aimed to locate, identify, and document the sunken wreckage of Pan Am flight A5. The team hoped to characterize an archaeological site with major significance to the region and to aeronautical history while determining the final resting place of seven pioneering aviators and collecting evidence as to what led to their fate.

Samoan Clipper was a Sikorsky S-42B type flying boat (Figure 1) that went down during an attempt to inaugurate regular air mail service between Honolulu, Hawai'i, and Auckland, New Zealand, with the loss of the entire crew, including Pan Am's celebrated Chief Pilot, Captain Edwin C. Musick (Figure 2). Shortly after takeoff from Pago Pago, American Samoa, on January 11, 1938, an oil leak forced the shutdown of one of the plane's four engines, and Musick elected to return to base. His stricken craft was mere minutes away from safety when all communication ceased. Soon eyewitness reports of a crash and rising smoke filtered in from the island's northwest coast, leading to a US Navy air search that discovered an ominous oil slick on the ocean surface (Figure 3). At dawn the next day, the seaplane tender USS *Avocet* (AVP-4) reached the scene and recovered small items of floating debris definitively tied to *Samoan Clipper*. Investigators from the Bureau of Air Commerce (BAC) speculated that the plane had caught fire and exploded while dumping fuel to lighten the aircraft prior to landing. However, a precise determination of cause was impossible without examining the wreck, believed to rest 1,000 fathoms (1,830 m) beneath the waves, far beyond the reach of any technology available at that time.

Not until E/V *Nautilus* sailed from Pago Pago could the proper tools and expertise finally be brought to bear on the challenge of finding *Samoan Clipper*. A brief transit brought the ship to an area roughly 20 km north of Tapu Tapu Point (the westernmost tip of Tutuila Island), where the combined science team and navigators had plotted an initial 13.7 km^2 search box centered on the loss coordinates as listed in the BAC accident report of 1938. This grid was overlaid on a bathymetric map created using data collected by NOAA Ship *Okeanos Explorer* at the request of the project team back in April 2017. That *Okeanos Explorer* survey revealed water depths even greater than originally estimated, ranging from 2,800 m to 3,500 m, which meant the remains of the 36 m-wingspan *Samoan Clipper* would not be discernible in the bathymetry given the resolution limitations of data that had been captured from the surface using a hull-mounted multibeam system. The team would have to get closer to have a chance of achieving their goal.

FIGURE 1. Photo of *Samoan Clipper* at Pago Pago, American Samoa, taken on December 24, 1937. *Image credit: Pan Am Historical Foundation*

FIGURE 2. Captain Edwin C. Musick. *Image credit: Pan Am Historical Foundation*

Accordingly, EdgeTech 4200 dual frequency side-scan sonar transducers were attached to the sides of ROV *Argus* and towed solo (without ROV *Hercules*) by *Nautilus. Argus* was equipped with a specially designed fin to minimize vehicle wobble. While unusual, a similar configuration had been effective in pinpointing ancient shipwreck sites off the Mediterranean coast of Turkey in 2010.

Survey lines were initially spaced at 300 m, assuming a range of 150 m to each side for the low frequency sonar (300 kHz) and 100 m for the high frequency channel (600 kHz), though this was later changed to 200 m spacing to help account for *Argus*' movement behind the ship and to ensure 100% coverage. While initially running roughly north-south, winds in the area proved quite strong (at ~26 knots), and it was deemed prudent to reorient more southwest to northeast, pointing *Nautilus* into the prevailing wind, and running the sonar parallel to the undersea slope. As is often the case with deep-tow systems, pulling the weight of the 3,200 m of steel cable behind *Nautilus* restricted survey speed to 1 or 2 knots or less upwind.

The team found an added benefit of employing *Argus*'s HD camera. Maintaining an altitude of 15–20 m above the seabed resulted in almost continuous visual contact with the ocean floor directly under the vehicle. This effectively eliminated the nadir (or blind spot) associated with side-scan operations and lent confidence that even small debris would be detected among the bottom terrain that may not have been identifiable in the sonar record.

The sonar readouts and direct camera feeds from the seabed, along with audio of the science team on watch, streamed uninterrupted over the internet via satellite in real time throughout the expedition. An online audience in 100 countries around the globe followed the search for *Samoan Clipper*, while learning about its history, American Samoa, Ed Musick, Pan Am, and the era of the great flying boats.

Methodically scanning the ocean floor below for traces of *Samoan Clipper*, *Argus* crisscrossed the prime search area in disciplined rows for a total of 133 hours, including a record-setting 125 hours of continuous underwater operations.

Ultimately, the search area covered more than double the plan, expanding west and south to map and eliminate more than 25 km^2 of previously unexplored seabed. The volcanic origin of the Samoan islands was readily apparent in the rugged terrain, where small boulders, cobbles, and old lava flows were observed. Frustratingly, no sign of the lost airplane (or other man-made objects) appeared, though there can be no doubt that the wreck was nearby. The clock simply ran out on this expedition before it could be pinpointed.

Plans call for *Nautilus* to return to the area as early as the summer of 2021, and the project partners are already working together to identify new opportunities and new tools (perhaps autonomous underwater vehicles) with which to continue the hunt for *Samoan Clipper* and cast a wider net.

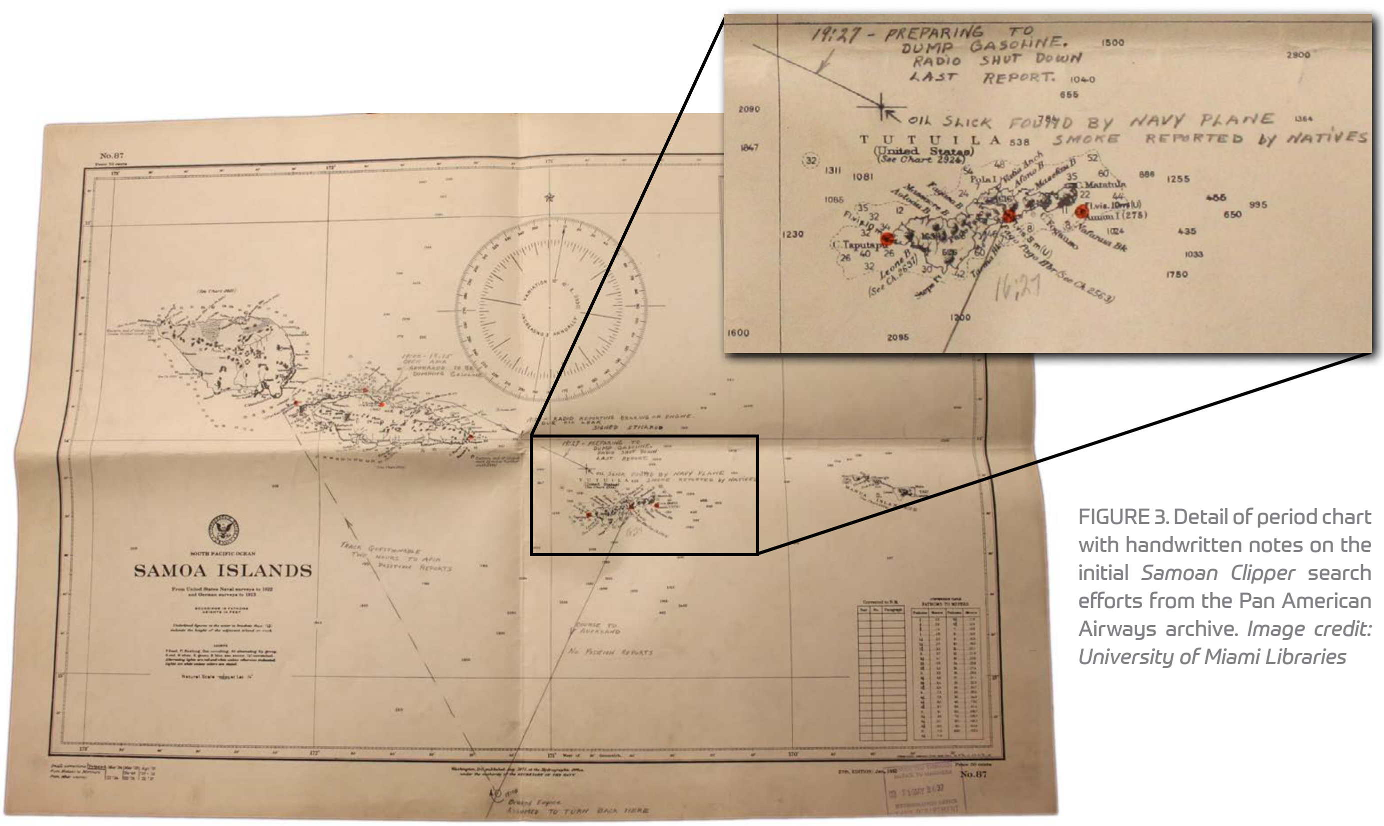


FIGURE 3. Detail of period chart with handwritten notes on the initial *Samoan Clipper* search efforts from the Pan American Airways archive. *Image credit: University of Miami Libraries*

Expedition to the National Marine Sanctuary of American Samoa

EXPLORING THE DEEP SEA IN THE AMERICAN SAMOA ARCHIPELAGO

By Mareike Sudek, Hanae Spathias, Georgia Coward, Nerelle Que, Renato Kane, Val Schmidt, Robert D. Ballard, and Christopher Roman

American Samoa, the southernmost US territory in the South Pacific, is composed of five volcanic high islands (Tutuila, Aunu'u, Ofu, Olosega, and Ta'u) and two atolls (Rose and Swains). The deep-sea habitat within this oceanic archipelago remains largely unexplored, so very little is known about the species that thrive there.

The National Marine Sanctuary of American Samoa (NMSAS) comprises six protected areas covering 35,175 km^2 of nearshore coral reef and offshore ocean waters across the Samoan Archipelago. It includes Fagatele Bay and Fagalua/Fogāma'a on Tutuila Island, as well as areas on Aunu'u, Ta'u, Swains Island, and Muliāva, a management area that overlaps with Rose Atoll Marine National Monument and includes nearby Vailulu'u and Malulu Seamounts.

In an effort to better understand the biodiversity of American Samoa's deep-sea habitats, NMSAS partnered with the Ocean Exploration Trust to further explore this important ecosystem. The 14-day expedition took place in July and early August of 2019 and visited all the islands in American Samoa and the hydrothermally active Vailulu'u Seamount. During 10 dives with ROV *Hercules*, the team collected 123 biological samples, some likely new species. In addition, 18 fish and benthic photo transects of varying lengths were completed. Using the ship's multibeam echosounder, six areas (7,344 km^2) were charted at high resolution, and three shallow areas were mapped using ASV *BEN* (Figure 1).

During the first leg, *Nautilus* visited Swains, Ofu-Olosega, and Ta'u Islands, where a variety of invertebrates, including deep-sea coral, sponges, sea stars, crinoids, and crustaceans, were recorded. At Swains Island, the ROV dive started at 2,452 m depth and ascended to 1,258 m following the ridge line and encountering a multitude of giant glass sponges (Amphidiscosida). Although weather conditions limited both dive times and locations for the rest of this leg, a dive conducted at Ofu-Olosega Island marked the first deep-sea ROV dive in this area. The dive started at 1,837 m depth and ascended to 1,735 m. This site was characterized by high densities of crinoids as well as many dead coral skeletons and remains of gorgonian holdfasts, indicating a possible past mortality event. Evidence of such an event was also observed at Swains Island. At neighboring Ta'u Island, the team conducted a shallower dive starting at 780 m depth.

During the second leg, *Nautilus* visited Aunu'u Island, Tutuila Island, Vailulu'u Seamount, and Muliāva. During the dive near Aunu'u Island, a large shark was spotted at around 500 m depth. The pinnacle (136 m depth) was characterized by large black corals, gorgonians, and dense populations of yellow hard coral; several large sharks, schools of fish, and dogtooth tuna were observed there as well. The dive on Tutuila's north side started beyond the shelf edge at 899 m, where the team surveyed a vertical wall with extensive overhangs. During the dive near Rose Atoll in the Muliāva Management Area, areas densely populated with sea anemones and sea whips were observed at 340 m depth.

The highlight of the cruise was exploring the hydrothermally active Vailulu'u Seamount. Mapping prior to the dive revealed no notable changes in the crater's bathymetry since the

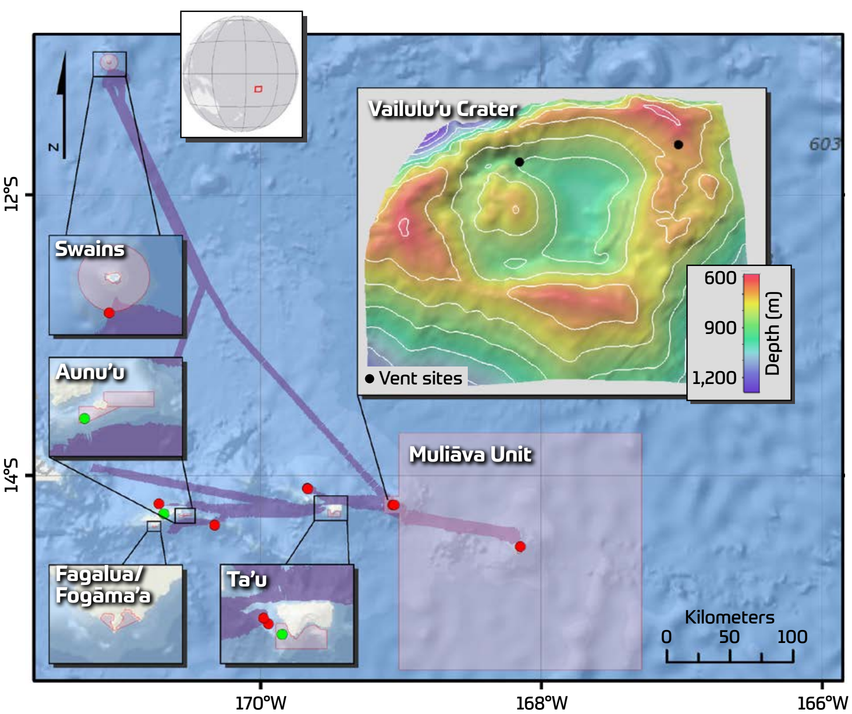


FIGURE 1. Map of the National Marine Sanctuary of American Samoa's six management areas, with mapping coverage and ROV dive locations from the expedition. Multibeam coverage is shown in purple and NMSAS areas in pink. ASV deployments are marked with green circles and ROV dives with red circles.

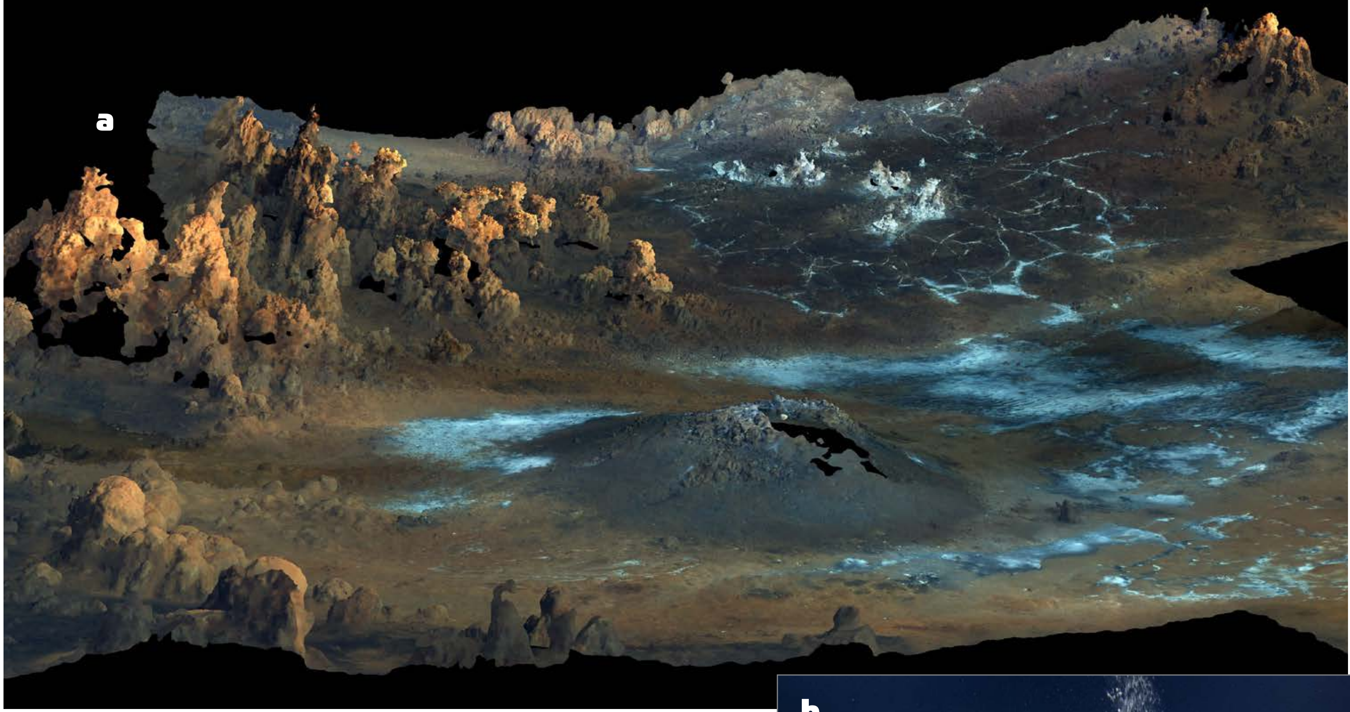


FIGURE 2. (a) Three-dimensional photomosaic reconstruction of the active vent site at Vailulu'u Seamount. *Image credit: OET and Chris Roman* (b) Newly discovered active hydrothermal plume found on the east side of the Nafanua crater in Vailulu'u Seamount.

2017 NOAA Ship *Okeanos Explorer* surveys. However, the ship's sonar indicated a potential new plume on the eastern side of the crater. The first dive at Vailulu'u started at the base of the Nafanua cone at 900 m depth and moved upward toward the crater rim at 709 m. Large pillow basalts were observed with little colonization of organisms and few *Dysommina rugosa* eels present, similar to what *Okeanos Explorer* documented. The vent site previously explored on the *Okeanos Explorer* cruise was successfully relocated and observed to have a large crack in the rock surrounded by white microbial mats. The water temperature at this vent was 22.9°–27.4°C.

Along the crater rim at about 900 m depth the team located a steeply sloping, fine-grained, dark-colored hydrothermal deposit covered with a fine-grained orangy-brown hydrothermal deposit. An orange and yellow venting cloud appeared to contain large fragments of possible microbial mats, suggesting a subsurface supply, but the source of this cloud was not identified. ROV *Hercules* was then towed to the newly discovered active plume identified with the shipboard multibeam sonar. Good visibility enabled a quick discovery of the vent. The maximum water temperature measured at the top of the plume outflow was 202.7°C. Surrounding the plume outflow near the base, warmer water was seeping out all around the plume, with a maximum temperature of 114°C. Around the plume's peak outflow, a high abundance of crabs (Bythograeidae), shrimp, and isopods were present. Near the active plume, there was a field of dormant chimneys ranging in height from 0.5 m to about 2 m. Some of the chimneys still released warm water, but no bubbles were present. A second dive was made to complete a large photo survey of the chimney area for three-dimensional image reconstruction (Figure 2). In addition, samples of organisms, rocks, and the bacterial mats were collected and are being analyzed by collaborators (see page 21 Gastropod).

The expedition prioritized communications about the science conducted aboard the ship and shared images from this fascinating deep-sea world. The team conducted 25 live ship-to-shore telepresence events with K–12 students, undergraduates, and various science interest groups. Additionally, the telepresence live stream allowed the public to participate in all dives in near-real time to see the diversity of American Samoa's deep-sea marine life. The livestream was viewed a total of 817,548 minutes, generating 66,129 views from 80 countries.

Currently, efforts are underway to analyze the video footage and post-process data. Information gathered by this expedition will enhance understanding of American Samoa's unique ecosystems. Additionally, there is a plan for E/V *Nautilus* to return to American Samoa and Vailulu'u in the next two to three years.

Expedition Amelia

By Robert D. Ballard and Allison Fundis

In partnership with National Geographic, the Ocean Exploration Trust conducted a three-week expedition at Nikumaroro Island in August 2019 in an attempt to solve the 82-year mystery of famed aviation pioneer Amelia Earhart's disappearance. Earhart disappeared with her navigator, Fred Noonan, in July 1937 during the latter part of their attempt to circumnavigate the world (Figure 1a). The expedition was prepared to locate her Lockheed Electra aircraft, or a piece of the aircraft, in any terrain by utilizing multiple mapping technologies, ROVs, a land-based archaeology team with forensic dogs, scuba diving, and aerial drones.

There are multiple theories surrounding Earhart and Noonan's disappearance, one of which suggests they ran out of gas while searching for Howland Island—their intended refueling target—and ultimately crash-landed in the open ocean within the vicinity of the island.

Our search efforts were predicated on a theory by The International Group for Historic Aircraft Recovery (TIGHAR), which postulates that Earhart and Noonan veered off course from Howland Island and landed some 560 km to the southwest on Gardner Island, now called Nikumaroro, in the Republic of Kiribati (Figure 1b). The island was uninhabited at the time of their disappearance. Over the past 30 years, TIGHAR has mounted multiple expeditions and has conducted research that uncovered multiple pieces of compelling evidence.

Once we arrived off Nikumaroro, we spent two days mapping the entire offshore area surrounding the island to a depth of up to 4,500 m in preparation for visual surveys of the terrain. Using the Kongsberg EM302 multibeam sonar mounted on E/V *Nautilus* and a similar, but higher frequency, sonar on the University of New Hampshire's autonomous surface vehicle (ASV), we were able to construct bathymetric and backscatter maps of 783 km^2 of seafloor (Figure 2).

These maps revealed that the flat-topped coral island is surrounded by a series of vertical scarps with interconnecting rubble ramps at an approximately 45° angle. Fragments broken off from the reef's outer edge were transported via mass wasting processes, resulting in a series of alluvial aprons extending several nautical miles offshore.

Three key theories about the ill-fated aircraft were investigated. The first was that after landing near the edge of the reef, the prevailing winds and waves on the northwest corner of the island washed the plane offshore near the location of a known 1929 shipwreck on the reef, SS *Norwich City*. Once the plane sank offshore, it tumbled down steep rock scarps, breaking into pieces and resting on the alternating series of steep rubble ramps.

The second alternate theory was that after it initially came to rest on those steep ramps, parts of the broken up plane were incorporated into a network of debris channels. Once in these channels, the large and small plane fragments, along with the continuous supply of reef rubble from above, were transported into deeper water.

The third alternate theory was that at some point after landing and before a search plane flew over the island seven days after their disappearance, the rising tide and empty fuel tanks floated the plane off the reef. After fully flooding, the plane glided to the bottom and landed on the alluvial ramp.

FIGURE 1. (a) Photo of Amelia Earhart released December 1937. (b) Nikumaroro Island in the Republic of Kiribati. *Photos courtesy of National Geographic*

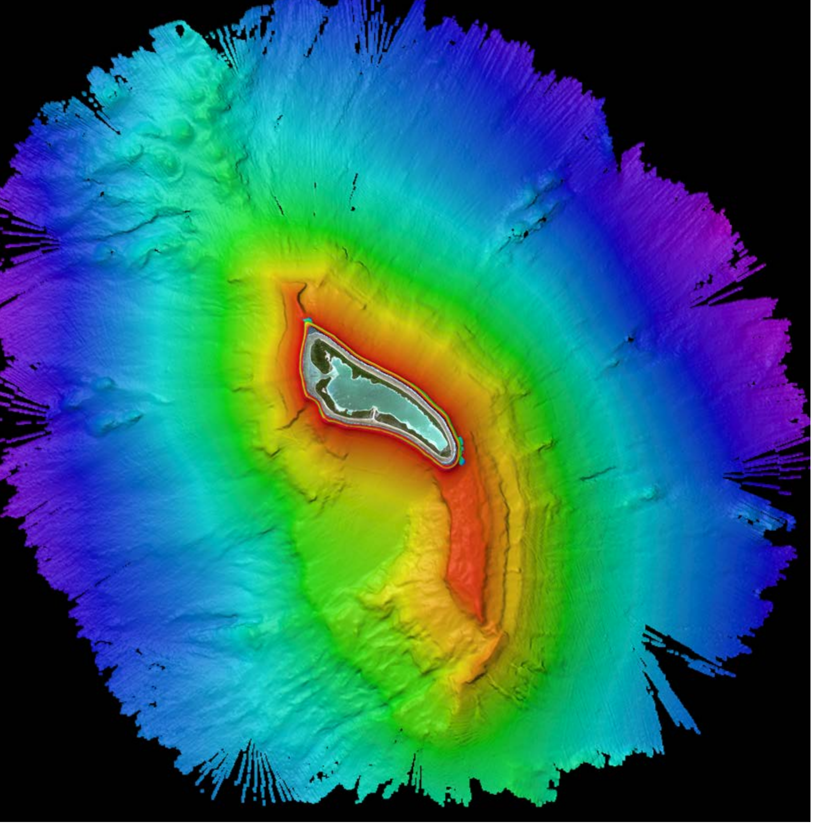


FIGURE 2. The seafloor mapping coverage from the *Nautilus* EM302 multibeam and ASV *BEN*.

FIGURE 3. Expedition team members Allison Fundis and Samantha Wishnak conduct visual surveys via scuba in areas of the reef unreachable by the ship and ROVs. *Image credit: National Geographic Society*

To investigate each of these scenarios, a broad range of technologies were deployed. In addition to mapping, aerial drones were used to visually inspect the terrain on either side of the surf zone down to an average depth of 20–30 m around the perimeter of the island. Scuba divers were prepared to dive on interesting objects seen by the drones or the camera mounted on the bottom of the ASV during its initial mapping effort (Figure 3). No promising leads were seen in the more than 3,800 color images collected, nor were they any targets detected on the ramp at the base of the first vertical scarp to a depth of 150 m.

ROVs *Hercules* and *Argus* visually inspected the rubble ramps around the entire island, starting in less than 50 m of water and working down to a depth of 300 m. With the exception of debris from SS *Norwich City*, the team did not locate any metallic fragments.

After this initial regional search was completed, the team concentrated on the first alternate theory with the ROVs and visually searched 100% of the terrain to a depth of 900 m downslope from the northwest tip of the island to the SS *Norwich City* wreckage and then to the southeast corner of the island. This area was downslope of the photo evidence taken on Nikumaroro a few months after Earhart's disappearance, which suggested an object—about the size and shape of Lockheed Electra landing gear—may have been embedded in the reef. Our team only located debris from the SS *Norwich City* wreck.

Next, we focused on the second alternate theory by conducting a series of slope-parallel visual search lines with the ROVs to locate and map the drainage network of gullies transporting reef debris into deeper water to a depth of 1,500 m. Once delineated, ROVs traversed up and down the axis of those gullies in search of plane debris.

To help guide this effort, we mapped the distribution of iron fragments traveling down slope from SS *Norwich City*, to depths in excess of 1,500 m. Again, no components from Earhart's Lockheed Electra were found.

To investigate the third alternate theory, we used a dual-frequency side-scan sonar on ROV *Argus* to conduct a series of overlapping survey lines parallel to the strike of the island on alluvial aprons down to depths greater than 1,800 m. During this side-scan survey, no targets of interest were detected on this relatively flat and featureless terrain several kilometers offshore.

Although we did not conduct as extensive a search off the northeast side of the Nikumaroro Island and cannot definitely rule out the theory that Earhart and Noonan landed there and perished as castaways on the island, we believe the next search effort should be expanded and also conducted off Howland Island utilizing autonomous underwater vehicles.

Pacific Remote Islands Marine National Monument

EXPLORING THE HOWLAND AND BAKER ISLAND UNIT AND JOHNSTON ATOLL UNIT

By Emil Petruncio, Alexis Weinnig, Colleen Peters, Dwight F. Coleman, Samuel Georgian, and Holly Richards

During September 2019, E/V *Nautilus* gathered baseline information about the bathymetry, geology, and biology of the Howland and Baker Island and Johnston Atoll Units of the Pacific Remote Islands Marine National Monument (PRIMNM) and nearby seamounts. Contributing to the knowledge base established through expeditions by NOAA Ship *Okeanos Explorer* and R/V *Falkor* in 2015 and 2017, this cruise mapped more than 31,669 km^2 of seafloor. Seven ROV dives focused on investigating deepwater coral and sponge habitats and characterizing the geology of seamounts, islands, and atolls (Figure 1). Across this broad area, 160 samples were collected, including 26 water samples to support eDNA analyses, 39 geological samples to facilitate age dating of seamounts and characterization of ferromanganese crusts, and 95 biological samples to document the composition of deepwater coral and sponge ecosystems.

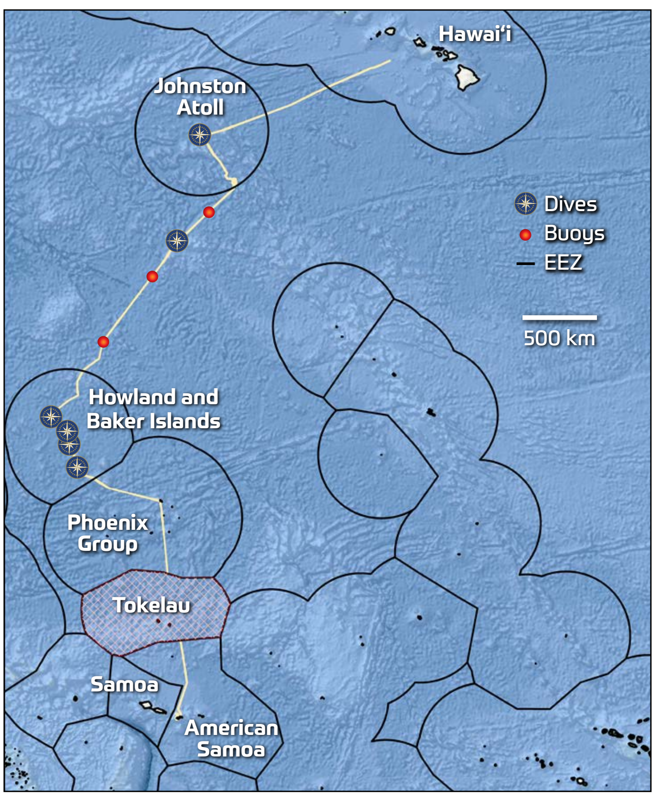


FIGURE 1. Overview map of expedition NA114, which began in Pago Pago, American Samoa, on August 26 and ended in Honolulu, Hawai'i, on September 16, 2019. Black lines represent the boundaries of Exclusive Economic Zones.

The first portion of the expedition focused on exploring in and near the Howland and Baker Islands Unit of the PRIMNM. Complementing the 2017 *Okeanos Explorer* expedition, two ROV dives were conducted on the slopes of Baker and Howland Islands. On the southwest side of Baker Island, ROVs ascended along the spine of a ridge comprised of basalt boulders, rubble, and sheet flows, leading to the carbonate cap at 600 m. Several coral and sponge species were observed along the transect, including a large *Chrysogorgia* sp. at 1,580 m depth. Among the macrofauna observed was a Cirroteuthid octopus at 1,600 m (Figure 2). A ridge on the northwest side of Howland Island was explored between 1,637 m and 501 m depth. Transect highlights include high density coral colonies at 1,350 m, a 2 m wide black coral (possibly *Leiopathes* sp.) with over a dozen associated squat lobsters and several crinoids, a colony of *Madrepora oculata* at 950 m, and a prickly shark (*Echinorhinus cookei*) at 660 m.

Next, *Nautilus* visited two previously unexplored seamounts: one southeast of Baker Island and another situated 140 km northwest of Howland Island at the northern corner of the PRIMNM boundary. The ROV dive on the seamount south of Baker Island ascended the spine of a ridge on the southwest side from 2,252 m depth to the sediment-covered summit at 1,143 m. The ROV dive on the seamount northwest of Howland Island began on a flat portion of the seafloor at 2,959 m depth. Several spherical gromiids were observed, possibly *Gromia sphaerica* (Gooday et al., 2000), near chunks of basalt in soft sediment at 2,800 m. This appears to be the first sighting of these large testate amoeboid protists in the PRIMNM. During the ascent along

FIGURE 2. Cirroteuthid octopus at Baker Island, observed 1,600 m depth. This rarely seen octopus was ~1.5 m in length.

the spine of a ridge on the southern side of the seamount, diverse assemblages of corals and large sponges were observed between 1,900 m and 1,800 m depth.

During a transit through international waters between Howland Island and Johnston Atoll, five drifting wave buoys were deployed in support of efforts by the Scripps Institution of Oceanography and Sofar Inc. to improve meteorological and oceanographic observations in this region. One ROV dive was conducted on a previously unexplored seamount on the western end of the Goldsborough seamount chain, 280 km south-southwest of the Johnston Atoll Unit boundary, with an estimated minimum depth of 22 m. Our multibeam sonar mapping of this seamount revealed a flat summit approximately 11 km wide and 1,300 m deep (pages 30–31). An ROV transect of a ridge on the southwest side of this guyot revealed basalt cobbles and boulders with botryoidal texture due to ferromanganese crusts, along with diverse sponges and corals, including a dense assemblage on a large basalt boulder at 1,880 m depth (Figure 3). The summit was sediment covered, and a carbonate cap was not readily apparent.

At Johnston Atoll, a deep ROV dive focused on several knolls southwest of the atoll, at depths ranging from 2,604 m to 1,667 m, and a shallow dive focused on slump escarpments on two terraces on the southwest side, ranging from 1,838 m to 103 m. The deep dive revealed numerous stalked Euplectellidae sponges and hundreds of living and dead Farreidae sponges (*Aspidoscopulia* sp.), numerous large Isididae whip corals, and abundant Chrysogorgiidae (likely *Pleurogorgia militaris*) on a basalt wall at 2,038 m depth. The shallow dive revealed abundant yellow Plexaurid corals, orange stalked crinoids, and anemones attached to a basalt escarpment and the underside of a ledge at 1,250 m, as well as a spectacular wall of columnar basalt at 1,280 m (Figure 4). At 200 m depth, near the top of a terrace, carbonate rocks festooned with what appeared to be reddish-purple crustose coralline algae hosted moray eels (likely *Gymnothorax berndti*), a magnificent snake eel (*Myrichthys magnifies*), and Hawaiian spikefish (*Hollardia goslinei*).

This expedition significantly expanded the areal coverage of multibeam sonar mapping and increased the video documentation and physical sampling of the geology and biology of the Howland and Baker Island and Johnston Atoll Units of the PRIMNM and of nearby seamounts. In so doing, this expedition will contribute to a better understanding of mineral resources and biogeographic patterns of species distribution within the US Exclusive Economic Zone and across the broader Central Pacific. Most of the seafloor within the PRIMNM remains unexplored, and further mapping and ROV dives will be necessary to fully document and protect the natural resources within this remote but ecologically important US territory.

FIGURE 3. A diverse assemblage of corals and sponges on a previously unmapped guyot in the Goldsborough seamount chain. The corals include members from the genera *Hemicorallia*, *Chrysogorgia*, and *Paragorgia*, and the sponges include members of the Euplectellidae and the finger-like Dendoricellidae families.

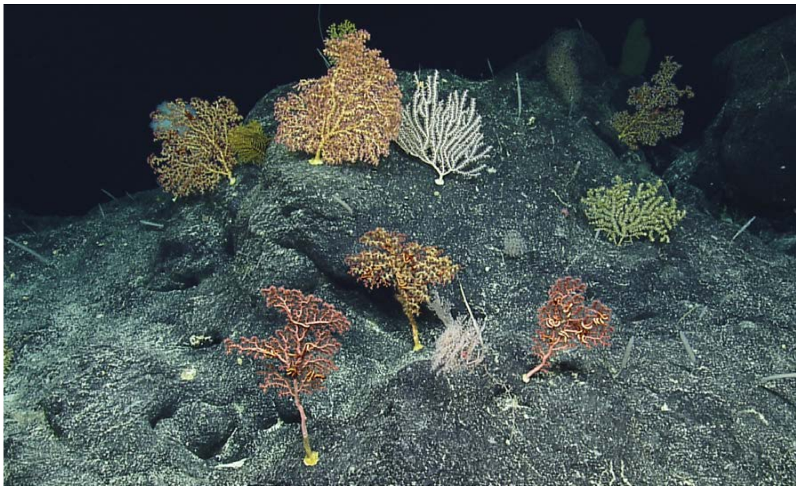
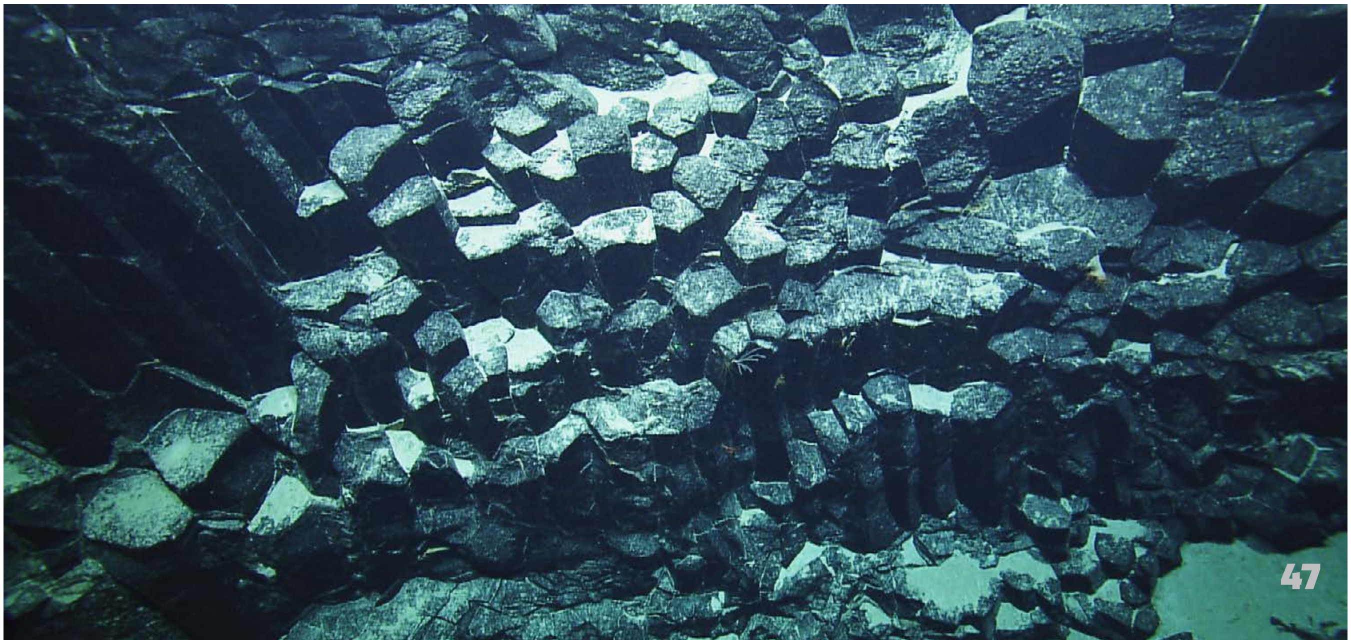


FIGURE 4. Columnar basalt formation on the southern slope of Johnston Atoll at 1,280 m depth.



Exploring Northern California National Marine Sanctuaries

By Jan Roletto, Danielle Lipski, Kaitlin Graiff, Gary Williams, Guy Cochrane, Jennifer Stock, and Sage Tezak

Cordell Bank (CBNMS) and Greater Farallones National Marine Sanctuaries (GFNMS) in north central California are two of 14 US national marine sanctuaries and two marine national monuments managed by NOAA. National marine sanctuaries are areas of special national significance designated to provide conservation, management, and enhanced public awareness of the ocean. CBNMS encompasses 3,330 km^2 offshore of Point Reyes, California. Its centerpiece is Cordell Bank, a rocky feature that rises from the continental shelf to within 35 m of the surface. It is surrounded by continental shelf to the east, and deep slope and canyon habitat extends to its western boundary, about 100 km offshore. GFNMS encompasses 8,500 km^2, stretching from San Francisco to Point Arena and more than 80 km offshore. It includes estuaries, mainland and island beaches, continental shelf and slope, banks, and deep canyons. During October 2019, the NOAA Office of National Marine Sanctuaries (ONMS) and the Ocean Exploration Trust worked together to map and characterize benthic habitats to aid in better protection and management. Additional collaborations with the California Academy of Sciences and the US Geological Survey contributed biological and geophysical expertise.

The objectives and target locations in CBNMS were informed by exploration with E/V *Nautilus* in 2017, which provided the first look at deep areas in the sanctuary. Post-survey analysis identified organisms and distributions but raised more questions about the taxonomy and ecology of the sanctuary's deep-sea communities. The goals for 2019 were to build upon the 2017 work in order to learn more about these communities, explore new areas, and add to the inventory and taxonomy of the organisms living there.

In 2019, ROVs *Hercules* and *Argus* conducted visual surveys of the habitat and biological communities and collected biological and environmental samples. Target areas for new exploration were Bodega Canyon and the continental slope habitat depth zones that were similar to and deeper than areas surveyed in 2017. During 20 hours of ROV bottom time at Box Canyon reaching a maximum 2,178 m depth, we observed and collected specimens of bamboo corals, black corals, and sponges (Figure 1). This dive also yielded a first observation of sulfur-seep-dwelling tube worms, possibly *Lamellibranchia* sp., for the area.

A six-hour dive was conducted in Bodega Canyon at 3,300 m, the deepest site ever surveyed in the sanctuary. This dive revealed invertebrates that had not been observed in the sanctuary previously, including stalked sponges and black corals that were collected for identification (Figure 2). Twenty-two biological samples were collected during these two dives, including sponges, corals, and associated organisms. In addition, seven water samples for ocean acidification analysis and eDNA studies were collected, as well as three sediment samples to look at past ocean conditions. The dives added to our species inventory for CBNMS and will help us better understand the taxonomy and distribution of the species living here, in addition to the physical conditions they experience.

FIGURE 2. Stalked sponges in various morphologies are common deep in Bodega Canyon. *Image credit: OET and ONMS*

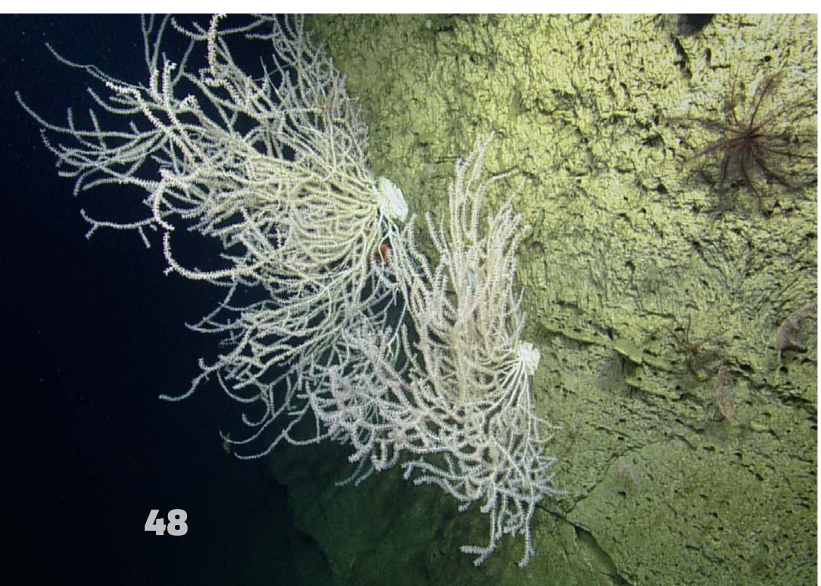


FIGURE 1. These large bamboo corals were oriented vertically off the Bodega Canyon walls in Cordell Bank National Marine Sanctuary. *Image credit: OET and ONMS*

FIGURE 3. This white sea fan coral (*Parastenella ramosa*) is home to numerous brittle stars and a large crinoid in Greater Farallones National Marine Sanctuary. *Image credit: OET and ONMS*

The primary goal of the GFNMS portion of this cruise was to gather enough information to characterize the Point Arena South Essential Fish Habitat Conservation Area and surrounding areas (PAS). PAS has an area of approximately 260 km^2 and is located 85 km west of Havens Neck near the northern Sonoma County border and approximately 150 km northwest of San Francisco. Prior to 2019, little was known about PAS seafloor biota (Figure 3) other than through bycatch of corals and sponges and a few brief visual surveys in the central-western portion. During this cruise, two ROV dives were conducted at depths ranging from 160 m to 1,800 m, one that was 22 hours along the southwestern portion of PAS and another that was 20 hours along the southern portion and adjacent areas. Data collected along 27 transects across several substrate types will be used to analyze deep-sea coral and sponge species composition and associated fish and substrate types. During the dives, 16 biological samples were collected of several unknown corals and sponges, including a newly described carnivorous sponge, *Aspestopluma* sp., nudibranchs, and brachiopods, all of which are being reviewed for identification. Two fractured rocks, two water samples for ocean acidification analysis and eDNA studies, and one sediment sample for climatology studies were also collected on the PAS dive.

During this cruise, live ROV views reached over 63,000 people from 80 countries. We also provided 37 live ship-to-shore interactions to science institutions and schools around the United States. Video highlights from the expedition shared with the public via Nautilus Live included observations of California deep-sea sea stars feeding on krill. We also observed a more active deep-sea sea star overtaking the typically slower moving splitnose rockfish (Figure 4).

FIGURE 4. A California deep-sea seastar (*Rathbunaster californicus*) encounters a splitnose rockfish (*Sebastes diploproa*) in Greater Farallones National Marine Sanctuary. *Image credit: OET and ONMS*

E/V *Nautilus* cruises greatly expand our understanding of the diversity and richness of the deep-sea communities in our national marine sanctuaries, but much remains to be discovered. Serving the wider scientific community, we collected 17 of 56 specimens requested by scientists from numerous research institutions from around the country. Discoveries regarding the high diversity of invertebrates and fish on and around the sanctuaries' canyons and rocky seafloor are excellent examples of the need for further investigation and quantification. The deep waters of the sanctuaries are rarely explored, and the ROV dives reveal many secrets of North America's most ecologically rich underwater treasures in the San Francisco Bay area.

Octopus Gardens and a Whale Fall in Monterey Bay National Marine Sanctuary

By Chad King, Jennifer Brown, Erica Burton, Amanda Kahn, Anne Hartwell, Amity Wood, and Dane Hardin

In October 2018, Monterey Bay National Marine Sanctuary (MBNMS) and OET personnel conducted a 34-hour dive to 3,300 m depth at the base of Davidson Seamount, an inactive volcanic undersea mountain off the coast of central California. During the last hour of the dive, we encountered hundreds of female brooding octopuses (*Muusoctopus robustus*) associated with shimmering water venting from cracks in a relatively small volcanic feature (1 km × 600 m) to the southeast of the seamount (King and Brown, 2019).

Return visits in March 2019 with HOV *Alvin* and in August 2019 with the Monterey Bay Aquarium Research Institute's ROV *Doc Ricketts* confirmed that mixing of warmer venting seawater (up to 10.4°C) with ambient seawater caused the shimmer. This venting seawater is most likely part of a low-temperature hydrothermal system originating at Davidson Seamount (G. Wheat, MBARI, *pers. comm*., 2019).

MBNMS and OET returned to this area in October 2019 to further characterize the "octopus garden," to explore a ridgeline on the southeastern apron of Davidson Seamount, and to investigate a small volcanic cone that might host more brooding octopuses (Figure 1).

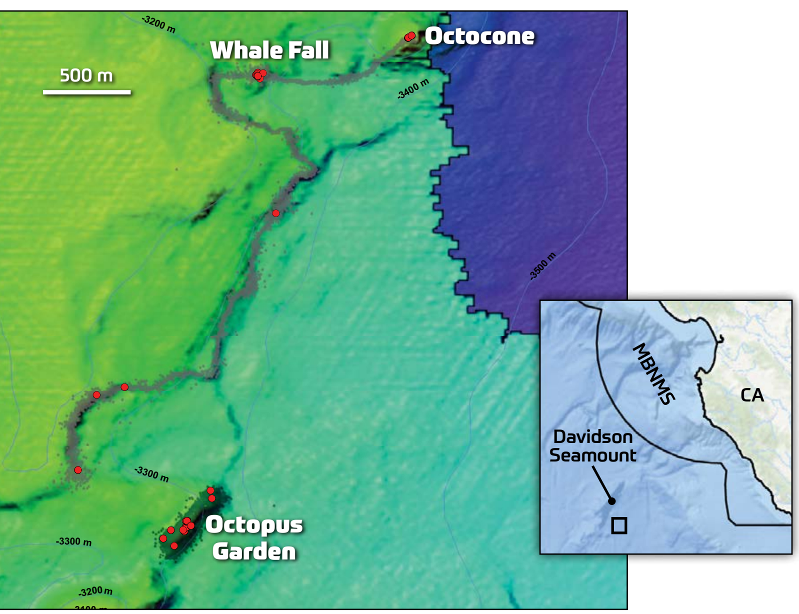


FIGURE 1. The 2019 expedition included dive H1795 at the octopus garden and dive H1796 that encountered a whale fall and a second octopus garden, dubbed "octocone." Gray dots represent reported locations of ROV *Hercules* (including outliers). Red dots indicate sample locations.

At the octopus garden, we measured temperature and dissolved oxygen to identify areas with high venting rates for long-term placement of OsmoSamplers and temperature and oxygen loggers. In situ temperature reached a high of 10.4°C, and dissolved oxygen was markedly lower than the surrounding seawater. At one vent, we left two OsmoSamplers, one dissolved oxygen/temperature logger, and two additional temperature loggers. At another vent, we deployed three temperature loggers. We expect to retrieve them during the 2020 field season. Once the equipment was deployed, we surveyed the seafloor to estimate the size of this octopus population.

During 28.3 hours of bottom time, we collected 18 samples, including samples for water chemistry and microbial presence, sediment cores for persistent organic pollutants (POPs), Niskin bottle water samples for eDNA, and rocks with attached fauna, plus whelks, anemones, octopus eggs, squat lobster, shrimp, and sponges. In addition, we sampled seawater using a Sea-Bird pump and special sample media.

The majority of the second 34-hour ROV dive followed a ridgeline along the southeast apron of Davidson Seamount that turned out to be composed of kilometers of large outcrops of sedimentary rock (Figure 2). We estimated some cliffs to be more than 50 m high. Long-lived corals were very rare along these highly erosive scarps, but many soft-bodied animals, such as anemones, were common.

In the last six hours of the dive, we made two remarkable discoveries. The first was a whale fall at 3,240 m depth (Figure 3). The rorqual whale skeleton, approximately 5 m long, was mostly exposed, with some remaining internal organs, baleen, and blubber. Scavengers and opportunistic predators, including octopuses, eelpouts, grenadier, and

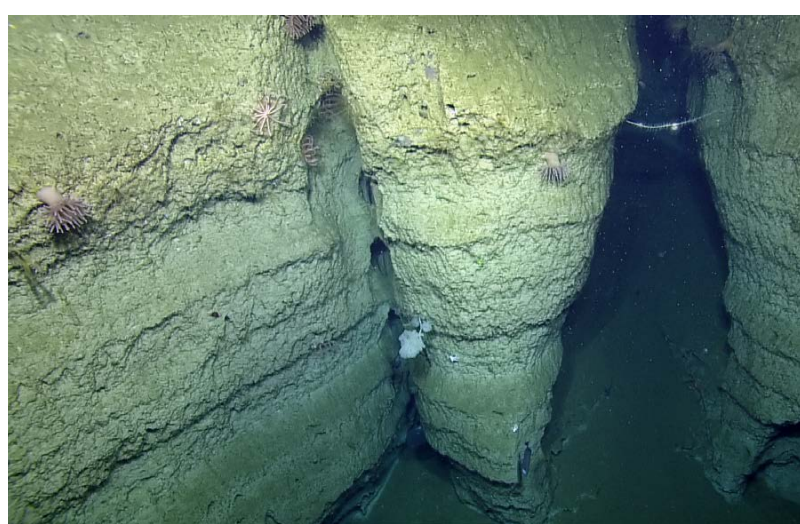


FIGURE 2. Large sedimentary outcrops dominated the landscape for the majority of ROV *Hercules* dive H1796. Differential erosion created a variety of channels, canyons, and caves.

FIGURE 3. A whale fall encountered during ROV *Hercules* dive H1796 at 3,240 m depth. It is estimated that this whale was several months old and approximately 5 m long. It was covered with scavengers, and the bone-eating worm (genus *Osedax*) covered most of its bones.

squat lobsters, were abundant on and around the carcass. Bone-eating worms of the genus *Osedax* coated most of the exposed bone and were particularly dense along the mandible and ribs. We collected two small bones coated with *Osedax* worms; preliminary results of DNA sequencing from one morphology of *Osedax* indicate it is a new species. The carcass was surrounded by a halo of ampheretid worms, presumably supported by enriched sediments. Sediment enrichment patterns will be examined using cores collected from areas with high and low worm density.

The second discovery was made within the last two hours of the dive as ROVs ascended a 250 m tall volcanic cone. Near the summit, we discovered seawater venting from cracks in the basalt and measured a maximum temperature of 5°C in one vent. Hundreds of brooding octopuses were lined up along these fractures (Figure 4). This second octopus garden is distinct from and approximately 17 km from the original. Seawater was collected to compare the chemistry with the original garden. We explored only a small portion of the summit due to inclement weather.

The 22 samples collected during the second dive included *Osedax*, ampheretid worms, sediment cores near the whale fall, water adjacent to the whale fall and from low-temperature vents, sediment cores for POPs, Niskin bottles for eDNA, rocks with attached fauna, whelks, anemones, squat lobster, shrimp, and sponges. The Sea-Bird electric pump sampled seawater for POPs for almost 23 hours.

Confirming a second distinct octopus garden is an exciting development, perhaps supporting the idea that more of these brooding sites exist around Davidson and other seamounts. It may be that these nurseries are common but have remained undiscovered until now because we tend

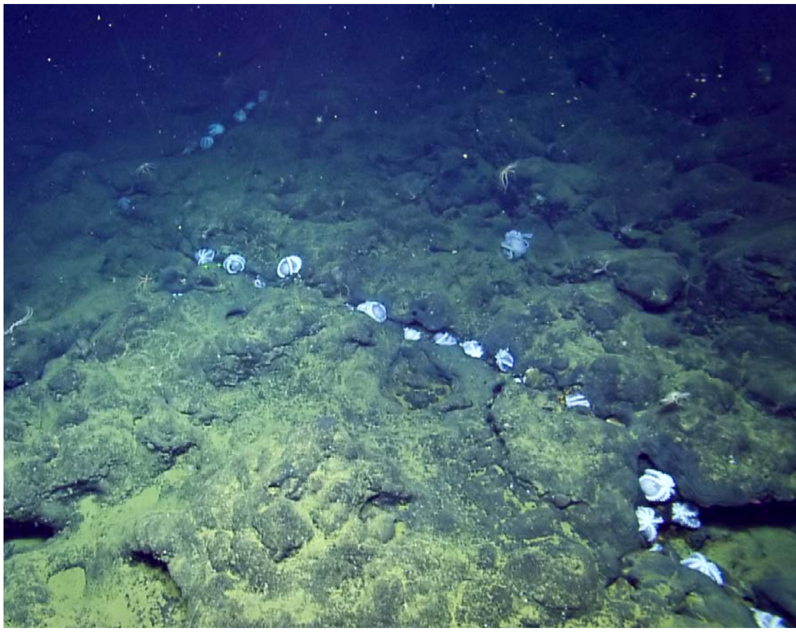


FIGURE 4. A second octopus garden was discovered on a small volcanic cone near the end of ROV *Hercules* dive H1796. Hundreds of brooding octopuses were associated with warm-water seeps located in cracks and crevices in the pillow basalt.

to explore major seafloor features such as seamounts, not small geologic formations kilometers from the seamount base. MBNMS will be returning with *Nautilus* in 2020 to retrieve the data loggers, explore the second octopus garden, and potentially find additional octopus nurseries.

Discovery of a new species of *Osedax* is an exciting byproduct of this mission, and there is potential for additional new species from samples waiting to be processed. Finding a whale fall is rare—it is even more rare to find one estimated to be only several months old. Future expeditions will be able to monitor the ecological succession and diversity of this deep-sea faunal community.

E/V *Nautilus* 2021–2023 Pacific Field Proposal

UNDER THE NEW NOAA OCEAN EXPLORATION COOPERATIVE INSTITUTE

By Robert D. Ballard

In May 2019, the NOAA Office of Exploration and Research announced that the University of Rhode Island would be the lead institution for its new Ocean Exploration Cooperative Institute (OECI). In partnership with the University of New Hampshire, the University of Southern Mississippi, the Woods Hole Oceanographic Institution, and the nonprofit Ocean Exploration Trust, the consortium will receive an initial five-year award of up to $94 million.

The OECI mission is threefold: (1) explore the 12 million square kilometers of submerged US ocean territory in order to strengthen our nation's Blue Economy, aid responsible management, and promote greater scientific understanding of our nation's vast underwater territory, known as the Exclusive Economic Zone; (2) develop the technology needed to carry out this effort, including greater use of autonomous vehicle systems operating from a broad range of seagoing platforms to explore the entire water column; and (3) train the next generation of scientists, engineers, and educators needed to maintain our nation's leading role in growing STEM-related professions.

For the last 10 years, OET has conducted telepresence-enabled exploration and outreach with funding from NOAA and other sponsors. These efforts are summarized in the annual *New Frontiers in Ocean Exploration* supplements to *Oceanography* (see https://tos.org/ocean-exploration for the full set). In the next five to 10 years, under the new

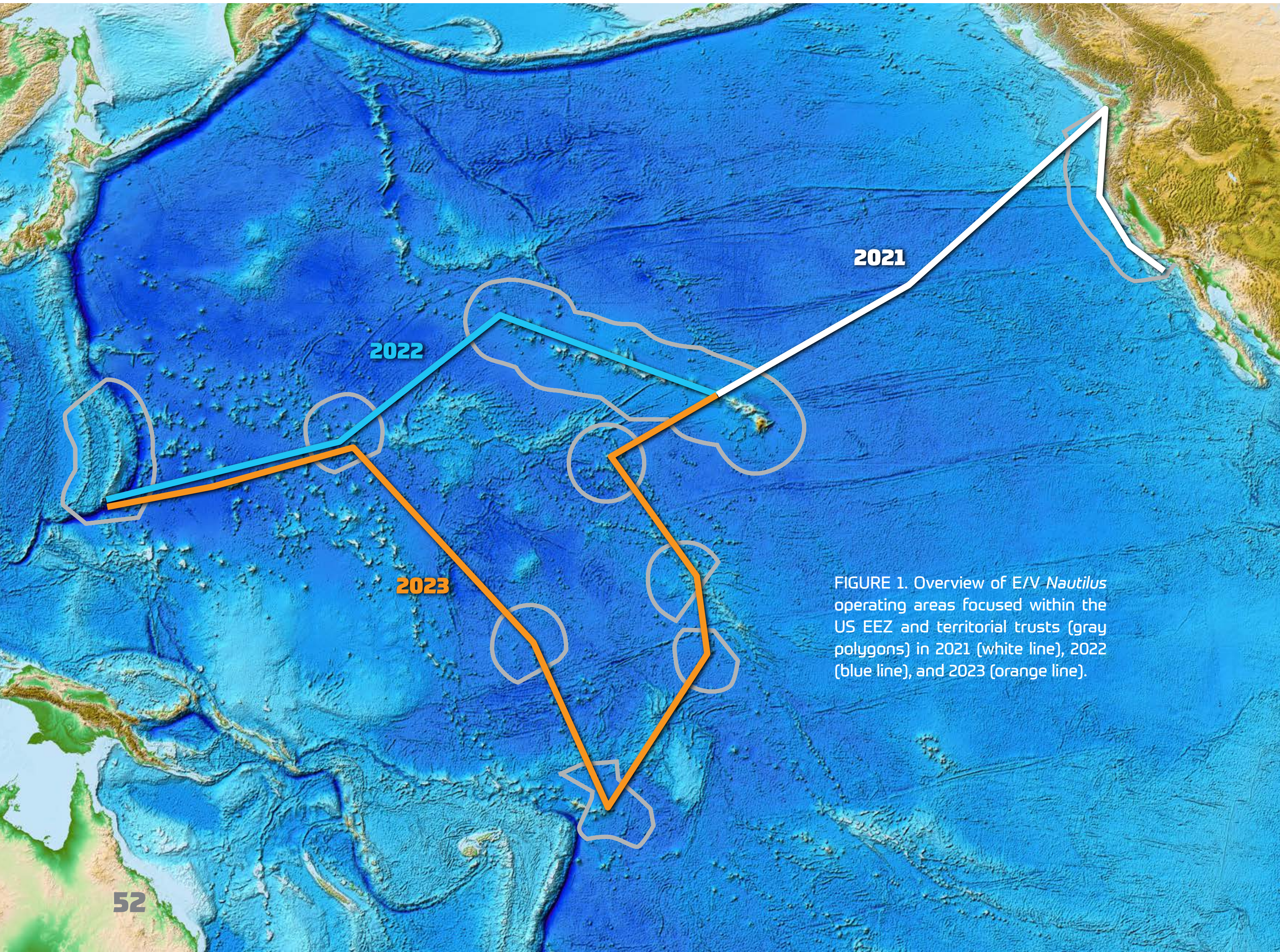


FIGURE 1. Overview of E/V *Nautilus* operating areas focused within the US EEZ and territorial trusts (gray polygons) in 2021 (white line), 2022 (blue line), and 2023 (orange line).

NOAA OECI, these endeavors will be greatly expanded to accomplish the mission goals articulated above.

Beginning in 2021, the field programs carried out by E/V *Nautilus* will focus on three primary regions of the US EEZ: the central and western Pacific, including the northern Hawaiian Islands, Guam, and the Northern Marianas Islands, and American Samoa and the trust islands of the central Pacific. During this period, *Nautilus* will remain in these regions and not return to its home base in San Pedro, California, until the end of 2023 or 2024 to maximize time spent in remote and undercharacterized or unexplored parts of the US EEZ.

Because these expeditions will involve *Nautilus* working near islands, atolls, and reefs where the ocean floor rises abruptly from abyssal depths, we plan to utilize OECI partner technologies to optimize exploration potential. They include the University of New Hampshire's aerial drones and autonomous surface vehicles (ASVs) with multibeam echosounders capable of mapping down to 500 m, and drop cameras provided by the National Geographic Society. Both of these systems can be used while *Nautilus* conducts mapping surveys in adjacent deeper waters. In addition, the ASV will also serve as a "command/control" link for the University of Southern Mississippi's AUV *Eagle Ray*, which can work to depths of 2,000 m.

In the past, OET's ROVs *Argus* and *Hercules* have traditionally focused on exploring the deep sea's benthic and epibenthic zones. That effort will be expanded using WHOI's Nereid Under Ice hybrid ROV/AUV to conduct simultaneous explorations in the nearby area. That vehicle, which is capable of rendezvousing with ROV *Hercules*, uses an optical modem to relay the data it has collected to the surface; the data can then be transmitted via satellite to scientists ashore for analysis and to serve as the basis for possible redirection of the assets in the field in near-real time. When operating in 24/7 ROV mode, the vehicles will commonly remain on the bottom for days.

Characterizing the midwater is a challenge for current ocean exploration robotic platforms, but with OECI partners we will take advantage of the ROV's vertical cable to investigate the entire water column. Two systems are presently being brought online for this effort. The first is the University of Southern Mississippi's plankton imaging system that will be able to move up and down on the ROV cable, imaging marine life in the midwater zone. A second midwater vehicle will employ the eDNA sampling system developed under WHOI's Ocean Twilight Zone project. This sampling system will also use the ROV's vertical cable to collect water samples for characterization of the marine organisms living in various depth zones based upon their DNA signatures.

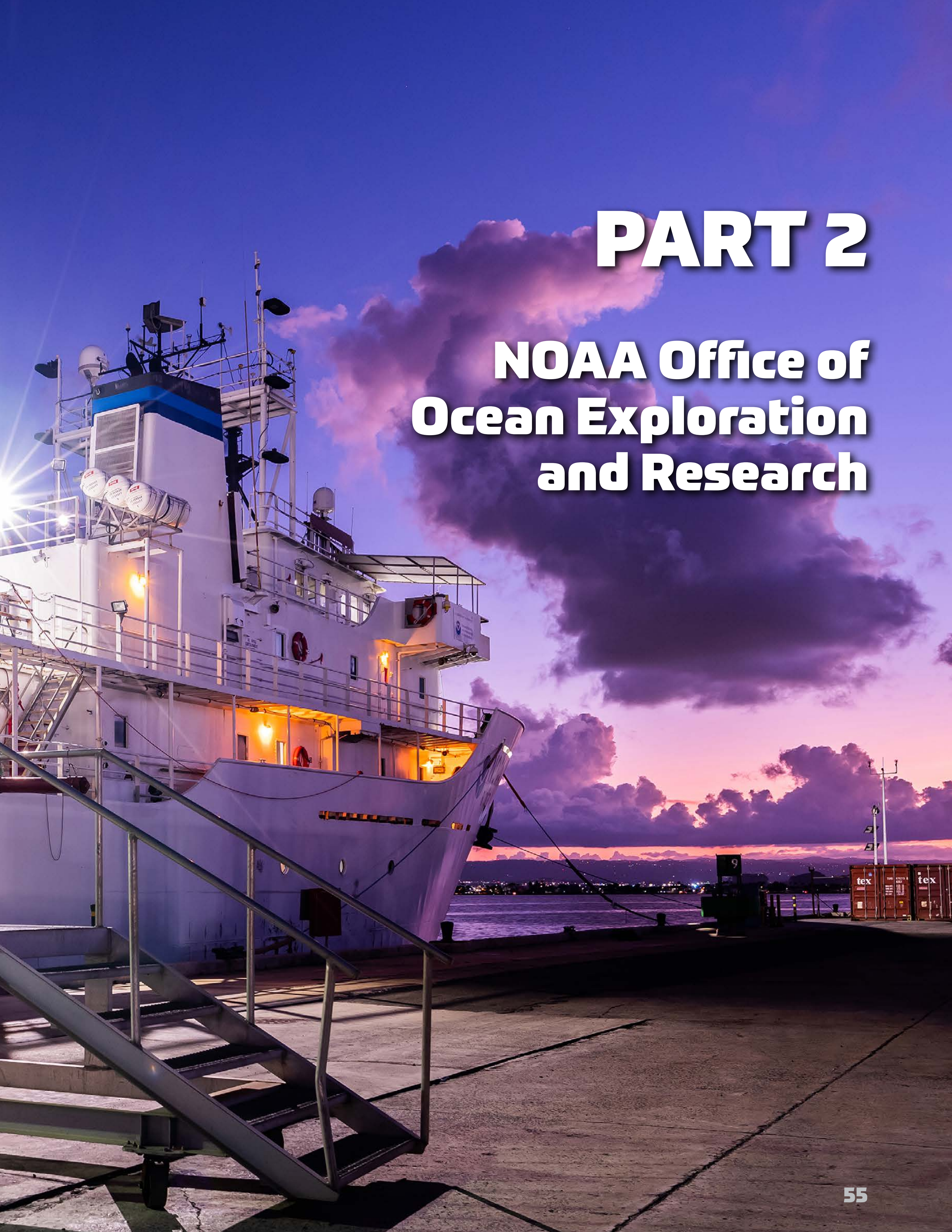
The long-term goal of this effort is to utilize and improve upon the Mesobot AUV that WHOI developed and is perfecting under separate funding. The Mesobot will follow midwater organisms to observe their behavior for long periods before reattaching to the ROV's vertical cable in order to return to the surface with samples and images and to be recharged so it can continue its work until the ROV is recovered.

To maximize the operational efficiency of *Nautilus* beyond its traditional joint mapping and characterization program under the OECI, OET plans to use the ship for additional purposes. Taking advantage of ship locations in the most remote regions of America's central and western Pacific EEZ, *Nautilus* will serve as a platform for supporting diving operations and scientists interested in island, reef, and/or atoll studies while also mapping the seafloor.

Another major focus of the new OECI is to utilize new 6,000 m mobile systems that come online in 2020. These systems will be capable of operating on a broad range of research platforms, including privately operated Global Class ships as well as Ocean Class Vessels and the new Regional Class Research Vessels (RCRVs) that are part of the University-National Oceanographic Laboratory System (UNOLS). Two of these RCRVs will be operated by two of the OECI partners, the University of Rhode Island and the University of Southern Mississippi.

Regarding the OECI's third mission focused on STEM education, this expansion of seagoing capabilities will make it possible to broaden our present educational programs—including 24/7 live streams of our expeditions, at-sea and onshore opportunities for educators and students, live ship-to-shore broadcasts to classrooms and public venues, curricular and educational resources for educators, and online outreach—over the entire year. The ship enhancements allow us to scale our programs along with our OECI partners to other ships and to amplify engagement of the public and the next generation of ocean explorers.

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



PART 2

NOAA Office of Ocean Exploration and Research

2019 Expeditions with NOAA Ship *Okeanos Explorer*

By Scott C. France

Following start-of-season engineering tests and sea trials in the Gulf of Mexico, which included a serendipitous discovery of a shipwreck, NOAA Ship *Okeanos Explorer* spent 2019 probing the margins of the US eastern continental shelf, collecting baseline information from under- or unexplored deepwater areas in the western North Atlantic.

Four expeditions comprised the 2019 field season, each contributing to the Atlantic Seafloor Partnership for Integrated Research and Exploration (ASPIRE) campaign, a major multiyear, multinational collaborative field program focused on increasing knowledge about—and understanding of—the North Atlantic Ocean. Collectively, the cruises explored diverse benthic habitats, conducted multiple horizontal transects through the water column to provide observations from the largest and least explored biome on the planet by volume, mapped >175,000 km^2 of seafloor, included the introduction of a suction sampler to the toolkit of the remotely operated vehicle (ROV) *Deep Discoverer* to enhance capabilities for collecting mobile fauna, and marked the one-hundredth mission during which ocean exploration data were collected using *Okeanos Explorer*.

From a science perspective, the addition of the suction sampler was a significant development that expanded collection capabilities for previously difficult-to-sample mobile fauna, including those in the midwater. It was used frequently and successfully in its first season, returning to the surface a range of fauna, from dandelion siphonophores and squid to a variety of gelatinous zooplankton (e.g., ctenophores, jellyfish). Overall, primary collections of more than 200 biological samples and 17 geological samples (plus any epifauna) were preserved and made available in shore-based archives for future study by the scientific community.

161 Days at Sea

38 ROV Dives

175,000+ km^2 of Seafloor Mapped

89,600+ km^2 of Seafloor Mapped in US EEZ

12 CTD Casts

359 Biological and 25 Geological Samples Collected

12 EITs, Hollings Scholars, and EPP Interns

~535,000 Live Video Views

NOAA SHIP *OKEANOS EXPLORER*

LENGTH | 68 meters (224 feet)

BEAM | 13 meters (43 feet)

DRAFT | 5.1 meters (16 feet, 10 inches)

DISPLACEMENT | 2,312 long tons

MAIN PROPULSION | Diesel electric with twin inboard turning screws (1,600 Shaft HP)

SPEED | 10 knots

ENDURANCE | 40 days at sea

RANGE | 17,780 kilometers (9,600 nautical miles)

DYNAMIC POSITIONING (DP-1) | 550 HP retractable azimuth bow thruster and two 250 HP stern thrusters

BUILT | 1987, Halter Marine in Pascagoula, MS, USA

BERTHING | 49 persons (23 mission/science, 26 crew)

FLAG | United States of America

HOME PORT | North Kingstown, RI, USA

FIGURE 1. High-quality in situ imaging provides opportunities for valuable rarely seen behavioral observations, such as this *Chaceon* red crab feeding on a patch of eggs, likely those of a pallid sculpin, at 920 m depth in Roanoke Minor Canyon.

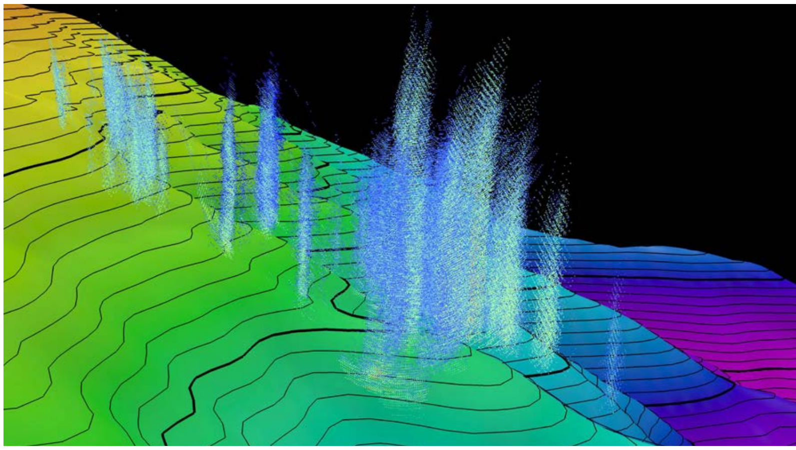


FIGURE 2. Three-dimensional view of the Bodie Island seeps, with the upper slope bathymetry contoured at 10 m. Bathymetry is shown with vertical exaggeration. Blue and green clouds in the water column imaged by *Okeanos Explorer's* multibeam sonar represent acoustic returns from ascending bubbles associated with methane plumes generated at seafloor gas seeps.

FIGURE 3. A large mussel bed associated with the Bodie Island seeps was home to spider crabs, quill worms, blackbelly rosefish, eelpouts, sea stars, and anemones.

SOUTHEASTERN US CONTINENTAL MARGIN

Expeditions in 2018 revealed one of the largest deep-sea coral reef habitats in US waters. Because much of this area offshore of the southeastern United States was still unexplored, there was plenty of interest from the ocean management and scientific communities to return there. During the 2019 field season, *Okeanos Explorer* conducted two cruises over 38 days to this region, the first focused on mapping and the second on deploying 19 ROV dives during the day while mapping at night. About 28,988 km^2 of seafloor were mapped, including previously uncharted areas on the Blake Plateau that revealed many unexpected small mounds and knolls.

The ROV dives collected just over 100 hours of seafloor video, with additional video recorded during dedicated midwater exploratory transects. The majority of dives traversed the bottom between 600 m and 1,100 m depth, but sites as deep as 3,100 m (Pamlico Canyon) and as shallow as 430 m (Bodie Island Seep) were also explored. In addition to distribution data on deep-sea coral and sponge communities, the video provided valuable rarely seen behavioral data and interactions, such as goniasterid seastars and cidaroid sea urchins feeding on a sponge, a frenzy of dogfish sharks feeding on a recently dead swordfish, and a *Chaceon* crab feeding on a cluster of pallid sculpin eggs (Figure 1). Three dives investigated locations where water column data suggested the presence of methane cold seeps, and two cold seep communities were discovered. At the Bodie Island seeps, methane bubbles were observed escaping from the seafloor (Figure 2), surrounded by mats of filamentous bacteria and *Bathymodiolus* mussels (Figure 3), the first observation of chemosynthetic mussels between offshore Virginia and South Carolina.

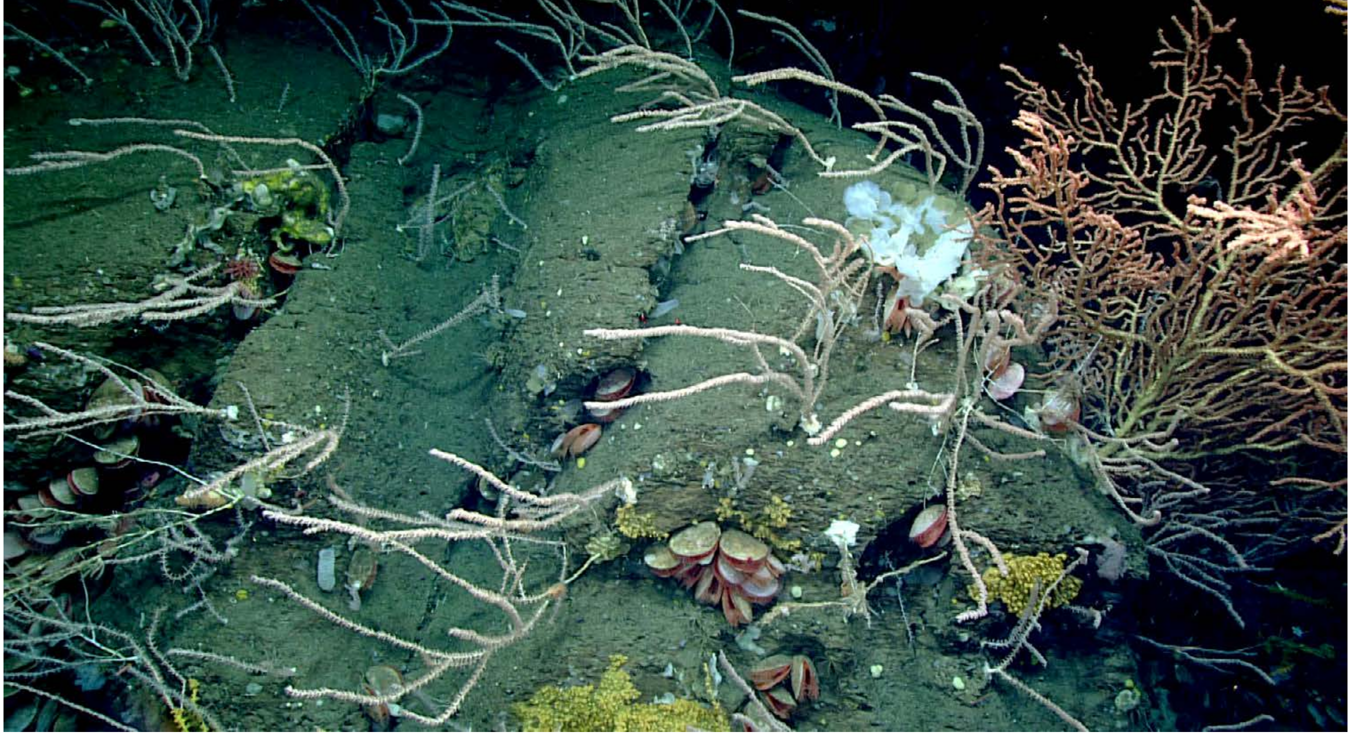


FIGURE 4. At 1,180 m depth in Canada's Gully Marine Protected Area, a diversity of species, including *Acesta* bivalves, sponges, zoanthids, and crinoids, live among a dense stand of bamboo corals.

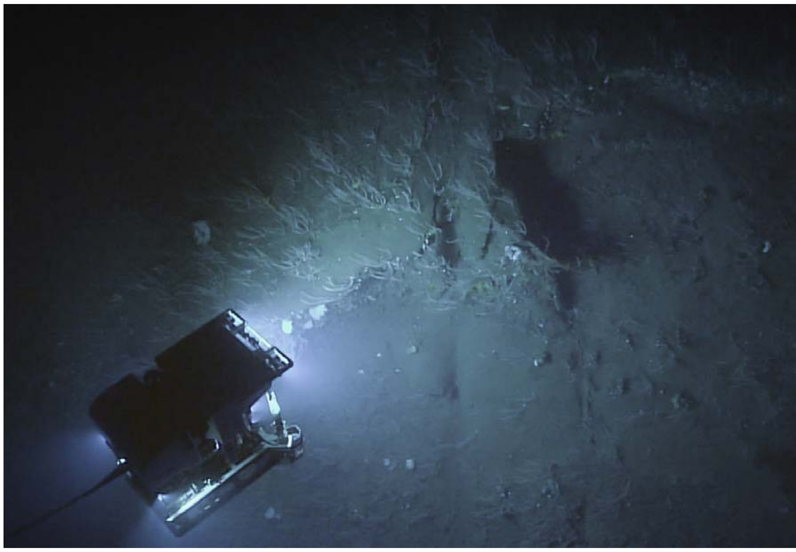


FIGURE 5. ROV *Deep Discoverer* passes over a dense stand of bamboo corals at 1,180 m depth in Canada's Gully Marine Protected Area.

NORTHEASTERN US CONTINENTAL MARGIN AND CANADA

The *Okeanos Explorer* team worked with international partners in 2019 on two cruises to map and explore the northeastern continental margin, including deep-sea coral, sponge, and fish habitats, submarine canyons, seamounts, marine managed areas, and submarine landslides. Four ROV dives and mapping operations took place in Canadian waters. Six ROV dives were conducted in three marine managed areas and included first observations of a high-density bamboo coral forest in Canada's Gully Marine Protected Area (Figures 4 and 5). A highly diverse and dense assemblage of deep-sea sponges that may be the deepest high-density community known in the US northeast region was discovered in the Northeast Canyons and Seamounts Marine National Monument on Retriever Seamount at 2,668 m depth.

TECHNOLOGY ADVANCES AND DEMONSTRATIONS

During the July *Okeanos Explorer* expedition, two legs were dedicated to testing and evaluating five emerging or novel technologies for possible future integration into NOAA operations. These included an autonomous underwater vehicle (AUV), an advanced towed platform with synthetic aperture sonar, a 360-degree camera, a laser line scanning system for generating high-resolution, three-dimensional representations of objects on the seafloor, and a navigation system capable of supporting multiple AUVs. These technology demonstrations are critical to future efforts by NOAA's Office of Ocean Exploration and Research to map and characterize the US Exclusive Economic Zone.

Exploring America's Deep Ocean

By Craig W. Russell and Mashkoor Malik

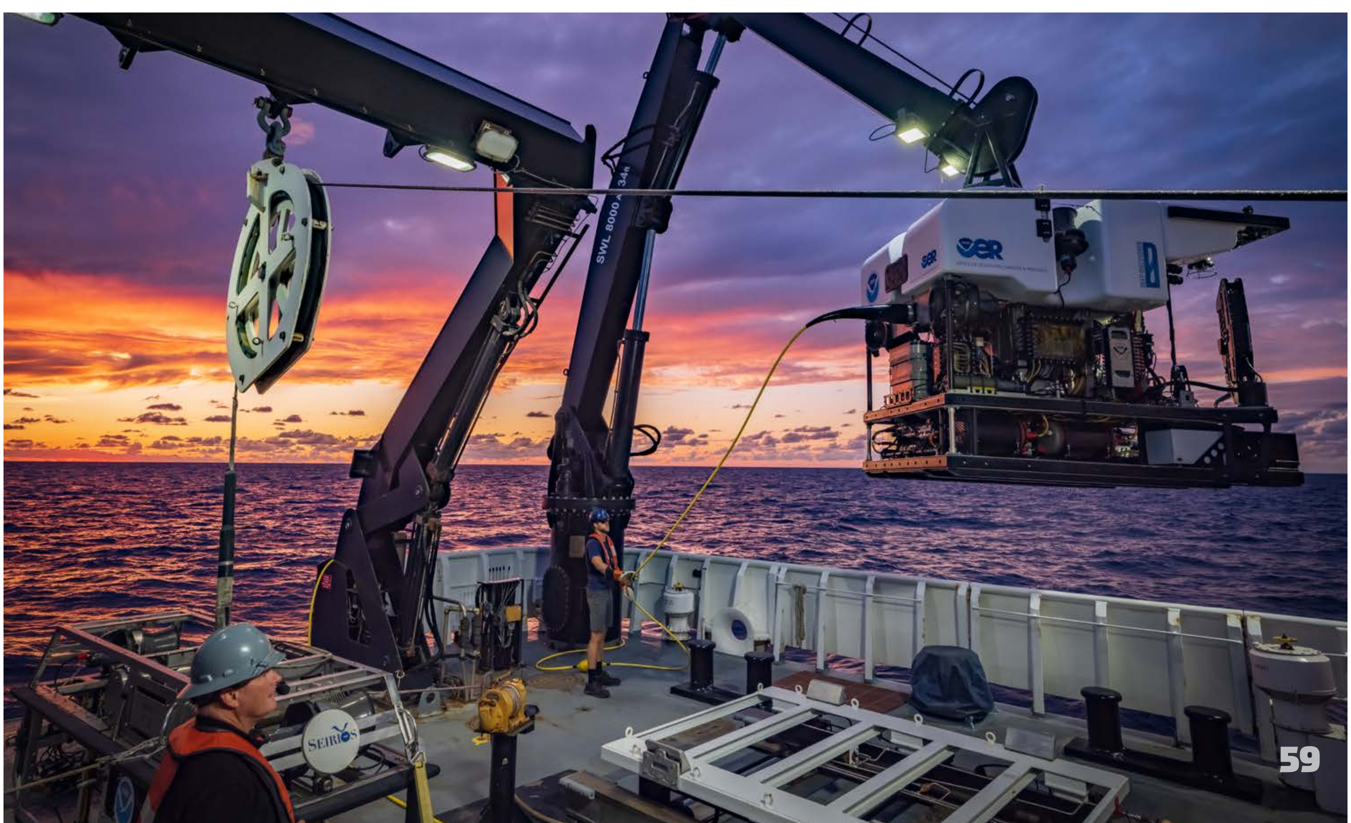
NOAA's Office of Ocean Exploration and Research (OER) supports NOAA mission priorities and national objectives by providing high-quality scientific information about the deep ocean. NOAA Ship *Okeanos Explorer* is the only US federal vessel dedicated to exploring our largely unknown ocean for the purpose of discovery and the advancement of knowledge. Using advanced technologies, and in close collaboration with government agencies, academic institutions, and other partners, OER routinely conducts deep-ocean expeditions, ranging from exploring, mapping, and characterizing previously unseen seafloor to collecting and disseminating physical, biological, and geological information about the ocean. This work helps to establish a foundation of information, fill data gaps, and produce new lines of scientific inquiry. Data collected on the ship follows federal open-access data standards, ensuring swift delivery of reliable scientific data needed to identify, understand, and manage key elements of the ocean environment. Seafloor mapping extends bathymetric mapping coverage in the US Exclusive Economic Zone (EEZ) in support of Seabed 2030 and NOAA's goal to explore, map, and characterize the US EEZ.

Okeanos Explorer is equipped with four types of mapping sonars, a dual-bodied ROV that can dive to 6,000 m, and a conductivity, temperature, depth (CTD) rosette.

Telepresence technology allows video from the two ROVs, *Deep Discover* and *Seirios*, to be streamed live over the Internet to millions of people around the world, allowing viewers to share in the excitement of discovery. In 2019, the team evaluated and implemented new methods and tools. Partners from the Global Foundation for Ocean Exploration (GFOE) designed and integrated a new suction sampling system on *Deep Discover* for bottom and midwater sampling and evaluated still cameras to provide 35 mm quality photographs. The Ocean Networks Canada SeaTube 2.0 system was further enhanced with additional integrated data streams. Industry and academic partners tested several new technologies, including a synthetic aperture sonar and a shipboard stereolithography apparatus (SLA), and assessed AUV mapping operations, while also collecting critical data for multiple stakeholders.

Okeanos Explorer missions in 2020–2021 are expected to examine the poorly known areas of southeast United States, Caribbean Sea, Mid-Atlantic Ridge, and northwest Atlantic Ocean. Expeditions will also test improved data collection and telepresence capabilities, review eDNA collections and analysis options, characterize samples collected, and target detection to inform future investments in mission capabilities.

ROV *Deep Discoverer* being deployed from the stern of NOAA Ship *Okeanos Explorer. Image credit: Art Howard, GFOE*



Deep-Sea Data Needs Addressed by the NOAA Office of Ocean Exploration and Research

By Katharine Egan, Amanda N. Netburn, James W.A. Murphy, Margot Bohan, Adrienne Copeland, Megan Cromwell, Clint Edrington, Stephen R. Hammond, David McKinnie, Derek Sowers, Nathalie Valette-Silver, and Daniel Wagner

NOAA's Office of Ocean Exploration and Research is the only US federal organization dedicated to exploring previously undocumented areas of Earth's ocean. NOAA Ship *Okeanos Explorer* collects and disseminates primary observations (Table 1), facilitating the discovery and initial characterization of unexplored regions of the deep sea. OER supports further exploration through a competitive grants program (see page 90), through various inter- and intra-agency partnerships, and through telepresence-enabled exploration using NOAA Ship *Okeanos Explorer*. The data collected from these exploration initiatives provide initial insights into unexplored deep-sea areas. The intent of these expeditions is to generate important data sets to inform future deep-sea activities, such as research, resource extraction, conservation, and regulation.

To identify the data requirements of the deep-sea science and management communities, a literature review was conducted of published white papers and reports and peer-reviewed publications in order to synthesize data needs; it included OET (2012, 2014), UNOLS (2016), NOAA OER (2011), Sayre et al. (2017), Netburn (2018), and Woodall et al. (2018). A list of important observation types was compiled and were categorized based on number of report mentions as well as whether the observations are currently collected on *Okeanos Explorer* expeditions.

Seven reports were assessed and a total of 78 important spatially referenced data types were identified, 14 of which are currently collected on *Okeanos Explorer* expeditions (numbers in parentheses designate the number of reports that mention the data type):

- Dissolved oxygen (6)
- Sea surface and subsurface temperature (5)
- Seafloor mapping (5)
- Surface and subsurface currents (4)
- Sea surface and subsurface salinity (4)
- Bottom pressure (3)
- Occurrence and distribution of large marine vertebrates or megafauna (3)
- Light (including irradiance, scattering, transmission) (3)
- Fish abundance and distribution (2)
- Invertebrate abundance and distribution (1)
- Chlorophyll-*a* fluorescence (1)
- In situ imaging (1)
- Acoustic sensing of water column biomass (1)
- Records of litter and anthropogenic damage (1)

An additional 13 data needs described by these reports can be derived through further analysis of the data or physical specimens collected on *Okeanos Explorer* expeditions:

- Biodiversity on the seafloor and in the water column (4)
- Cold-water coral coverage (3)
- Connectivity of species (3)
- Genetic and behavioral characteristics of biota (2)
- Variables to characterize geohazards (2)
- Vent chemistry (2)
- Distribution of mud volcanoes, cold seeps, and vent communities (2)
- Relative cover of living habitats (2)
- Species specific density and counts (2)
- Size-specific body size and biomass (1)
- Turbidity (1)
- Food web analysis (1)

Though *Okeanos Explorer* observations provide enough information to satisfy 27 of the 78 data needs, 51 of these data needs are currently not addressed on *Okeanos Explorer* expeditions. Current work is underway to identify partners and technologies that can address these data gaps. Such efforts are vital to ensure OER continues to provide relevant information in accordance with continual expansion of exploration goals and needs, including those with respect to NOAA-relevant initiatives, such as the Blue Economy. These efforts complement existing observations through partnerships and exploration grants and will provide resource managers, scientists, and the public the information they need to identify, understand, and manage ocean resources for current and future generations.

TABLE 1. OER utilizes multiple mechanisms to collect ocean exploration data. NOAA Ship *Okeanos Explorer* collects a combination of physical, biological, and geological data in a systematic methodology using acoustic mapping, ROV surveys, and deploying various oceanographic instrumentation. Data from these missions are made available to the public within 90 days of an expedition to provide stakeholders with observational data as soon as possible. Data can be accessed here: https://oceanexplorer.noaa.gov/data/access/access.html. *Background graphic by Matt King, NOAA OER, adapted from the Mayo Clinic*

MAPPING OPERATIONS

		XBT	MULTIBEAM BATHYMETRY/ BACKSCATTER	SUBBOTTOM PROFILER	EK60/EK80
COLLECTION RATE DURING OPERATION		2–6 hours	continuous	continuous	continuous (based on sonar frequency)
WATER COLUMN	BIOLOGICAL		X		X
WATER COLUMN	CHEMICAL/ PHYSICAL	X	X		X
SEAFLOOR/SUB-SEAFLOOR	BIOLOGICAL				
SEAFLOOR/SUB-SEAFLOOR	CHEMICAL/ PHYSICAL		X	X	X
SEAFLOOR/SUB-SEAFLOOR	GEOLOGICAL		X	X	X
SEAFLOOR/SUB-SEAFLOOR	ARCHAEOLOGICAL		X	X	

CTD ROSETTE OPERATIONS

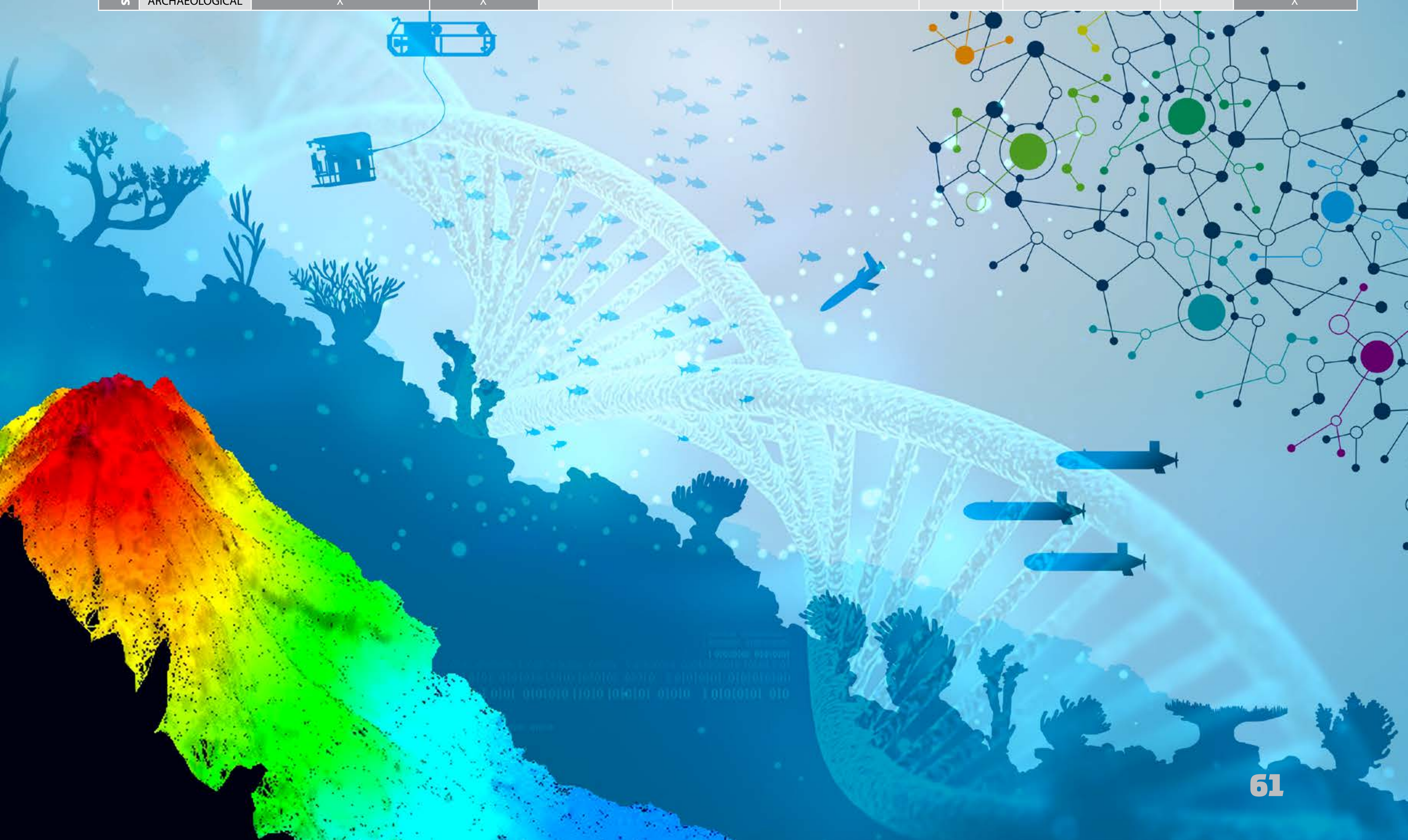
		CTD-O	TURBIDITY & OXIDATION REDUCTION POTENTIAL AND FLUOROMETER	WATER SAMPLES	CTD ROSETTE SUMMARY FORM
COLLECTION RATE DURING OPERATION		continuous	continuous	≤12/cast	1/cast
WATER COLUMN	CHEMICAL/ PHYSICAL	X	X	X	X

SHIP-BASED MEASUREMENTS

		METOC SENSORS	THERMOSALINOGRAPH	ADCP
COLLECTION RATE DURING OPERATION		continuous	continuous	continuous
ATMOSPHERE	BIOLOGICAL			
ATMOSPHERE	CHEMICAL/ PHYSICAL	X	X	
WATER COLUMN	BIOLOGICAL			
WATER COLUMN	CHEMICAL/ PHYSICAL			X

ROV OPERATIONS

		HD VIDEO WITH LASERS FOR SCALE	ANNOTATIONS	PRIMARY BIOLOGICAL SAMPLES	PRIMARY ROCK SAMPLES	ASSOCIATED BIOLOGICAL SAMPLES	CTD-O	TURBIDITY & OXIDATION REDUCTION POTENTIAL	WATER SAMPLES	DIVE SUMMARY FORM
COLLECTION RATE DURING OPERATION		continuous (turned off for close-up imaging)	variable	≤8/dive	≤3/dive	variable	continuous	continuous	≤5/dive	1/dive
WATER COLUMN	BIOLOGICAL	X	X	X		X		X	X	X
WATER COLUMN	CHEMICAL/ PHYSICAL						X	X	X	X
SEAFLOOR/ SUB-SEAFLOOR	BIOLOGICAL	X	X	X	X	X		X	X	X
SEAFLOOR/ SUB-SEAFLOOR	CHEMICAL/ PHYSICAL	X			X		X	X	X	
SEAFLOOR/ SUB-SEAFLOOR	GEOLOGICAL	X	X		X	X		X		X
SEAFLOOR/ SUB-SEAFLOOR	ARCHAEOLOGICAL	X	X							X



Deep-Sea Discoveries in the Mysterious Midwater

By Adrienne Copeland, Michael Ford, and Herbert Leavitt

With a volume of over a billion cubic kilometers, the mesopelagic or midwater zone of the ocean is the largest habitat on Earth. Spanning the water column from 200 m below the surface to near the seafloor, this environment provides crucial support for commercially important fisheries, drives carbon sequestration, and plays numerous roles in ocean chemistry and climate. This ocean zone is almost completely unexplored, with few data from instruments and many fewer visual surveys of fauna. Though the volume, operating depths, and dynamic nature of the midwater zone make exploration difficult, discoveries of new life and increased understanding of such a large part of the planet compel us to explore.

Shipboard acoustic systems (Simrad EK60 and EK80) on NOAA Ship *Okeanos Explorer* and a dual-bodied ROV system deployed from the vessel work together to explore the midwater realm. The acoustic systems are used to detect the deep scattering layer, a ubiquitous zone at about 300–800 m depth that consists of organisms ranging in size from 2 cm to 20 cm, including abundant small fishes (mostly myctophids), crustaceans (mostly larger euphausiids and shrimp), and cephalopods. Once the scattering layer is identified, ROV transects are planned to visually survey the fauna below, then within, then above it.

During 2019, we completed water column exploratory transects on June 22, 27, 29, and 30 during the Windows to the Deep 2019 leg 2 expedition (Figure 1). These transects were at depths ranging from 1,000 m to 300 m. Some of the species seen during the water column exploration ranged from small fishes to crustaceans, gelatinous organisms (medusa and ctenophores), and cephalopods (Figure 2).

FIGURE 1. Map of water column dives made during the Windows to the Deep 2019 expedition. The pie charts represent the individual organisms seen in the video during the various transects ranging in depths from 1,000 m to 300 m.

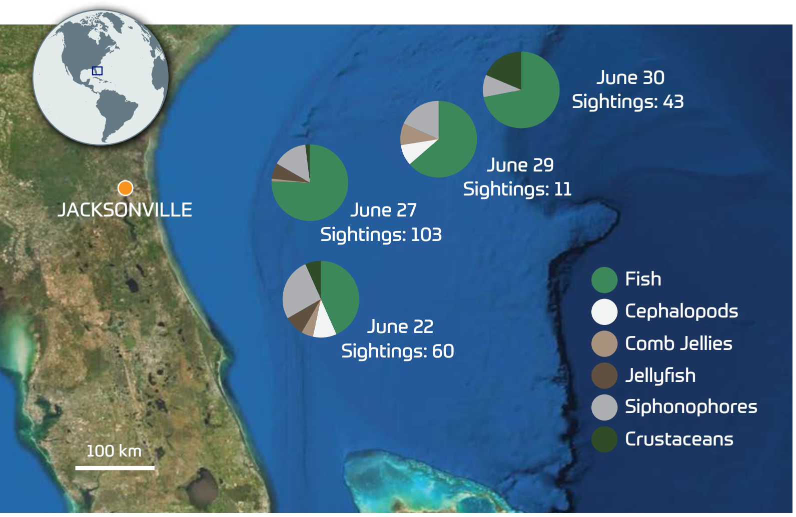
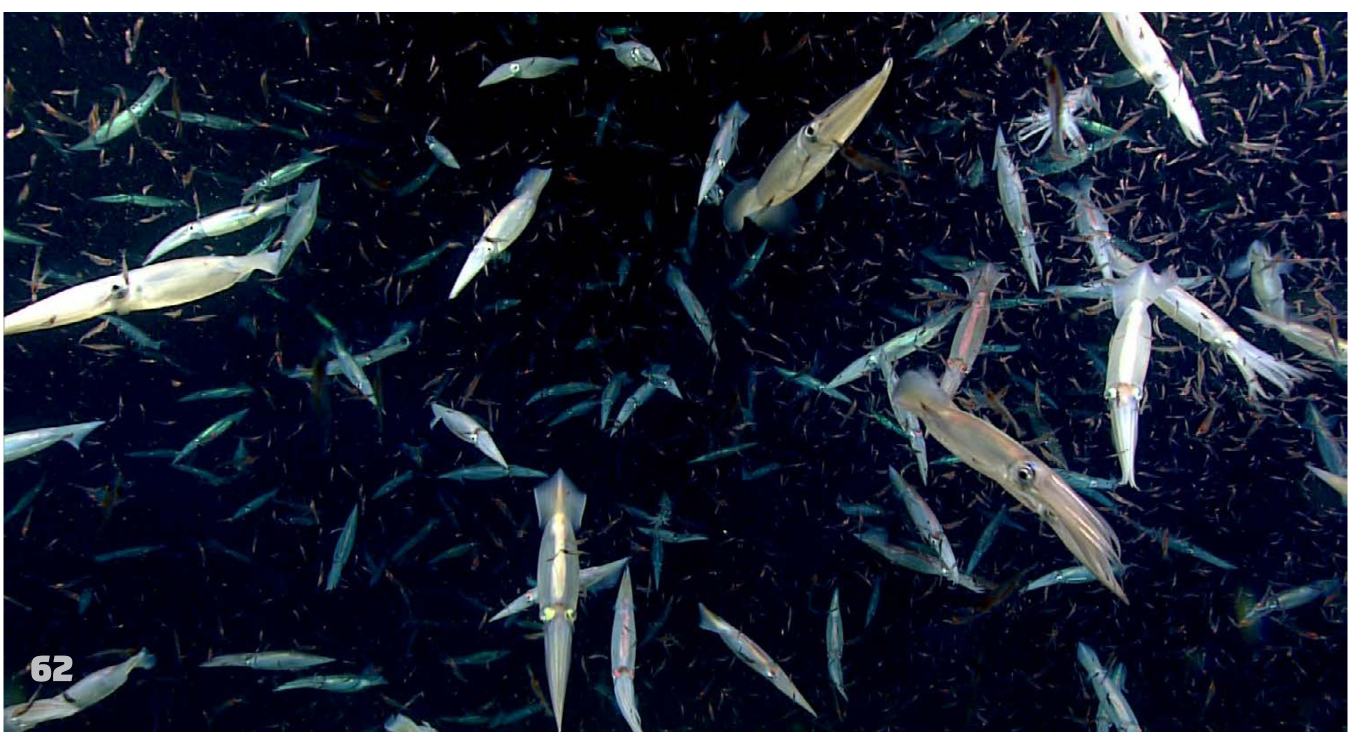


FIGURE 2. From the surface to the seafloor, the water column teems with life, providing crucial support for many important species. Here, northern shortfin squid (*Illex illecebrosus*) are seen actively feeding on a large swarm of crustaceans during dive 3 of the Deep Connections 2019 expedition.



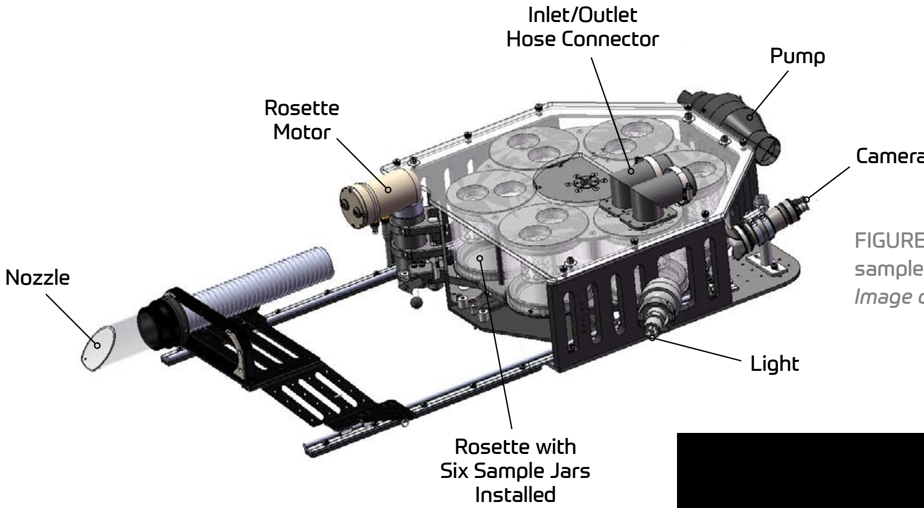


FIGURE 3. Drawing of the new suction sampler and rosette of sample jars. *Image credit: GFOE*

FIGURE 4. A close-up of a squid that was collected using ROV *Deep Discoverer* suction sampler. *Image credit: Art Howard, GFOE*

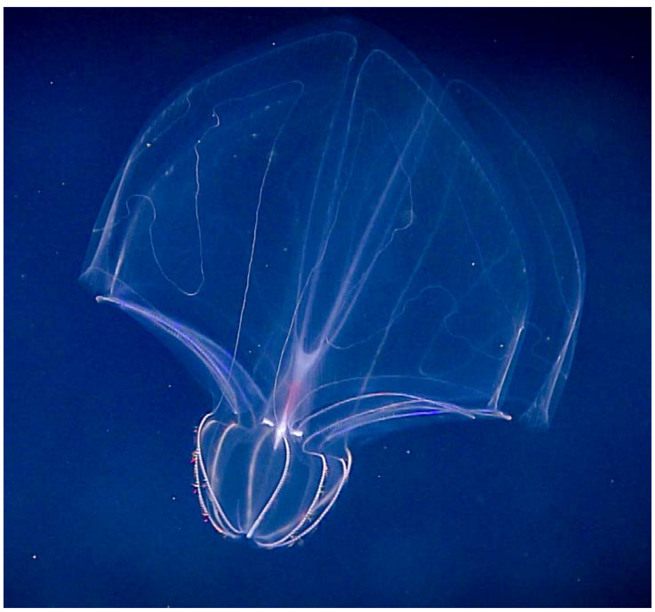


FIGURE 5. This lobate ctenophore was imaged during the water column exploration of the Windows to the Deep 2019 expedition.

The year 2019 marked the first time we could collect mobile organisms within the water column using the new suction sampler outfitted on ROV *Deep Discoverer* (Figure 3). This suction sampler is an underwater vacuum designed to collect biological samples that are too small, too delicate, or too quick to pick up using other sampling techniques. This is especially important when studying animals in the water column, as many of the species of interest are soft bodied or gelatinous and would not survive normal sampling methods like trawl nets (e.g., Figure 4). During sampling, the animals are suctioned into holding jars and then transported back to the lab for identification and analysis. The priorities for collection this year were lobate ctenophores (Figure 5) and Rhopalonematid medusae because physical samples are vital for the taxonomic identification of these groups.

In 2019, an undergraduate scholar had the opportunity to work with the data from these transects. The goal of the student's project was to better understand the distribution of the fauna in the midwater and the response of the fauna to the ROV. The scholar looked at the depth and distribution of various organisms and how they related to the presence of the deep scattering layer. In addition, the scholar looked for signs that fish and krill evade the ROV during transects, which may cause lower estimates of midwater species. Moving forward, we plan to explore other variables that may play a role in species distribution. Environmental drivers such as sea surface temperature, productivity, and the presence or absence of the Gulf Stream may play a role in faunal abundance and, consequently, frequency of sightings.

ASPIRE Explores Atlantic Margin, Prepares for Mid-Atlantic Ridge Expedition

By Caitlin Adams

In 2019, the Atlantic Seafloor Partnership for Integrated Research and Exploration (ASPIRE) campaign focused on three key areas for both mapping and ROV missions: the southeastern US continental margin, the US Mid-Atlantic, and the eastern Canadian continental margin.

ASPIRE is a multiyear, multinational project to increase knowledge and understanding of the North Atlantic Ocean. It includes 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.

Fieldwork that supports the Atlantic Seabed Mapping International Working Group has included exploring submarine canyons of the US and Canadian Atlantic continental margins, characterizing the sensitive habitats of the US South and Mid-Atlantic Ocean, and mapping deepwater areas within international waters. Efforts in 2019 also included a northeast US Technology Demonstration cruise on NOAA Ship *Okeanos Explorer* and OER's first-ever hydrographic survey contract awarded to the multinational geodata company Fugro. This survey, once completed, will add as much as 5% to the mapping coverage of US East Coast waters deeper than 200 m. A total of 11 cruises were part of the ASPIRE campaign in 2019.

ASPIRE also encompassed Northern Neighbors 2019, a joint effort of scientists from NOAA's National Marine Fisheries Service and Dalhousie University in Canada to explore the submarine canyons and continental slope off the northeast United States and Atlantic Canada, as well as the relatively shallow Gulf of Maine. This 14-day expedition was aboard NOAA Ship *Henry B. Bigelow* sailing from Naval Station Newport, Rhode Island.

Upcoming ASPIRE expeditions are being shaped by the results of a multiagency workshop held in Silver Spring, Maryland, in November 2018, as well as an online geospatial survey that has received significant feedback from a wide array of sources—academic partners, federal agencies, nonprofits, and international partners.

During the summer of 2020, OER will use *Okeanos Explorer* to conduct a 70-day expedition to characterize unexplored areas of the Mid-Atlantic Ridge and the Azores Plateau. Bisecting the Atlantic basin, the Mid-Atlantic Ridge extends for approximately 16,000 km and features a central rift valley that is about the depth and width of the Grand Canyon. This dynamic plate boundary, segmented by deep fracture zones along its length, contains numerous hydrothermal vent fields. This region is of great interest to resource managers and scientists as they try to understand the connectivity among sensitive marine habitats, such as deep-sea coral and sponge ecosystems, across the Atlantic.

Okeanos Explorer Finds Shipwreck During Shakedown Cruise

By Derek Sowers and Shannon Hoy

After its winter drydock and dockside shipyard repair period, NOAA Ship *Okeanos Explorer* set sail from Pascagoula, Mississippi, on May 12, 2019, for its annual shakedown cruise. While underway, 24-hour operations focused on preparing deep-sea mapping and water-column sonars and ROV systems for the remainder of the 2019 field season. The tight schedule was interrupted when, on the third day of ROV testing, the pilots investigated an anomaly in the ROV's forward-facing sonar and stumbled upon a previously unknown nineteenth-century shipwreck. No evidence of the shipwreck's presence was observed in the mapping data collected by the ship. Discovery of a shipwreck in this manner is exceptionally rare.

Once the onboard team figured out what the ROV's sonar was imaging, within half an hour, NOAA's Office of Ocean Exploration and Research staff were able to get several maritime archaeologists watching and narrating the live video feed through telepresence. These experts helped to interpret and guide the shipwreck exploration as it was unfolding, reinforcing the value of telepresence-enabled exploration missions.

Okeanos Explorer's Commanding Officer and the mission team agreed to extend the dive for three hours to enable a more thorough characterization of the wreck (Figure 1). The ROV captured high-resolution images, which were then assembled into a continuous mosaic of the shipwreck that experts could examine in more detail (Figure 2). No artifacts or personal belongings were found that might have given clues as to its origin or passengers, although the experts agree that construction appears to date around the 1850s.

There is some evidence of burnt wood, which could indicate a fire on board or perhaps a purposeful scuttling of the ship. But what happened to this 38 m vessel is still a mystery, according to Jack Irion, a marine archaeologist at the Bureau of Ocean Energy Management's New Orleans office who examined the photos and videos.

Three "engineering dives," including the dive during which the shipwreck was discovered, were conducted during the first part of the shakedown cruise. Toward the end of the cruise, the team completed a multibeam sonar survey of a previously unmapped area of the Straits of Florida between Key West and Cuba. The resulting new maps revealed a large plateau adjacent to numerous carbonate mounds, providing new insights into the seafloor character of this ecologically productive region.

FIGURE 1. ROV *Deep Discoverer* approaches the shipwreck.

FIGURE 2. A photomosaic of the wreck site, produced by Bureau of Ocean Energy Management Marine Archaeologist Scott Sorset, was assembled using video imagery collected during the dive. *Image credit: BOEM*

Insights from Windows to the Deep 2019

DEEP-SEA CORALS, SUBMARINE HAZARDS, AND METHANE SEEPS

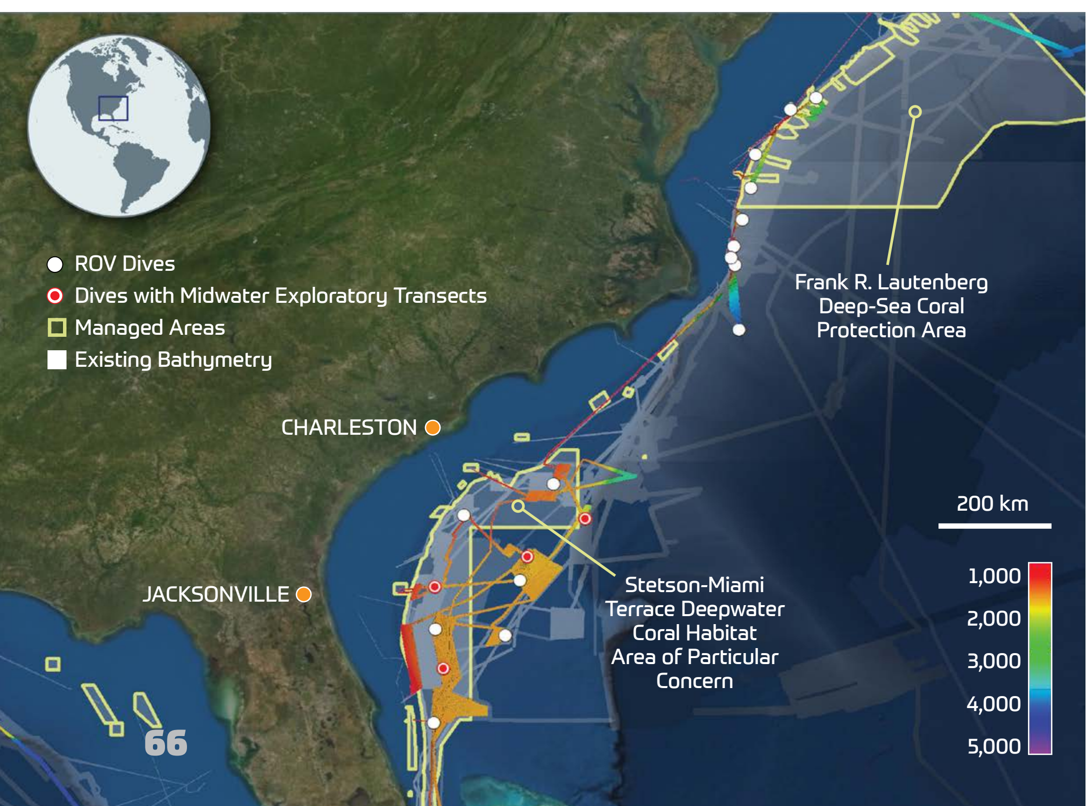
By Kasey Cantwell, Shannon Hoy, Amy Wagner, Alexis Weinnig, and Michael P. White

The ambitious 38-day Windows to the Deep 2019 ROV and mapping expedition shed new light on both the marine life and seafloor geography off the southeastern US coast. From May 30 to July 12, NOAA Ship *Okeanos Explorer* conducted 19 ROV dives, mapped 36,000+ km^2 (an area larger than the State of Maryland), and discovered a new cold seep and extensive deep-sea coral and sponge habitats. This expedition marked *Okeanos Explorer*'s 100th mission, a celebratory achievement that is a credit to the shoreside and seagoing teams who have participated in the last decade of expeditions and to NOAA's commitment to ocean exploration.

The first leg of Windows to the Deep departed from Key West, Florida, on May 30 and arrived in Port Canaveral, Florida, on June 14. It was solely focused on mapping the seafloor and water column, and these data were used to guide placement of ROV dives for the second leg, which departed on June 20 from Port Canaveral and arrived on July 12 in Norfolk, Virginia. The second leg included ROV dives as well as additional mapping operations to fill knowledge and data gaps in the region.

The mapping operations targeted high-priority areas identified by the South Atlantic Fishery Management Council, NOAA, the Bureau of Ocean Energy Management, and the science community. Deepwater mapping systems (Kongsberg EM 302 multibeam sonar, Simrad EK60 and EK80 split-beam fisheries sonars, and a Knudsen 3260 chirp sub-bottom profiler) were used to collect baseline seafloor and water column data in the region of the Blake Plateau, the Stetson-Miami Terrace Deepwater Coral Habitat Area of Particular Concern (HAPC), and the Frank R. Lautenberg Deep-Sea Coral Protection Area. The expedition mapped more than 36,000 km^2 of seafloor offshore the southeast and mid-Atlantic United States (Figure 1). Additional seafloor coverage of the Blake Plateau, offshore Florida, Georgia, and the Carolinas brings the total mapping in this area supported by the NOAA Office of Ocean Exploration and Research since 2011 to more than 49,000 km^2.

Mapping during Leg 1 revealed new features and added new data that will offer insights into our understanding of this region. In a previously unmapped area of the central Blake Plateau, the expedition team discovered mound features that are too small to be seen in satellite data but that could be resolved for the first time by the ship-mounted multibeam sonar. Subsequent ROV exploration revealed these mounds to be the result of buildup of stony coral skeletons over time. On top of the dead coral matrix that formed the substrate of the mounds, the ROV dives revealed dense



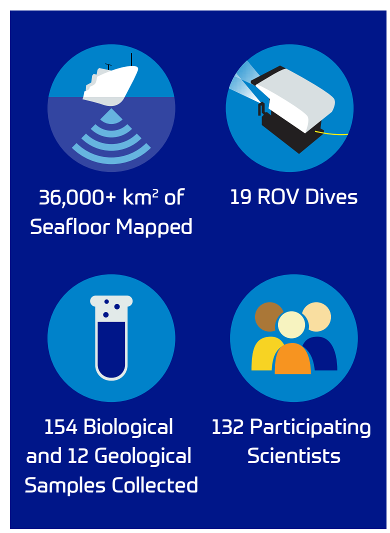


FIGURE 1. A summary map of the 2019 Windows to the Deep expedition locates ROV and mapping operations offshore the southeast and mid-Atlantic United States, including in managed areas such as the Stetson-Miami Terrace Deepwater Coral Habitat Area of Particular Concern and the Frank R. Lautenberg Deep-Sea Coral Protection Area.

and diverse deep-sea coral and sponge habitats (Figure 2). Data from this expedition open new lines of scientific inquiry about the habitats of the central Blake Plateau.

Since 2014, OER has conducted mapping operations in an area of the Stetson-Miami Terrace Deepwater Coral HAPC, also known as "Million Mounds." This area, running offshore from central Florida to the Carolinas, was named for the seemingly endless mounds that make up the southern portion of the HAPC. The expedition uncovered the first indication of the eastern boundary of the Million Mounds coral habitat. NOAA scientists now believe that the ecosystem encompasses more than 10,000 km^2 of mounding features ranging in height from 10 m to 80 m. The mounds of *Lophelia pertusa* coral have been growing for thousands and perhaps millions of years, providing shelter and habitat to a diverse range of marine life, including sponges, shrimp, crabs, and commercially important fish species.

This expedition also located new cold seeps at Bodie Island off the shore of North Carolina, and another at an unexplored extension of the Norfolk Deep Seep site. Cold seeps are important because they transfer methane carbon from long-term storage in seafloor sediments into the water, which changes ocean chemistry. The exploration of deep-ocean seeps is essential to understanding the future global carbon budget and to management of renewable energy resources. At the Norfolk Deep site, an unusual fluid seepage from the seafloor was observed, the first such seepage seen along the US Atlantic margin.

During ROV exploration, the team was amazed by the discovery of a fallen swordfish carcass being devoured by several dogfish sharks, one of which was subsequently devoured whole by a wreckfish in the Stetson-Miami Terrace Deepwater Coral HAPC (Figure 3). They also observed dozens of brooding warty octopuses *(Graneledone verrucosa)* in Wilmington Canyon. In Baltimore Canyon, the team made the first in situ observations of mating Jonah crabs, and also documented several instances of mating Chaceon crabs (both red and golden).

The expedition reached a significant public audience through direct ship visits and online views. Science leads Amy Wagner and Alexis Weinnig participated in an Instagram Takeover for the American Geophysical Union during the expedition, the cruise generated 200 news articles, and a repost of the highlight video "Oh My Grouper, Look at that Shark" received over four million views.

The 2019 Windows to the Deep Expedition built on previous expeditions in 2018 and 2014. The data collected will be used to inform future decisions about oceanographic exploration, resource allocation, and critical habitat protection.

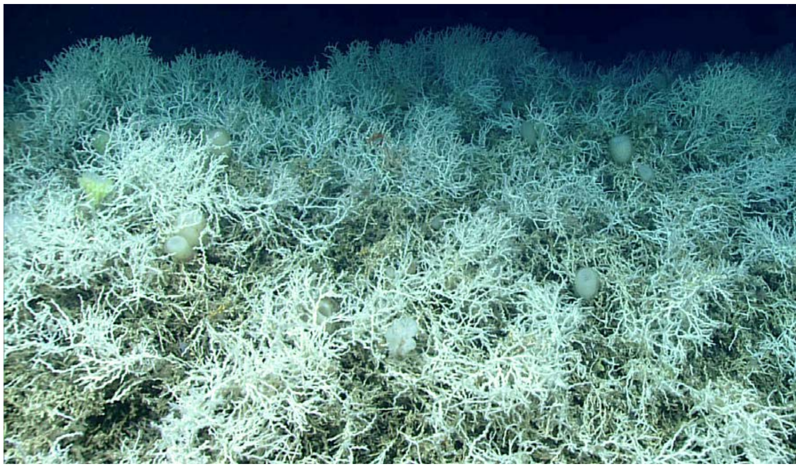
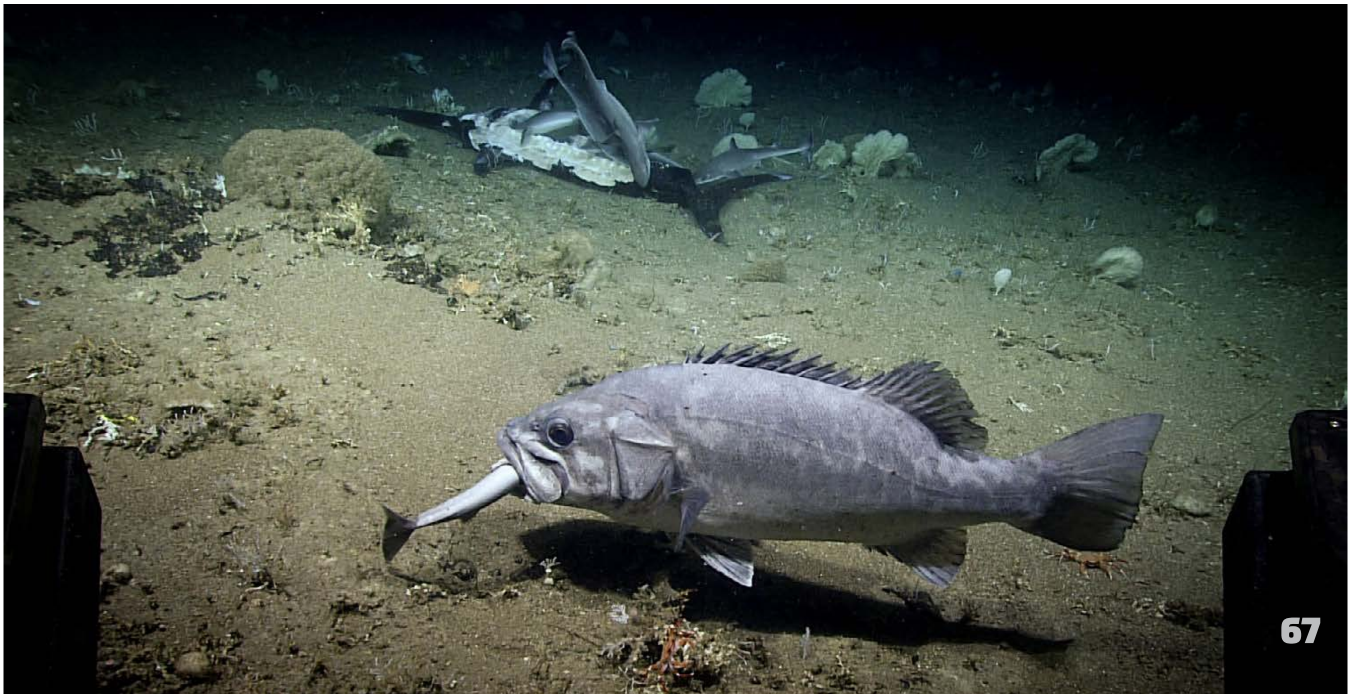


FIGURE 2. Scientists were stunned to see extensive, dense populations of coral during ROV dives on the central Blake Plateau.

FIGURE 3. During Dive 07 of the Windows to the Deep 2019 expedition, this wreckfish was observed capturing and eating a shark in the foreground of the swordfish fall.



New Ocean Technologies Prove Themselves at Sea, Discover World War II Shipwreck

By Michael P. White, Chris Beaverson, and Craig W. Russell

New technologies to explore the ocean are being developed at an increasingly rapid pace, driven by the needs of the research community to provide both scientists and the public with information about how the sea and marine ecosystems are changing, while also uncovering relics from the seafaring past. These technologies include new kinds of sonar to map the seafloor at high resolution, communications systems that are bringing vast amounts of data back to shore from ROVs and AUVs, and sampling devices that are helping to describe the chemistry and biology of rapidly changing marine ecosystems.

NOAA Ship *Okeanos Explorer* carried out technology demonstration expeditions in December 2018 and June 2019 that proved the ship is a highly efficient platform for demonstrating these new technologies and for evaluating which ones are best suited for characterizing the undersea world, while simultaneously gathering valuable oceanographic data for researchers on shore.

During a mapping and ROV expedition that departed San Juan, Puerto Rico, on November 28, 2018, and arrived in Charleston, South Carolina, on December 16, 2018, researchers from the NOAA Office of Ocean Exploration and Research, along with partners from JASCO Applied Sciences and the University of New Hampshire, deployed a deepwater mooring that housed two Autonomous Multichannel Acoustic Recorders (AMARs). These highly sensitive instruments can record soundscapes for months and are entirely autonomous. They were deployed to record the sound projected by various multibeam configurations on the ship (Figure 1). The information collected will be used to better understand the sonar's sound signature and its effect on the environment.

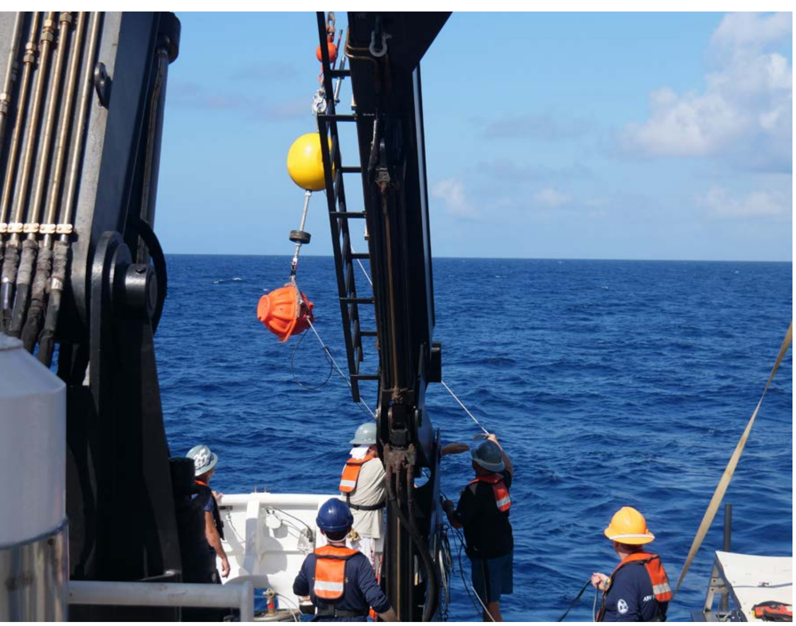


FIGURE 1. *Okeanos Explorer* crew deploys hydrophones used to listen for multibeam sonar pings in order to better understand where the multibeam transmits its sound. *Image credit: Levi Unema, GFOE*

For this experiment, the team deployed AMAR UDs (Ultra Deeps), which can be submerged to more than 6,000 m. They are housed in strong glass spheres, with each device containing two hydrophones. Each hydrophone has a different sensitivity in order to listen to different characteristics of *Okeanos Explorer*'s multibeam sonar. After testing, the mooring was released from the seafloor and recovered.

Also on this cruise, a team of undergraduates from the University of Rhode Island conducted 3D printing experiments using special stabilization technologies to keep the printer level on a moving ship. The students set up a stereolithography apparatus (SLA) style printer that uses an ultraviolet curable liquid and a laser to cure the liquid layer by layer. This results in a denser and higher-resolution print compared to the more commonly used extrusion style printers. The goal was to determine how well a GyroPro platform could stabilize the printer in a dynamic environment, an experiment that had not been done at sea before.

The students successfully printed several parts, including a complex "Devil's Playground" shape that tested the abilities of the printer to remain level as the ship moved through the water. After testing, the team printed a pressure housing to the ship's CTD rosette (Figure 2). The housing was then tested at 200 m depth along with a similar one printed on land. The results showed that both survived the pressure without losing structural integrity. Such

FIGURE 2. These pressure chambers were printed at sea by the URI team using a 3D printer. The chambers were sent to 200 m depth and successfully recovered without any leaks or structure failures.

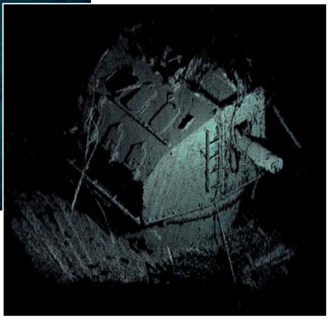


FIGURE 3. ROV *Deep Discoverer* locates *USS Baldwin*'s gun fire-control system by targeting the antenna array and cylindrical range finder located above the pilot house. Note the derelict fishing gear on the wreck. INSET. High-resolution 3D point cloud rendering from the SeaVision laser imaging system. *Image credit: Kraken Robotics and NOAA OER*

FIGURE 4. Illustration of a glider equipped with a one-way-travel-time inverted ultra-short-baseline transducer that "listens" for a signal from the surface to determine the glider's location. *Image credit: WHOI*

an expedition-deployable 3D printer could help future research missions make repairs without returning to port.

NOAA's testing of new tools for ocean exploration continued in 2019. From July 18 to August 1, 2019, NOAA and partners conducted a telepresence-enabled expedition on *Okeanos Explorer* to demonstrate, test, and evaluate five emerging and existing technologies for possible integration into NOAA operations. New technologies and novel integrations will aid and accelerate the fulfillment of OER's objective to map and characterize the US Exclusive Economic Zone by 2030. The 2019 Technology Demonstration expedition took place off the US East Coast, from Virginia to Rhode Island, in two legs.

Leg 1 operations included deployment of a REMUS 600 AUV in partnership with the NOAA Office of Coast Survey and a towed Kraken Robotics KATFISH with synthetic aperture sonar in partnership with Kraken Robotics and ThayerMahan Inc. Targets focused on the US northeast continental shelf and included areas with limited bathymetric coverage and underwater cultural heritage sites.

During Leg 2, the crew tested the integration of three technologies with ROV *Deep Discoverer*: a one-way travel-time inverted ultra-short baseline navigation system from the Woods Hole Oceanographic Institution; and a Kraken Robotics SeaVision, a compact underwater laser imaging system that delivers dense 3D point cloud images of subsea infrastructure with millimeter resolution in real time.

Originally identified using *Okeanos Explorer* mapping data collected during a 2011 mission, the wreck of *USS Baldwin* had remained silently on the seafloor until July 27, 2019, when a team led by OER used ROVs and the SeaVision laser scanner to image and document this World War II-era destroyer that sank in 1961 while under tow (Figure 3). OER baseline characterization data of the wreck are publicly available to archaeologists, historians, and other researchers.

The expedition also tested a WHOI low-power navigation system with a long-term goal of enabling remote robotic exploration of the global mid-ocean ridge and methane seeps in the Gulf of Mexico. To get to these places, autonomous gliders use GPS to determine their locations while on the surface. But GPS does not work underwater, and the accuracy of a glider's navigation quickly degrades until it comes back to the surface for another GPS fix.

The WHOI one-way-travel-time inverted ultra-short-baseline system provides gliders with accurate navigation underwater by listening for a location signal broadcast from an autonomous surface vessel (Figure 4). On the expedition, the team tested components of the WHOI navigation system inside a custom-built pressure housing mounted on the brow of ROV *Deep Discoverer*.

Overall, the testing of these technologies reaffirmed *Okeanos Explorer* as a demonstration platform while simultaneously collecting data to illuminate pressing scientific questions and inform an eager public.

OER-ONC Collaboration to Improve Video Annotations

By Mashkoor Malik, Gordon Rees, Megan Cromwell, Jessica Robinson, and Scott C. France

Underwater video imagery contributes important data to understanding and managing ocean resources. Several challenges to using video data include the need for a large amount of digital storage, users' unfamiliarity with video formats, the labor-intensive nature of video analysis, the inability to share video segments of interest with relevant experts for further analysis, and the integration of video observations with other oceanographic and environmental parameters.

Since 2016, Ocean Networks Canada (ONC) and NOAA's Office of Ocean Exploration and Research have collaborated to develop and improve video capture and annotation tools for adoption by NOAA Ship *Okeanos Explorer*. OER uses telepresence technology that enables geographically distributed experts to view and annotate high-definition video in real time as it is recorded during ROV dives. Several enhancements have been applied to ONC's annotation platform to better meet the needs of OER's remotely located participants. These improvements targeted interface usability, including implementing vocabulary standardization via the integration of the World Register of Marine Species (WoRMS) and the Coastal and Marine Ecological Classification Standard (CMECS); access to the archive-ready export of annotations and their associated environmental data; rapid annotation search function; and the capability to analyze video footage post cruise. Furthermore, enhancements to the user interface support seamless transitions from real-time to archived video data while retaining all functionality. This revised approach is ideal for both real-time and post-cruise annotating, viewing environmental data on demand, and real-time engagement by viewers.

Recent enhancements provide a map interface capable of displaying the real-time location of captured video integrated with a host of geographical data sets. These improvements have resulted in a sophisticated set of tools available through a web interface: https://data.oceannetworks.ca/SeaTubeV2. ROV video from OER (2016–present) and ONC (2006–present) expeditions are now freely available through this interface. The annotations are included in the archived video metadata, making them more discoverable and accessible than typical video data sets.

Further refinements are underway, including integration with the Ocean Biogeographic Information System (OBIS) and user-configurable options. As these tools mature, we envision expansion to other applications such as serving robust data sets to support machine-learning applications for underwater imagery, ingestion and analysis of historical underwater video, and achieving synthesis of observations to support decision-making by resource managers.

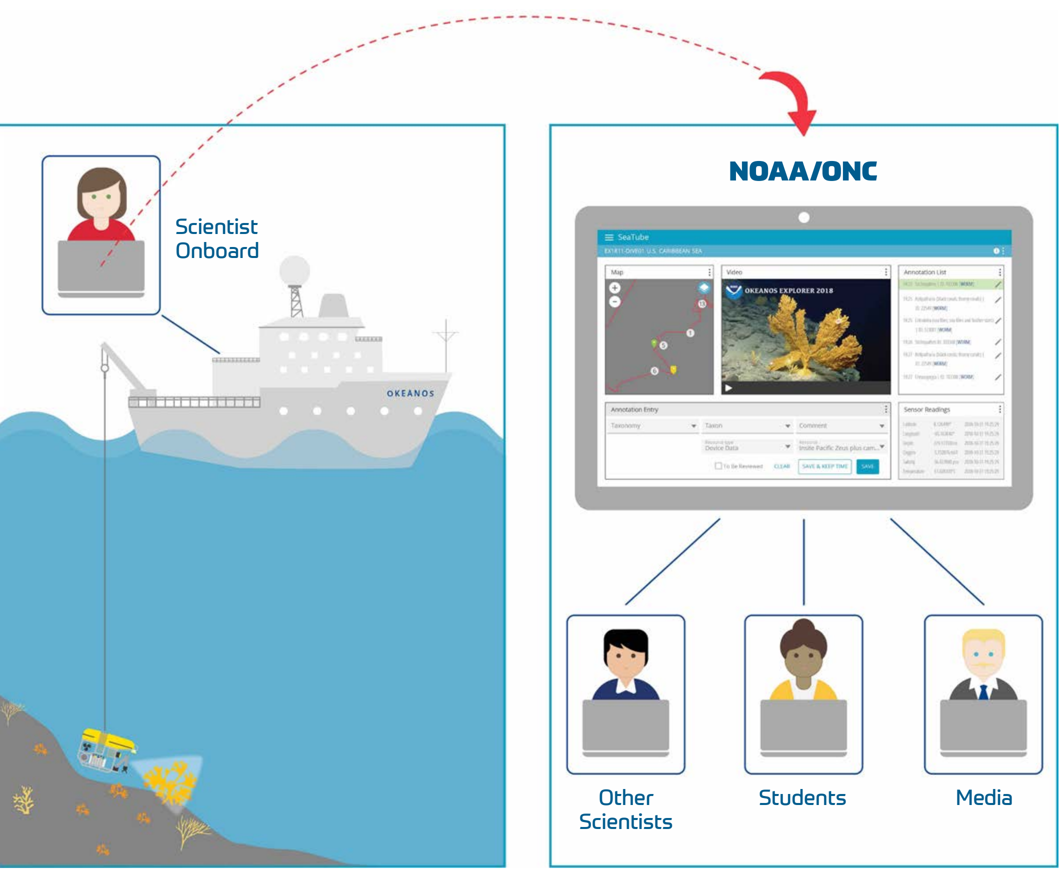


FIGURE 1. A depiction of the integrated video annotation platform SeaTube that captures real-time video footage with important corresponding data and makes it available to a broad user base dispersed throughout the globe. This software was developed in collaboration with Ocean Networks Canada to support and capture crowd-sourced video annotations applied to a suite of underwater video footage, accessible in both real-time and archived data sets. *Image credit: Ocean Networks Canada*

New Regions Explored During the Deep Connections 2019 Expedition

By Shannon Hoy and Daniel Wagner

From August 6 to September 28, Deep Connections 2019 explored poorly understood deepwater areas of the US and Canadian Atlantic continental margin (Figure 1). This two-leg mapping and ROV expedition was part of the ASPIRE campaign. NOAA's Office of Ocean Exploration and Research worked closely with many partners to address priorities recommended by US and Canadian scientists and managers and by international working groups supporting the Atlantic Ocean Research Alliance and the European Union's Horizon 2020 program. The team conducted mapping and ROV operations to identify locations of deep-sea habitats and acquired high resolution mapping data to better understand the morphology of deep-sea features. Mapping data were also collected to fill in regional data gaps and to contribute to Seabed 2030 goals for charting unexplored regions of Earth's ocean. Between the two legs, approximately 30,000 km^2 of seafloor were mapped in support of this effort.

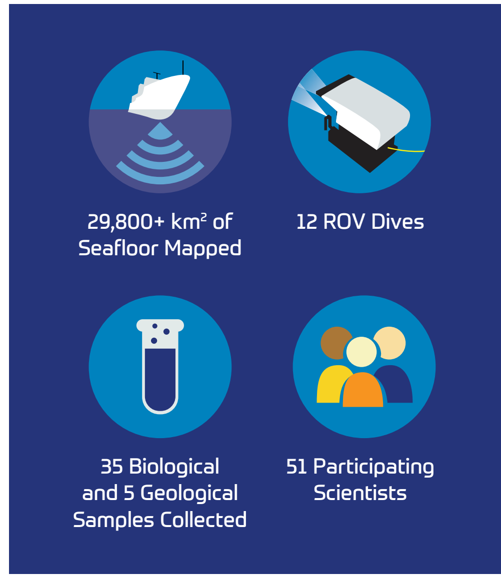
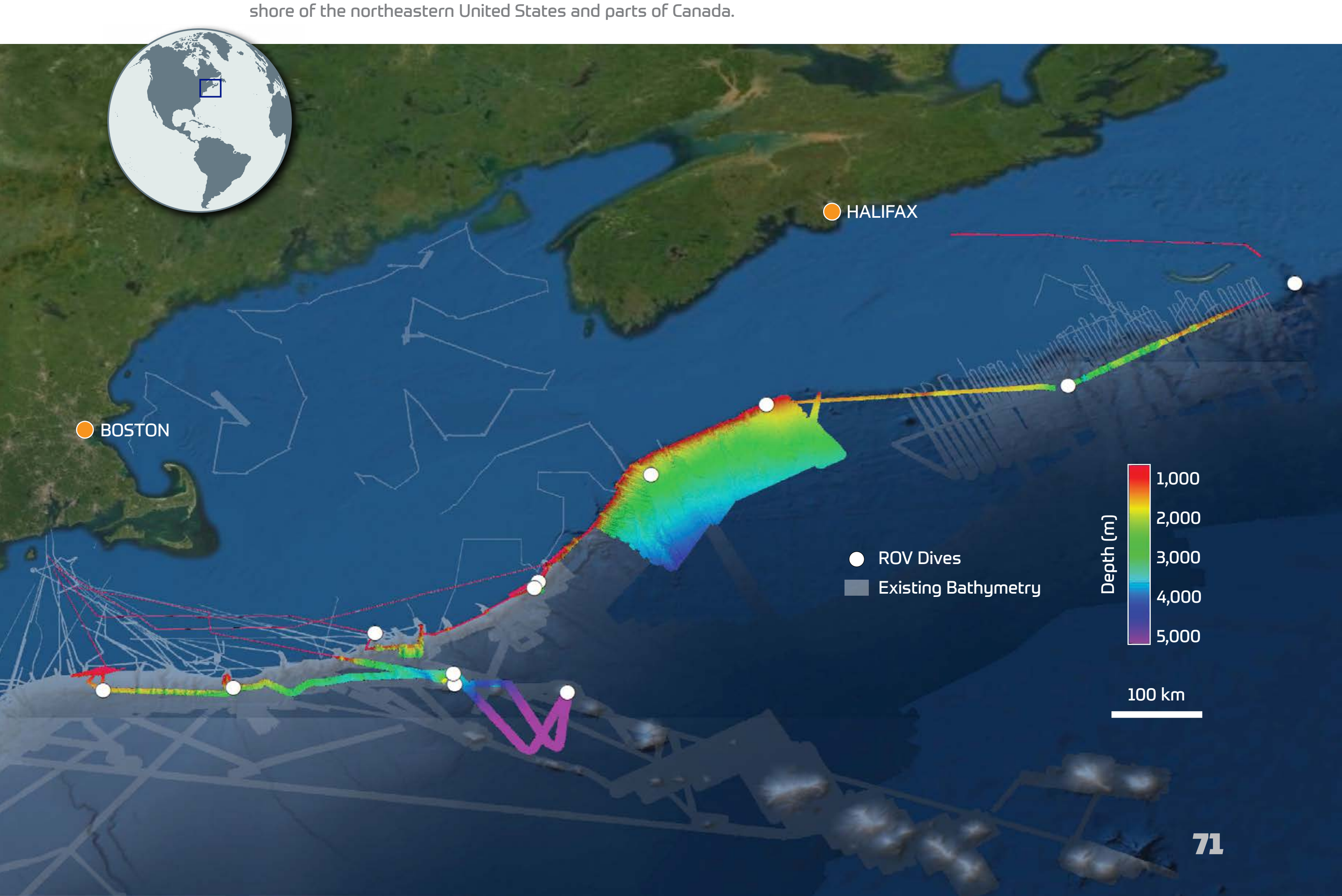


FIGURE 1. A summary map of the Deep Connections 2019 expedition showing ROV and mapping operations completed offshore of the northeastern United States and parts of Canada.



The first leg of this expedition focused on a large systematic survey of the Atlantic margin and canyons offshore Nova Scotia (Figure 2), extending the range of mapped seafloor by approximately 17,000 km^2 (about the size of Connecticut and Rhode Island combined). During the survey, the OER team also collected reconnaissance data that can be used by future attempts to find the wreck of the US Revenue Cutter *Bear* that sunk in 1963 as it was being towed from Halifax, Nova Scotia, to Boston, Massachusetts.

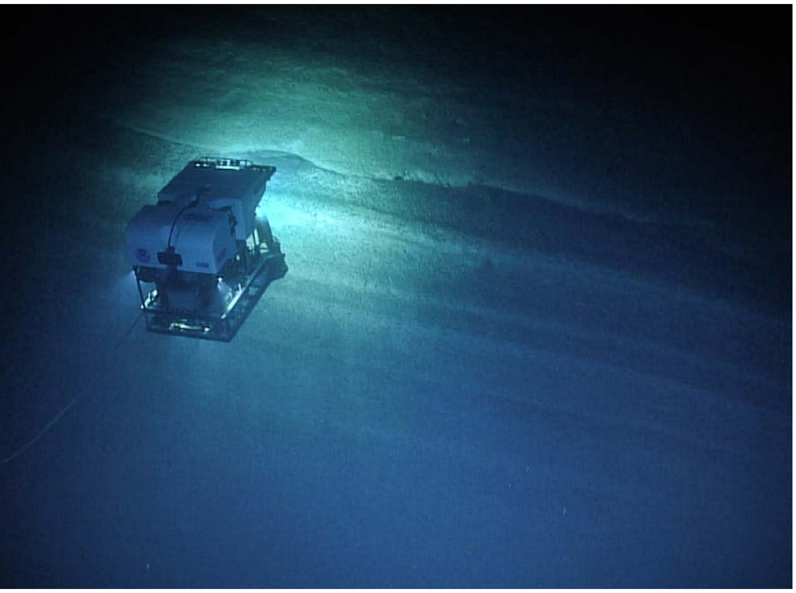


FIGURE 2. ROV *Deep Discoverer* surveys a stunning, near-vertical sequence of carbonate rock at Veatch Canyon. The wall is over 100 m tall.

The second leg of the expedition included both mapping and ROV operations. During the ROV dives, the Deep Connections 2019 team collected both biological and geological samples to improve our understanding of ecosystem connectivity, establish geologic age and composition, and facilitate identifications. Of the 35 primary biological samples collected during this expedition, 26 represent range extensions, and several more may be species new to science. These samples are now publicly available via repositories at the Smithsonian Institution and Oregon State University.

The power of telepresence allowed scientists all over the world to observe animal behaviors, associations, and forms in the context of their natural habitats in real time (e.g., Figures 3 and 4). Of particular importance were observations of several large endangered Atlantic halibut during

FIGURE 4. A lobster bites down on squid tentacles during the third dive of the Deep Connections 2019 expedition on August 31, 2019.

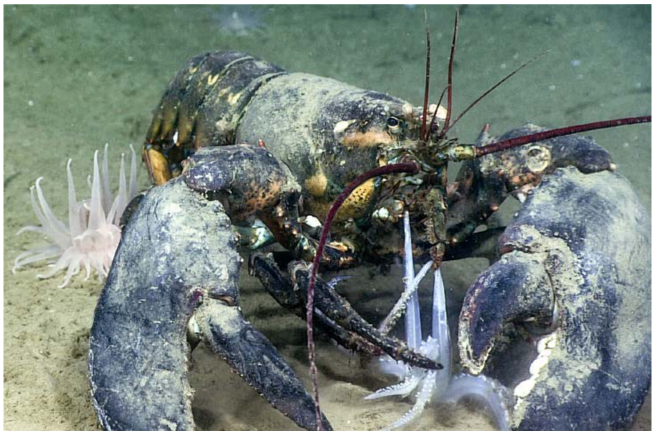
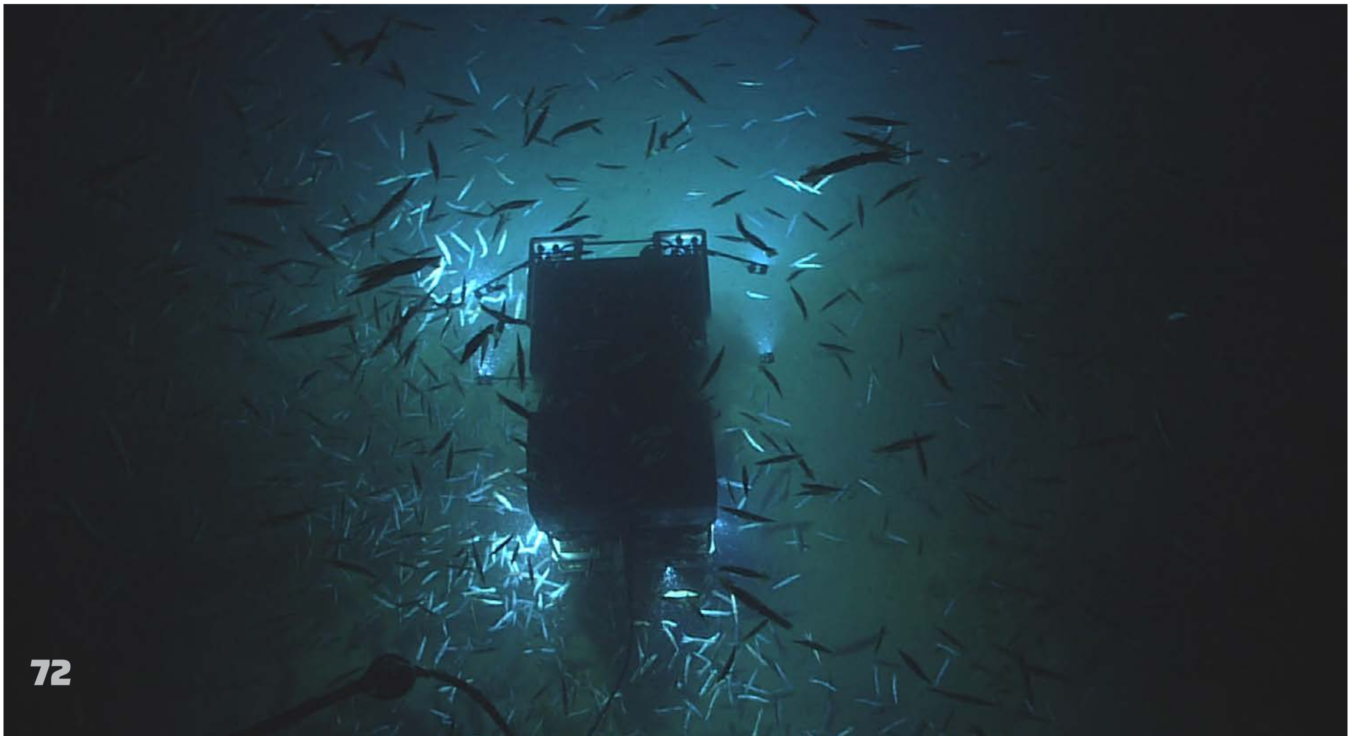


FIGURE 3. Swarms of short squid feeding on krill surround ROV *Deep Discoverer* during its descent on the third dive.



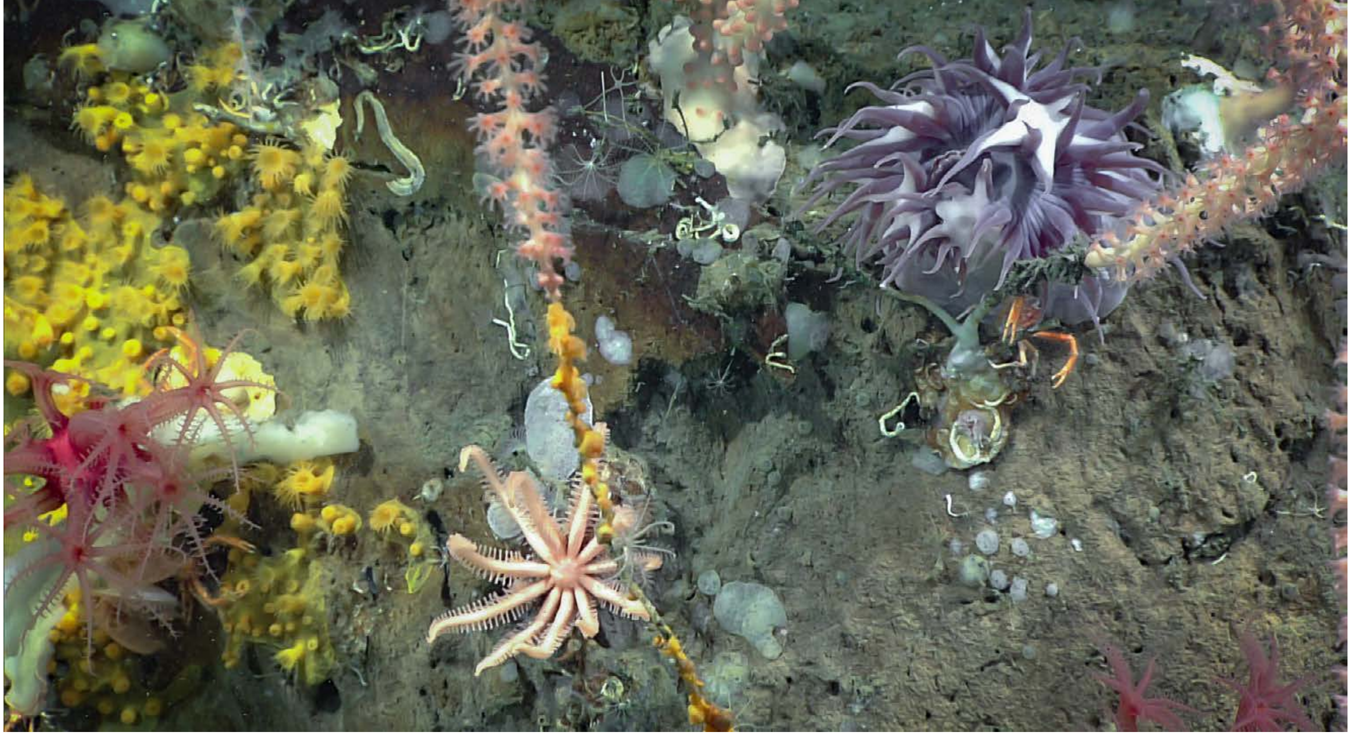


FIGURE 5. A close-up view of a diverse assemblage observed on Dive 01 inside Gully Canyon includes bamboo corals, zoanthids, encrusting demosponges, hydroids, an anemone, a *Freyella elegans* sea star, and a squat lobster.

FIGURE 6. A bubblegum coral with associated snake stars was documented during Dive 01 in Gully Canyon.

FIGURE 7. This *Graneledone verrucosa* octopus was seen on a steep sediment-covered slope on Bear Seamount during dive 8 of the Deep Connections 2019 expedition.

a dive in an unnamed deep-sea canyon north of Kinlan Canyon off the New England coast. Such observations provide resource managers with critical information that can be used to better understand where these species reside.

One exciting result of the expedition as a whole was the discovery on all 11 of the benthic-focused dives of deep-sea corals and sponges (Figures 5 and 6) at depths ranging from approximately 300 m to 2,500 m. Coral reefs that include deepwater corals and sponge grounds are some of the most important marine ecosystems on the planet because they create structures that provide shelter, food, and nursery habitat to other invertebrates and fishes.

High-density communities of deep-sea corals and sponges documented during five of the dives included a highly diverse and dense assemblage of deep-sea sponges observed on Retriever Seamount. At 2,668 m depth, this is currently among the deepest high-density communities known in the US Northeast Region. Other such communities included a high-density bamboo coral forest observed during a dive at a high-priority site for our Canadian partners in the Gully Marine Protected Area, as well as areas of high-density communities at Kinlan Canyon, Bear Seamount (Figure 7), and Veatch Canyon. These data will be important for improving the understanding and management of marine resources and increasing knowledge of deep-sea ecosystem connectivity across the Atlantic Basin.

Playing FAIR: Enabling Ocean Exploration Through Open Data Sharing

By Sharon Mesick, Susan Gottfried, Barry Eakins, Caitlin Ruby, Anna Lienesch, Clint Edrington, Jesse Varner, and Megan Cromwell

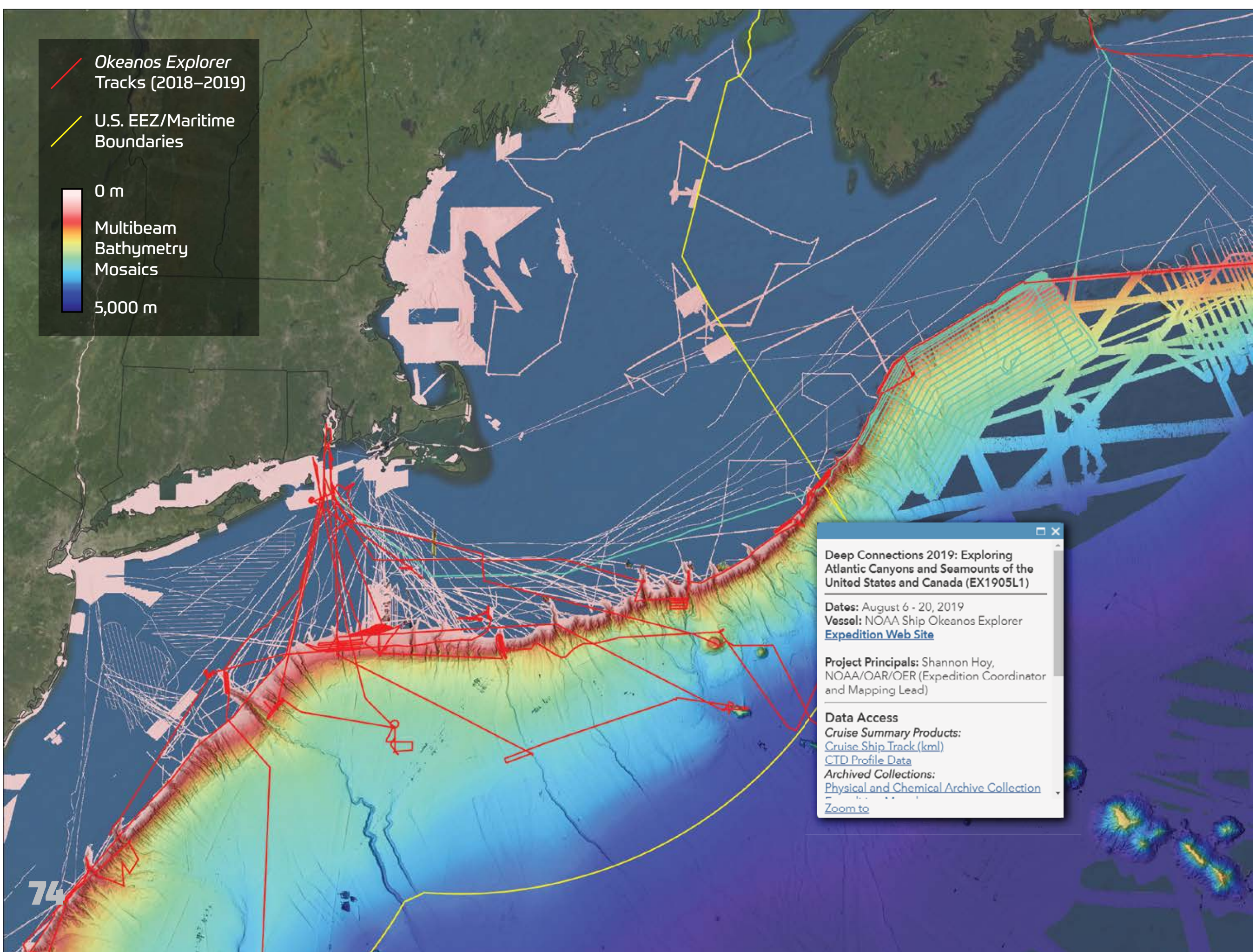
INTRODUCTION

Data are the enduring legacy of ocean exploration and hold a promise upon which the nation's economy, security, and environmental interests can rely. Realization of this promise depends on free and open data sharing. The 2001 President's Panel report, *Discovering Earth's Final Frontier: A U.S. Strategy for Ocean Exploration*, recognized the need for open data sharing and called for the "development of a comprehensive data management system focused on management of information on unique and significant features so that discoveries can have maximum impact for research, commercial, regulatory, and educational benefit."

In response, NOAA's Ocean Exploration and Research data systems were designed to "collect data and information from ocean exploration activities and share this information in such a way that is available to all stakeholders, including the general public" (Mineart, 2002a).

In partnership with OER, the NOAA National Centers for Environmental Information (NCEI) developed and operates the Cruise Information Management Services (CIMS), a collection of structured data systems and evolving services that generate rich metadata, ensure data security, and provide free public access to OER data collections through catalog-based data discovery and through public access data portals such as the OER Digital Atlas and the OER Video Data Portal.

FIGURE 1. This web map image displays NOAA Ship *Okeanos Explorer* track lines (2018–2019) with multibeam bathymetric data mosaics collated from sources including the NOAA Office of Coast Survey, the Rolling Deck to Repository program, and NOAA OER, illustrating that geospatial web services support data interoperability and reusability. *Image credit: Jesse Varner, NOAA NCEI*

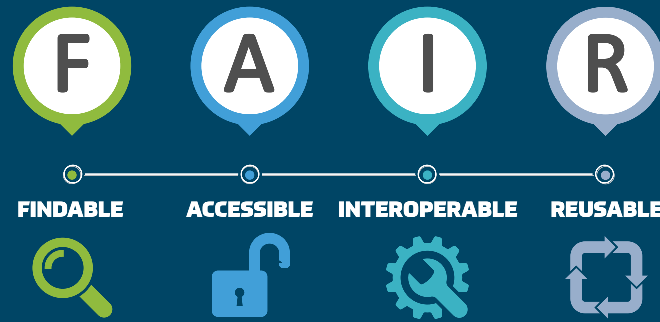


The concept of "FAIR Guiding Principles" is gaining acceptance in the scientific data community as a way to describe best data management practices that support open data sharing (Wilkinson et al., 2016). FAIR practices strive to produce data that are findable, accessible, interoperable, and reusable. OER's standards-based, free and open data sharing practices uphold FAIR principles. OER champions standards-based data management and develops and shares methods and tools to advance the practice.

ENABLING TECHNOLOGIES SUPPORT FAIR DATA

Metadata provide the information needed for anyone to make full and accurate use of a data set (Mineart, 2002b). OER data collections create rich metadata that are understandable by humans and machines. CIMS generates metadata records for OER expedition data collections using ISO 19115-2 compliant templates. OER metadata records are validated using standard rubrics and are cross-referenced with metadata repositories of similar keywords. Unique and persistent identifiers link metadata to data stewarded in the NCEI trusted repository.

OER collaborated with NCEI metadata specialists to develop ISO-compliant templates that enrich metadata. A primary example is found in the 87,000 records generated using the NCEI-initiated ISO video metadata template. OER's video metadata can include the information collated by the Ocean Networks Canada SeaTubeV2 annotation system (see page 70). Scientists' annotations are cross-referenced with standardized vocabularies, including the World Register of Marine Species (WoRMS) and the Federal Geographic Data Committee-endorsed Coastal and Marine Ecological Classification Standard (CMECS), and are combined with ancillary environmental data parameters in ISO-19115-2 records. The integration of standardized WoRMS and CMECS vocabularies into the metadata have expanded the human-generated annotations by a remarkable 450%, exponentially enhancing targeted "find and access" functions and saving endless hours of visual data review. When combined with the OER Video Portal, the human experience is further enhanced by the custom interface with dropdown lists of scientific terms, environmental parameters, and general information, and by the video data preview function.



Findable. Accessible. Interoperable. Reusable. These four characteristics define FAIR, a set of guiding principles first presented in 2016 by a consortium of researchers to describe data management practices that enable standards-based data sharing and reusability (Wilkinson et al., 2016).

OER's mission relies on open data sharing so that discoveries can have maximum impact for research, commercial, regulatory, and educational benefit. OER's standards-based, free and open data-sharing practices uphold FAIR principles. OER champions standards-based data management and develops and shares methods and tools to advance the practice.

FINDABLE. OER's data management team publishes comprehensive metadata records so that data can be found easily and quickly by both human and machine.

ACCESSIBLE. OER metadata are published to permanent NOAA metadata catalogs and include persistent links to the data they represent. Metadata records are linked to the data-use standard and to secure protocols for user accessibility.

INTEROPERABLE. Wherever possible, OER metadata and data are preserved in open-source and internationally standard formats so that they can be exchanged, interpreted, and combined with other data.

REUSABLE. OER encourages and promotes its metadata and data for reusability in future research by others. This effort increases the relevance and return on investment of the data OER collects and produces.

Another example of rich metadata support for FAIR principles is the automated generation of file-level metadata for the advanced acoustic mapping instrumentation collected aboard NOAA Ship *Okeanos Explorer*. These granular data files and their related metadata contribute to NCEI's acoustic geospatial survey maps, which allow users to find and access specific multibeam bathymetry files within a given area of interest. The compatibility of metadata and systems allows users to visualize these data through dynamic, in-house geographic information system (GIS) and data visualization tools.

NCEI has also developed a widely used template for NetCDF data, enabling access to self-describing, machine-readable data from the NCEI repository. OER was the first to apply this template to shipboard sensor data collections. The methods have since been adopted by the NOAA fleet. These and other examples describe NCEI and OER's commitment to FAIR principles through (meta)data innovation.

FAIR GEOSPATIAL SERVICES

NCEI is OER's trusted repository for exploration data, providing long-term stewardship and free public access to OER's authoritative data records. Metadata enable keyword searches and access to repository holdings. The OER Digital Atlas is a spatiotemporal index to OER's repository holdings. The atlas's data discovery functions are based on metadata keywords, and data access functions are based on persistent links to data in the NCEI repository. Data are not interoperable in the atlas.

NCEI is developing Open Geospatial Consortium (OGC) compliant web services for trusted exploration data holdings. This capability will significantly improve the FAIRness of OER data (Figure 2) and will (1) make these data more findable and accessible using intuitive map functions, (2) increase data interoperability and reduce the need for specialized software to visualize disparate data, and (3) improve the reusability of OER data for assessment, analysis, and decision support. For example, a data user will be able to view OER-related expedition ship tracks, query data collected by a specific ship, download the original data via hyperlinks, and/or incorporate the expedition service into numerous mapping applications (e.g., planning tools, real-time operation tools, and map product creation).

OER geospatial services are published on NOAA's GeoPlatform—a cloud-based GIS application using Esri's ArcGIS Online—that provides geospatial data, maps, and analytics in support of NOAA's mission. Each data type will be represented by a separate geospatial service; many versions of each service may exist to optimize certain user needs (e.g., one ship track service built for quicker visualization, another for detailed analysis). Collectively, these services will enable the public to holistically visualize OER's extensive data collections and to easily reuse the information for other purposes.

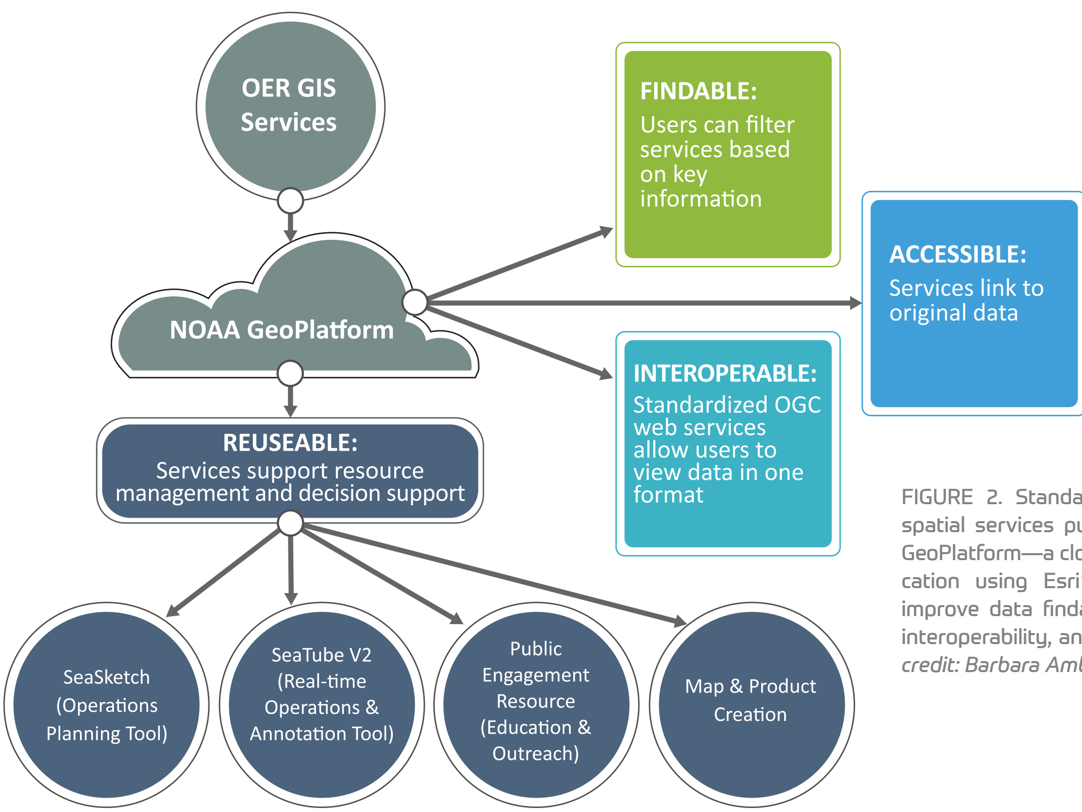


FIGURE 2. Standards-compliant geospatial services published on NOAA's GeoPlatform—a cloud-based GIS application using Esri's ArcGIS Online—improve data findability, accessibility, interoperability, and reusability. *Image credit: Barbara Ambrose, NOAA NCEI*

EXPLORATION INFORMED BY CLOUD SERVICES

Future ocean exploration scenarios envision a time when data acquisition occurs in parallel on multiple platforms, including an expanded array of unmanned systems. Data aggregation centralized in cloud locations such as "data lakes" will allow scientists to rapidly access data, analyze environmental conditions, and influence ongoing operations in near-real time. This approach has the potential to usher in a new era of ocean exploration enabled by dynamic interaction between shore-based scientists with the cloud-based data from one or more platforms (Figure 3).

Different types of analytics—from dashboards and visualizations to big data processing, real-time analytics, and machine learning—can operate in a data lake to inform near-real-time decisions. Data assembly centers (DACs) may aggregate, process, and quality control data collections, resulting in documented data in machine-readable, self-describing data formats.

Machine readability of shared data and information will support artificial intelligence/machine learning to analyze and integrate diverse ocean data and reveal patterns not easily detectable by analysis of single data sets. Information from results of such analyses will be fed back into the cloud data management system to enrich the metadata and spur further research, analysis, and product development.

OER's data systems rely on FAIR practices to optimize the management of multidisciplinary scientific data. As systems transition to cloud services, FAIR practices may be optimized as interoperability becomes dynamic and reusability happens in near-real time.

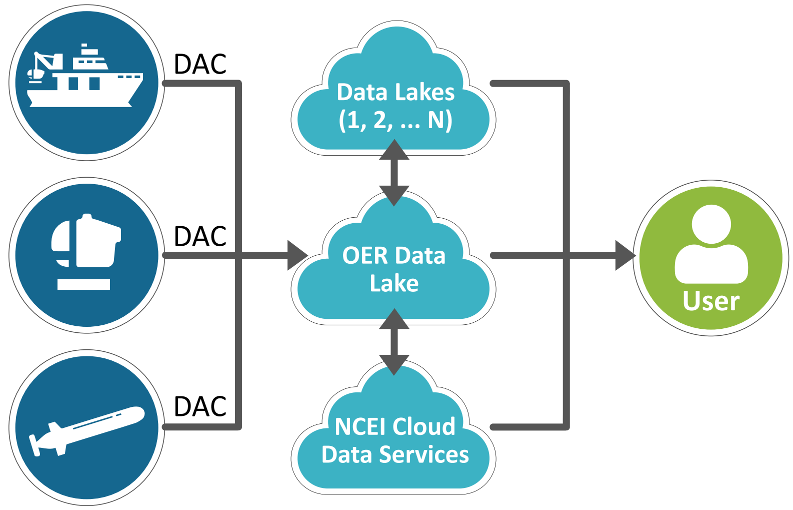


FIGURE 3. In future operational scenarios, data acquired on ocean observing platforms may be delivered to an OER "data lake," a centralized cloud-based repository that stores structured and unstructured data at any scale. Scientists may then rapidly access data, analyze environmental conditions, and influence ongoing expeditions in near-real time. Cloud-based data interoperability will be enabled by common (meta)data standards and shared services. *Image credit: Barbara Ambrose, NOAA NCEI*

SUMMARY

The future of ocean exploration is changing. It now relies more than ever on data interoperability and reanalysis. OER has established FAIR data practices in a robust framework adaptable for handling multidisciplinary scientific data from multiple sources. Application of FAIR data principles throughout the data life cycle—in combination with the realization of NOAA strategic science and technology initiatives in unmanned systems, cloud services, and artificial intelligence—will enable full utilization of exploration data to "improve our nation's understanding of our vast ocean resources and to advance the economic, security, and environmental interests of the United States" (Presidential Memorandum, 2019).

Deep Ocean Mapping in Support of Exploration

IDENTIFYING AND FILLING GAPS IN BATHYMETRIC COVERAGE IN US WATERS DEEPER THAN 200 m

By Rachel Medley, Mashkoor Malik, and Elizabeth Lobecker

Since its inception, NOAA's Office of Ocean Exploration and Research has used the best available technologies and methods to acquire bathymetric data of the deep seafloor in unexplored areas. OER views such data acquisition as a fundamental component of ocean exploration, and it also supports resource identification and improved understanding of deepwater ecosystems. NOAA's systematic approach to mapping all US waters also supports the Seabed 2030 objective to completely map the world ocean by 2030. OER generally focuses on exploring waters beyond the continental shelf (~200 m and deeper) and therefore most of OER activities are conducted in these depths. Given the many challenges inherent in mapping and exploring such deepwater regions, they remain the least explored globally and within the US EEZ. OER purposely devotes the majority of its exploration efforts to these unknown, or poorly known, regions.

Recognizing the challenge of mapping such a vast ocean region, close coordination of future mapping efforts among various partners is paramount as is discovery of data holdings that are not currently in publicly available archives. OER is tracking these endeavors and reporting on mapping activities funded by OER using NOAA Ship *Okeanos Explorer*, E/V *Nautilus*, and other platforms and mechanisms. As of September 2019, OER had contributed ~19% of all mapping data collected within the

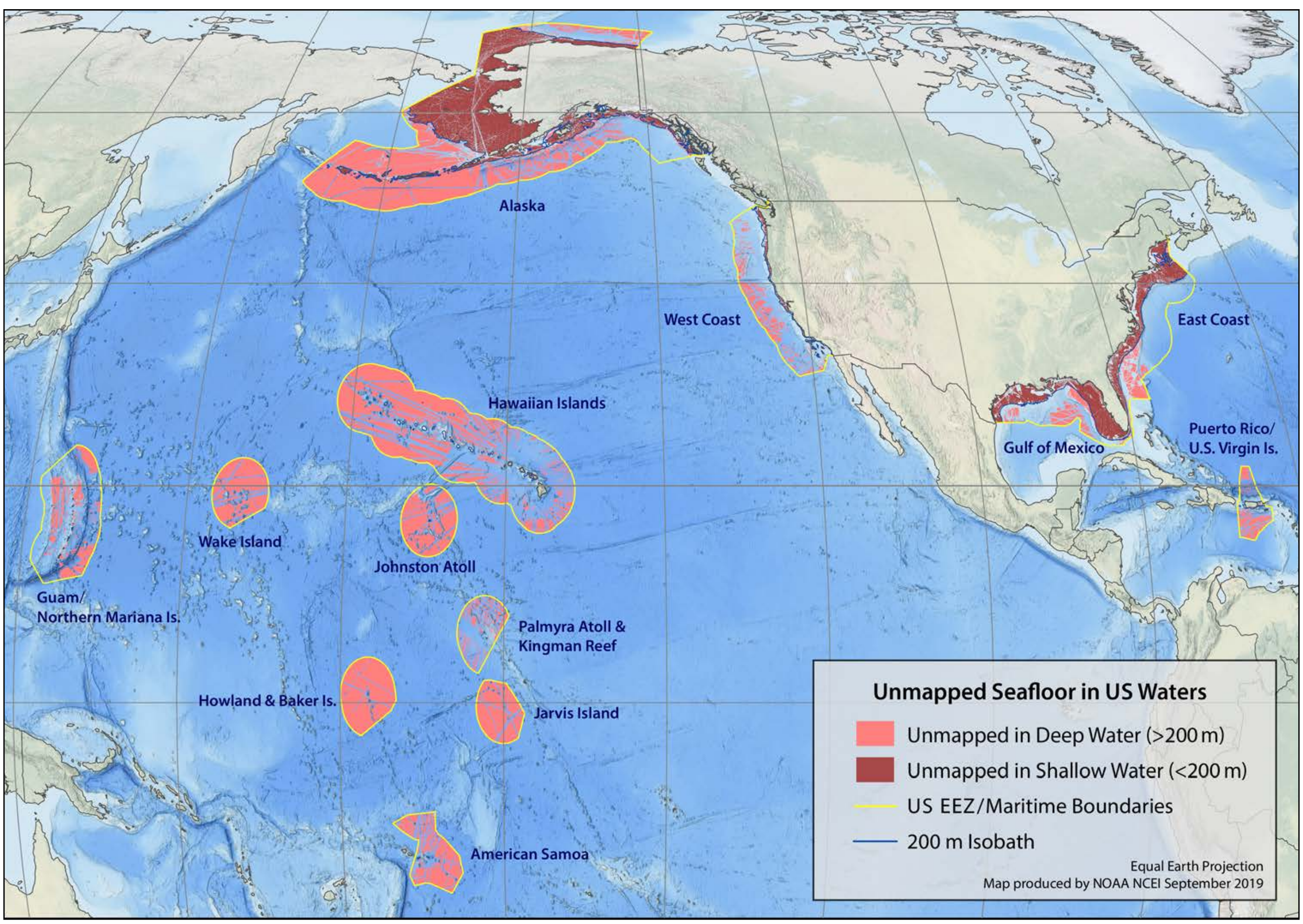


FIGURE 1. Bathymetric Gap Analysis results are produced based on the publicly held multibeam sonar data at NCEI (August 2019). This analysis and corresponding figure were created by Westington and Varner (2019) and NCEI, respectively. (Updated September 2019)

US EEZ >200 m depth and archived by NOAA. In FY20, it is anticipated that OER-funded cruises will contribute an additional 2% mapping coverage for depths greater than 200 m within the US EEZ.

OER and NOAA's Office of Coast Survey (OCS) and National Centers for Environmental Information (NCEI) collaborated to develop methods to identify and compute the areas in US waters with depths greater than 200 m that have been mapped (Figure 1). As of August 2019, it was calculated that approximately 51% of the seafloor deeper than 200 m was mapped to modern standards within US waters. For this analysis, the area of US waters with depths greater than 200 m was split into 13 regions for computational purposes and to provide a benchmark against which progress can be measured.

An area equal to ~5,000,000 km^2 remains unmapped and unexplored, with the largest gaps between 5,000 m and 6,000 m water depth (Figure 2). OER and its partners are using the analyses noted to help select future sites to explore as well as collaborative partnership projects and funding opportunities to pursue.

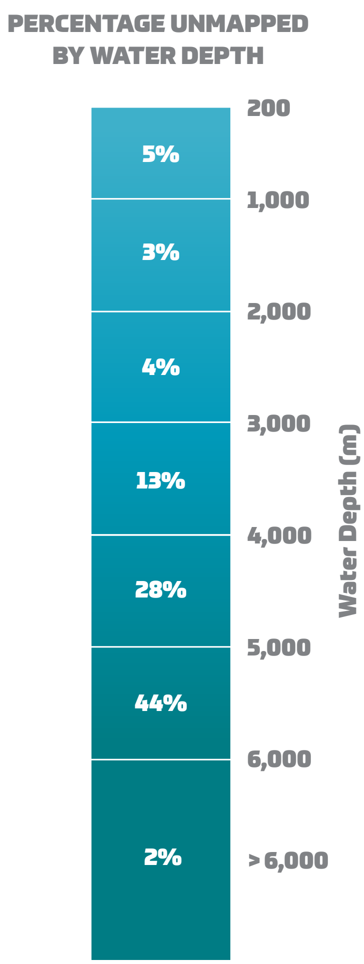


FIGURE 2. Distribution of unmapped areas as a percent by water depth (only displaying areas within US waters >200 m depth).

US EXTENDED CONTINENTAL SHELF PROJECT

Delivering Transformational Understanding of the Geology and Dynamics of US Continental Margins

By Margot Bohan and US ECS Project Partners

Under international law, every coastal nation is entitled to delineate the outer limits of its continental shelf beyond 200 nautical miles from shore. Within this extended continental shelf, the coastal state has sovereign rights over the natural resources on and beneath the seabed.

Defining the most seaward reach of our nation's continental shelf requires collection and analysis of large amounts of data that describe the depth, shape, and geophysical characteristics of the seabed and subseafloor.

When the multiagency US Extended Continental Shelf (ECS) Project was added to the President's budget in 2008, NOAA's Office of Ocean Exploration and Research assumed NOAA's project coordination responsibilities. Participation has involved 36 cruises on 15 different vessels to 10 ocean regions that amassed hundreds of terabytes of data during ~1,000 days at sea, spanning 16 years. More than 3,300,000 km^2 of seafloor were mapped, an area equal to approximately one-third of the land area of the entire United States and larger than all but 12 nations' exclusive economic zones. Revealed in the process were several previously undiscovered seamounts in the Arctic Ocean and Central Pacific and a 1,400 m high gas plume, likely methane, emanating from an amphitheater-like landslide on the northern California margin.

By harnessing combined scientific and data management expertise, the ECS project has not only improved understanding of this maritime zone's natural resources, it also pioneered an open data policy to ensure data availability within 180 days of each cruise's completion, enabling scientists and resource managers to readily access and use the data to inform subsequent science and management pursuits.

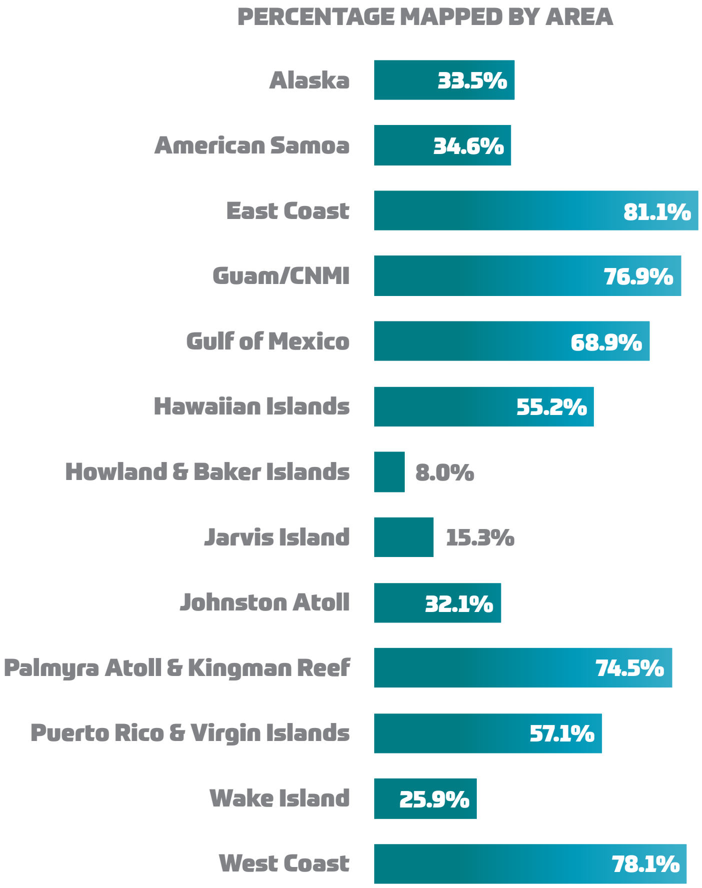


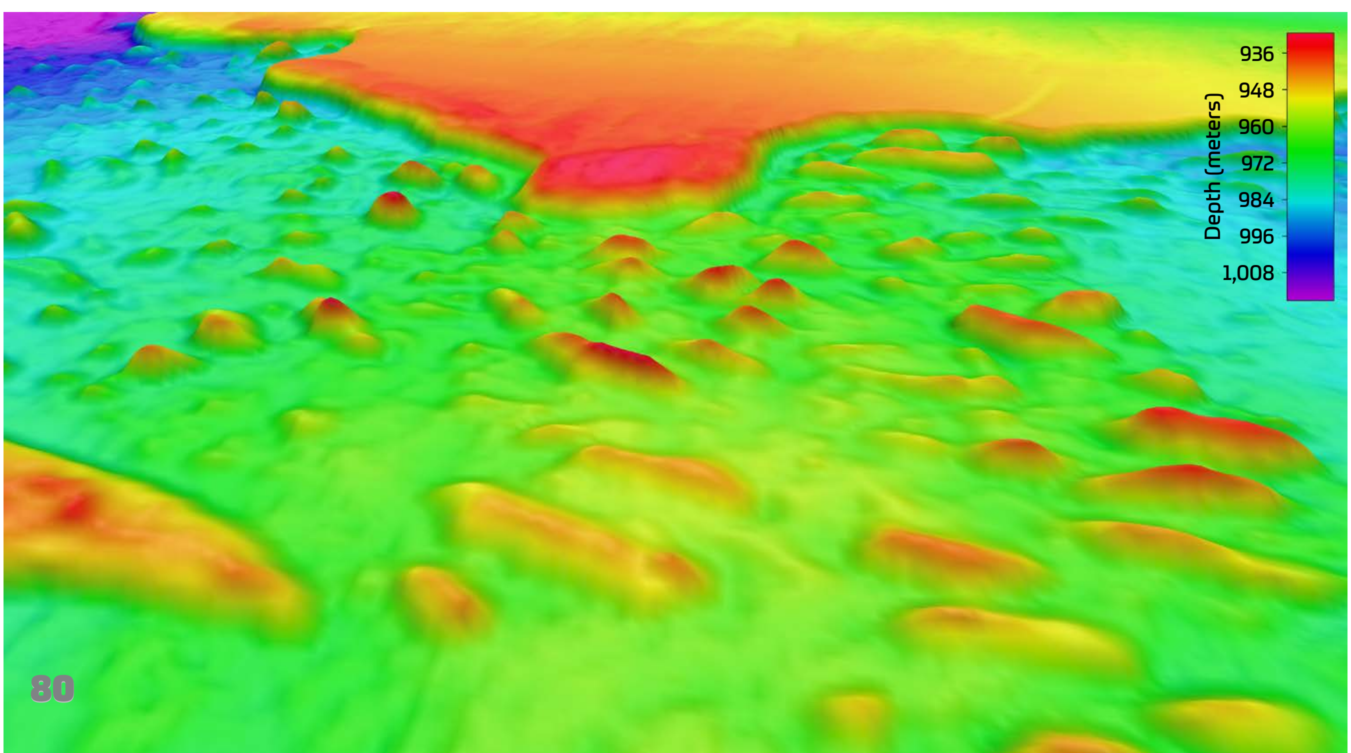
FIGURE 3. Estimates of the percentage of each US EEZ region mapped at >200 depth as of 2019 based on publicly available data holdings at NOAA NCEI. Thirteen separate deep ocean regions were designated to promote standard and consistent computation and reporting of area mapped vs. unmapped. (Updated September 2019)

Mapping data distribution is not uniform across US EEZ regions (Figure 1). For contiguous US regions (East Coast, West Coast, Gulf of Mexico), a higher percentage of waters is mapped, in contrast to many areas in the Pacific and Alaska regions (Figure 3) where there are large gaps in coverage.

OER is leveraging its mission to explore the deep ocean and make ocean exploration data more accessible by filling mapping data gaps within US and international waters. NOAA-wide efforts are providing critical deep-ocean data, information, and the awareness needed to sustain and accelerate the economy, health, and security of our nation (e.g., Figure 4). The bathymetric gap analysis is integral to situational awareness of what still remains unmapped within the US EEZ and will be updated twice a year (January and July) in support of better coordination among various government and nongovernment mapping entities.

The national goal of fully mapping US waters will only be accomplished through strong coordination and partnerships among federal agencies, academia, and the private sector. As NOAA continues to contribute to meeting the objectives set forth in Seabed 2030, additional partnerships, initiatives, and technologies are coalescing to accelerate the project. Over the next decade, OER will explore a variety of operating modes, funding mechanisms, and technologies; leverage fit-for-use applications for deep ocean exploration; prioritize the systematic mapping of unexplored US deep waters; and, with its NOAA partners, consistently track progress toward fully mapping US waters.

Figure 4. A three-dimensional perspective view of multibeam bathymetry collected by NOAA Ship *Okeanos Explorer* in the Straits of Florida showing a newly mapped plateau and numerous adjacent mounds and ridges.



DEEP SEARCH Project Completes Last Year of Fieldwork with Two Successful Expeditions

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

In 2019, the Deep Sea Exploration to Advance Research on Coral/Canyon/Cold seep Habitats (DEEP SEARCH) project completed its third and final field season with two successful expeditions aboard NOAA Ships *Ronald H. Brown* and *Nancy Foster*.

A MULTIYEAR, MULTIAGENCY STUDY

Funded by the Bureau of Ocean Energy Management (BOEM), the US Geological Survey (USGS), and NOAA's Office of Ocean Exploration and Research, DEEP SEARCH is a multiyear, interdisciplinary study to explore and characterize sensitive deep-sea habitats—submarine canyons and methane seeps—and deep-sea coral communities in the US south and mid-Atlantic. The project is managed by TDI-Brooks International, and principal investigators include scientists from six US academic institutions, one non-US academic institution, and five USGS science centers.

The project study area encompasses the majority of the BOEM Mid-Atlantic and South Atlantic Outer Continental Shelf planning areas, spanning deepwater offshore areas from Virginia to Georgia. With such a large study area, the field research program was designed to be comprehensive, utilizing multiple platforms and technologies. In 2017, NOAA Ship *Pisces* deployed AUV *Sentry* in the area to generate initial maps of potential study sites. In 2018, NOAA Ship *Okeanos Explorer* added significant multibeam bathymetry coverage, which was then used to plan an R/V *Atlantis* expedition with HOV *Alvin* and choose a site for deployment of two benthic landers from R/V *Brooks McCall*.

In 2019, the DEEP SEARCH team completed the program's final and most intensive field season, with a spring expedition on NOAA Ship *Ronald H. Brown* with ROV *Jason* and a fall expedition on NOAA Ship *Nancy Foster*. Both expeditions returned to sites identified by the earlier missions and significantly expanded our knowledge of the US southeastern continental margin.

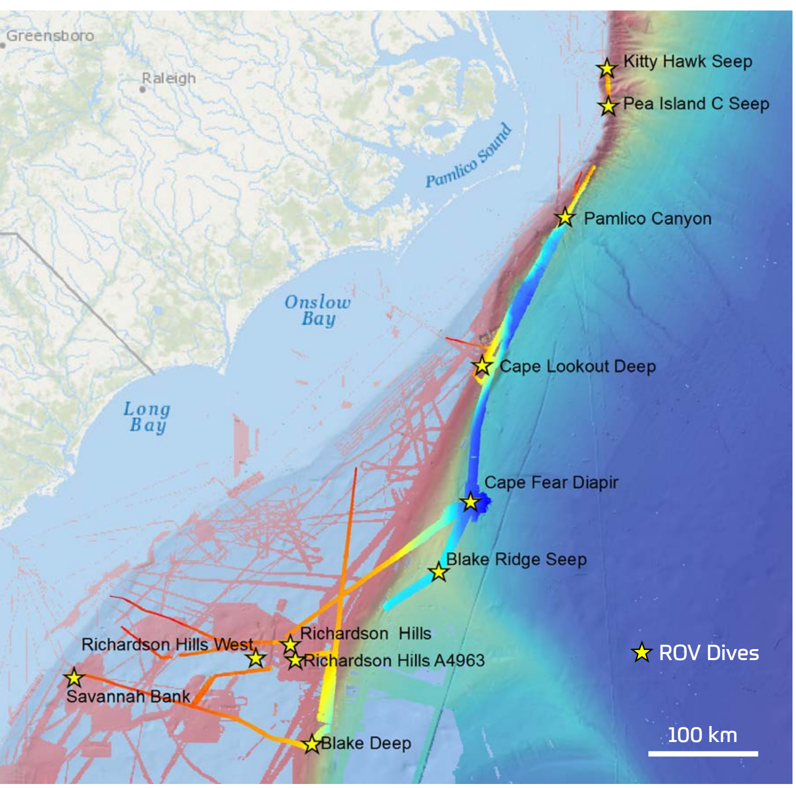


FIGURE 1. Map showing the DEEP SEARCH study area, with multibeam mapping data collected by NOAA Ship *Ronald H. Brown* overlaid on existing bathymetry coverage. ROV *Jason* dive sites are indicated by yellow stars. *Image credit: USGS*

NOAA SHIP *RONALD H. BROWN* EXPEDITION

From April 9 to 30, 2019, the DEEP SEARCH team conducted a research expedition on *Ronald H. Brown* with ROV *Jason*. Eleven dives, ranging in duration from four to 24 hours, were completed at one canyon, four seeps, and five coral sites from 200 m to 2,600 m depth (Figure 1). An additional 6,733 km^2 of multibeam bathymetry were acquired, and more than 1,600 biological and geological samples were collected with the ROV, by CTD, and with a monocore.

The team continued work at the Richardson Hills reef complex first characterized in 2018 and explored new sites to verify coral habitat prediction models. A benthic lander from the Royal Netherlands Institute for Sea Research was redeployed at Richardson Hills to collect long-term environmental data on the coral habitat (Figure 2). A sharp

FIGURE 2. The deck crew of NOAA Ship *Ronald H. Brown* launches the Netherlands Institute for Sea Research benthic lander for a long-term seafloor deployment near the coral mounds of Richardson Hills. *Image credit: DEEP SEARCH 2019 - BOEM, USGS, NOAA*

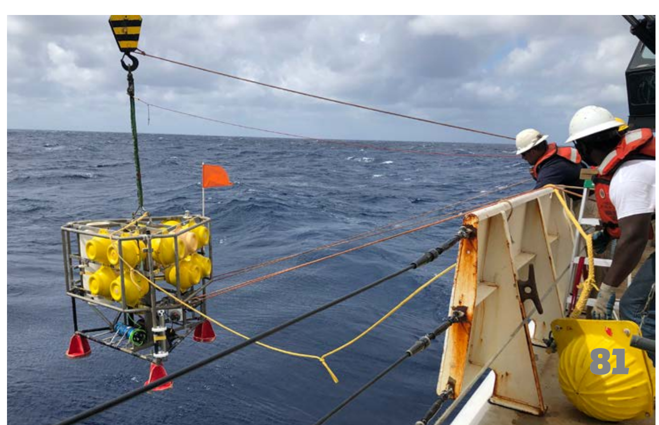


FIGURE 3. At Pamlico Canyon, canyon walls were covered in brisingid starfish and a diversity of octocorals and stony corals. *Image credit: Ivan Hurzeler, BOEM, USGS, NOAA, ROV Jason, ©WHOI*

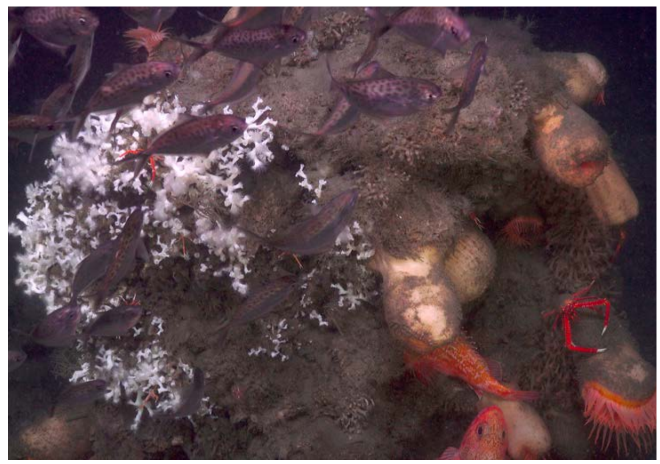


FIGURE 4. At Pea Island Seep, the team observed a small colony of *Lophelia pertusa* that had settled on carbonate rock and that attracted abundant fish. *Image credit: Ivan Hurzeler, BOEM, USGS, NOAA, ROV* Jason, *©WHOI*

thermocline was observed at the Richardson Hills site at the same depths as the highest cover of live corals, suggesting the presence of internal waves that can influence food supply and nutrients available to the corals.

The dive within Pamlico Canyon revealed eroded walls with sculpted outcrops and sharp overhangs covered in cup corals and octocoral sea fans that create habitat for a variety of fishes and octopuses (Figure 3). The benthic lander deployed at the site in October 2018 remained in place and continued to collect data about the current dynamics and other characteristics of this complex system.

At the northern extent of the study region, the team explored two recently discovered seeps (~300 m depth) and found that they are more complex and dynamic systems than previously understood. The carbonates produced as a byproduct of methane oxidation provide hard substrate for deepwater coral settlement, which in turn increases the complexity of the habitat that harbors a diverse fish assemblage (Figure 4). Vestimentiferan tubeworms, which had never been observed in this part of the Atlantic before, were discovered at both Kitty Hawk and Pea Island seeps. Two deeper seeps at Blake Ridge and Cape Fear were sampled intensively and will provide a good comparison with the shallower seeps.

NOAA SHIP *NANCY FOSTER* EXPEDITION

In October 2019, the DEEP SEARCH team spent nine days at sea on *Nancy Foster* to complete the last major fieldwork of the project. The benthic lander deployed at Richardson Hills was successfully recovered, bringing with it nearly seven months of environmental sensor, acoustic, and video data. Water sampled at four sites will be used to assess water chemistry, microbial and metazoan diversity, and environmental DNA. Midwater trawling of the deep scattering layer was accomplished at Blake Ridge Seep, Pamlico Canyon, and Richardson Hills. The data from these trawls will be used to examine the ecological interactions between the seafloor and the water column.

ANALYSIS UNDERWAY

With three years of fieldwork complete and thousands of samples now back at more than 10 research labs, the DEEP SEARCH team will continue to analyze data and develop a final report through 2021. The results of this study will be used to further understanding of these sensitive deepwater habitats and help BOEM make informed management decisions.

EXPRESS EXpanding Pacific Research and Exploration of Submerged Systems

By Elizabeth Clarke, Tom Laidig, Jeremy Potter, and Craig W. Russell

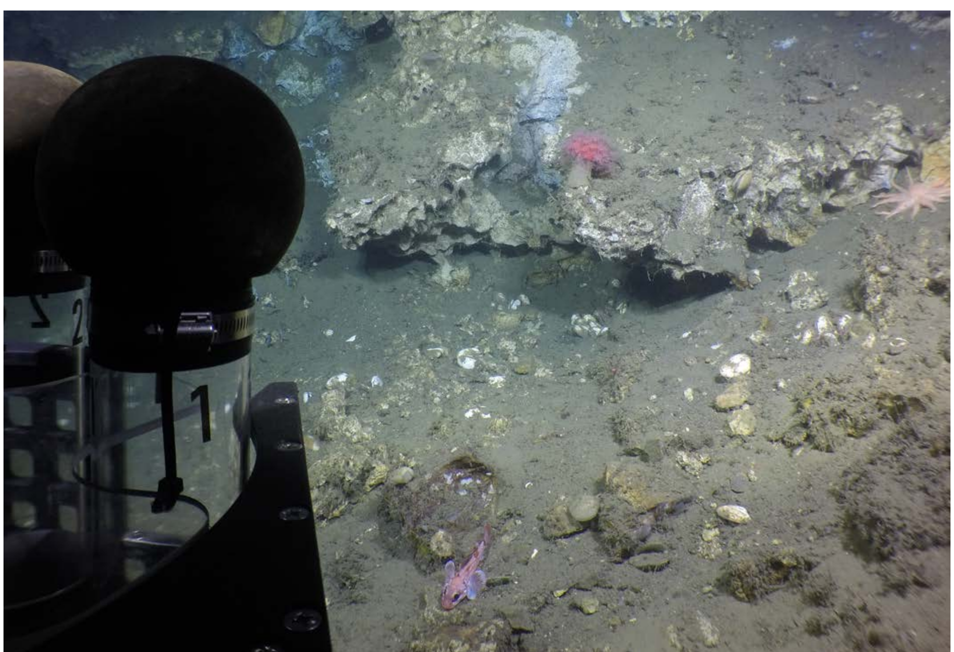
From October 7 to November 7, 2019, a team of scientists and engineers from NOAA, the Global Foundation for Ocean Exploration, the US Geological Survey, and the Bureau of Ocean Energy Management completed a 29-day expedition aboard the NOAA Ship *Reuben Lasker* along the California, Oregon, and Washington coasts, including sites within four national marine sanctuaries. The expedition was a part of the EXpanding Pacific Research and Exploration of Submerged Systems (EXPRESS) initiative, a multiyear, multi-agency project to survey and map undersea habitat and associated biota throughout the California Current Large Marine Ecosystem.

The mission collected essential fish habitat baseline information at 12 sites along the West Coast and characterized undersea habitat to inform prospective offshore wind energy decisions in northern and central California. The Pacific Fishery Management Council had proposed modifications to these habitats to better support commercially important groundfish.

Seventeen dives were conducted using ROV *Yogi* and its partner camera and lighting sled *Guru* (Figure 1), which are owned and operated by GFOE, and 20 dives were made with AUV *Popoki*, owned and operated by NOAA (Figure 2). Dives were completed in 15 locations, from Willapa Canyon, Washington, to Catalina Basin, California. ROV operations included over 50 quantitative visual surveys to assess the abundances of corals, sponges, and fishes. A minimum of 79 fish, 32 sponge, and 32 coral taxa were observed during the dives. The AUV collected approximately 200,000 images for quantitative analysis by automated image analysis software. Over 110 samples and specimens of corals, sponges, and water were collected by the ROV for eDNA analysis. Twenty CTD casts were conducted, and a monocore attached to the instrument's bottom collected a mud core on most CTD drops. All of these data will be analyzed in the coming months to provide a better idea of the coastwide distribution of deep-sea corals, sponges, and fishes, as well the associations between the corals and fishes.

Another accomplishment was the first use of GFOE's portable 1.7 m VSAT system to live stream ROV dives to the public from a NOAA Fisheries vessel. There were also three live interactions with shore, two to The Exploratorium in San Francisco and one to Pierpont Elementary in Ventura, California. A port event held with The Exploratorium in October 2019 provided federal, state, local, and academic partners and stakeholders the opportunity to learn about expedition results, tools, and vehicles, and to discuss future collaborations. Learn more at https://oceanexplorer.noaa.gov/explorations/19express/welcome.html.

FIGURE 1. A photo taken using the GFOE camera sled *Guru* shows a carbonate outcrop that provides suitable habitat for "mushroom" coral and evidence of active fluid venting supporting chemosynthetic clams and bacterial mats (white-gray zones). *Image credit: NOAA/USGS*



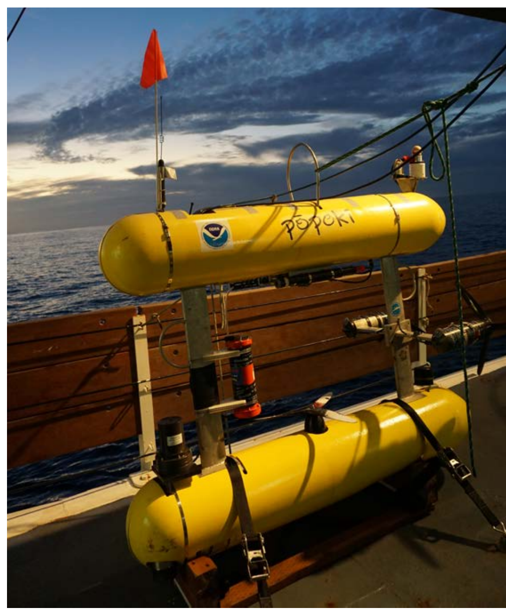
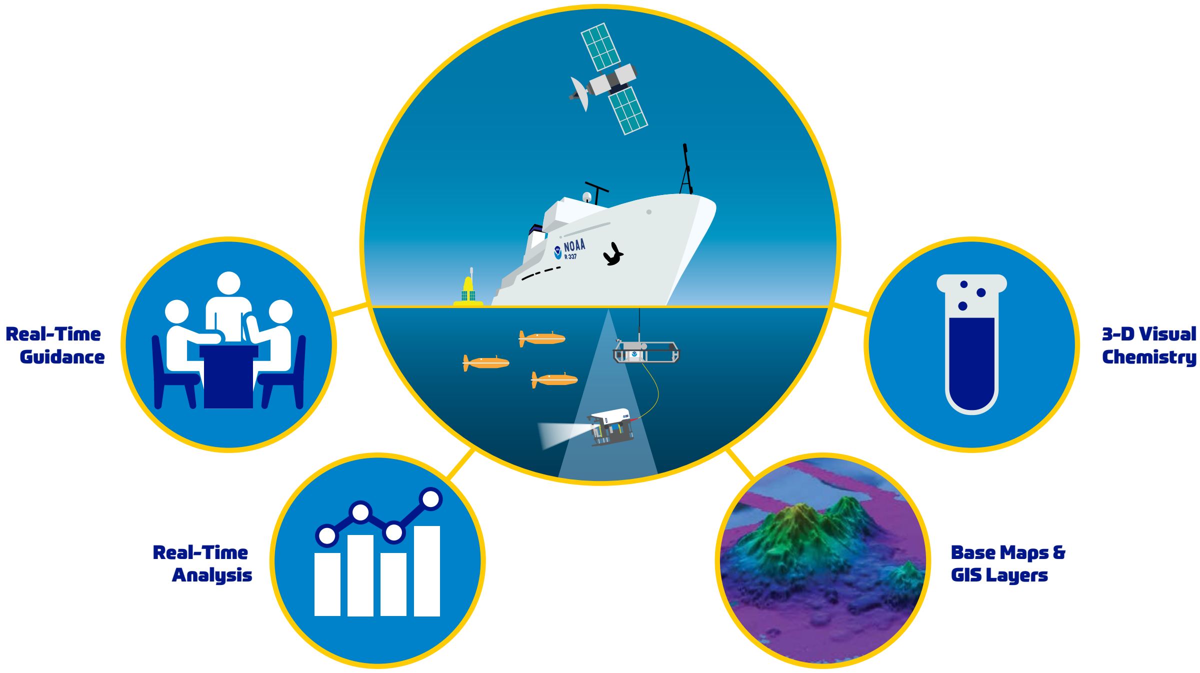


FIGURE 2. AUV *Popoki is ready* for operation on deck of NOAA Ship *Reuben Lasker*. *Image credit: NOAA/USGS*



Telepresence 2.0 Connecting Scientists and the Public to the Undersea World

By James Rawthorne and David McKinnie

Not too long ago, when seagoing scientists wanted to share what they discovered, they would take their samples or data back to their labs, collaborate on a paper, and send it off for publication to a journal where colleagues could read about the findings months later. Today, marine researchers can connect to a large audience of fellow scientists and the public through telepresence, a system that uses live video feeds from ROVs, high-bandwidth Internet connections, and satellite communications. For the past decade, NOAA Ship *Okeanos Explorer* has brought compelling scenes of marine life and seafloor geography to millions of online viewers and researchers. Telepresence has allowed experts from around the world to join the expedition remotely, identifying potential new species, shipwrecks, or underwater formations.

Now, NOAA's Office of Exploration and Research is embarking on an ambitious new "Telepresence 2.0" that will further push the boundaries of scientific collaboration. With upgraded data transmission speeds, cloud storage, and new kinds of data platforms, scientists will be able to view the undersea video feed while simultaneously monitoring streams of chemical, thermal, and other scientific data. The latency has already been reduced and access significantly improved during upgrades in the past two years. OER personnel are working to reduce that lag time even further to give researchers more precise control over ROVs and AUVs. Previously, scientists wanting the highest resolution video feeds had to be at one of NOAA's Exploration Command Centers based at academic institutions. As NOAA transitions to Telepresence 2.0, researchers are able to access this high-resolution feed on their personal laptops, and in time, via mobile devices.

The next step is Telepresence X.0, a system with multiple points of collaboration beyond a video camera to computer link. Scientists will be able to assemble three-dimensional visual chemistry models in real time from measurements taken by sensors on ROVs, AUVs, or nearby instrument arrays. Expedition coordinators will be able to create full situational awareness with base maps and GIS layers assembled using data from shipboard instruments, nearby gliders, Argo profiling floats, or other sources. That means increased efficiency during the cruise and improved chances of reaching scientific targets.

As NOAA moves to complete the Seabed 2030 project goals of fully mapping the US Exclusive Economic Zone, it will rely more on autonomous mapping vehicles to fill in the gaps. Telepresence 2.0 and X.0 systems will ease this transition from ship-based mapping to more remote data collection, allowing scientists to interpret and analyze data from their offices, while giving the public a deeper understanding and appreciation of the ocean.

Engagement

Access, Experience, and Knowledge

Introduction

By David McKinnie, Emily Crum, Susan Haynes, Debi Blaney, Monica Allen, and Joanne Flanders

The focus in 2019 was on enhancement and expansion. How can we improve access to information, provide new opportunities to learn, and reach more people? How can we further equip policymakers, educators, and the public with knowledge and tools that inform our missions? The year's engagement efforts included new partners, some international, and a port call that opened the ship to visitors in the most populous of Canada's three Maritime provinces, Nova Scotia. There was also an increase in "armchair" explorers. More people were involved than we expected. It was a very good year for OER. Highlights follow.

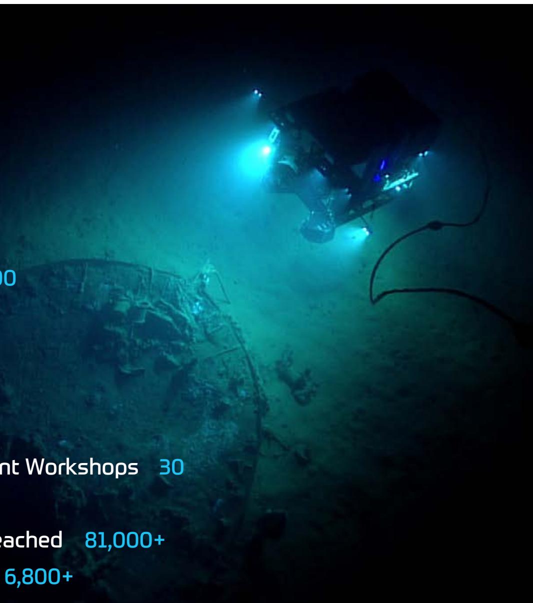
ONLINE COMMUNICATIONS

OER's online communication efforts are centered on the website https://oceanexplorer.noaa.gov/. The majority of its content is structured around OER-supported expeditions, allowing users, from shore-based scientists to the public, to follow, understand, and experience ocean exploration. During 2019, the site received more than 4.3 million page views of mission logs, daily updates, images, and videos, as well as educational materials that were posted in conjunction with 18 different ocean exploration expeditions.

Two popular sections of the website designed to increase public understanding of marine resources—"Ocean Facts" and the Education Theme pages—were overhauled in 2019 to update content and make them more visually appealing and accessible. The addition of two new interactive timelines—one celebrating 10 years of the collection of ocean exploration data from NOAA Ship *Okeanos Explorer* and the other covering the history of ocean exploration—now further allow site visitors to explore and understand the evolution and importance of ocean exploration.

Throughout the year, OER continued to use social media to entice more people to become involved in the ocean exploration experience. OER's presence on the combination of Facebook, Twitter, Instagram, and YouTube grew to reach more than 491,000 followers. Live video continued to be a top draw, with armchair explorers around the globe racking up more than 535,000 views and 170,000 hours of

2019 BY THE NUMBERS



WEB

Website Visits ~4,300,000

Live Video Views ~535,000

Expeditions Covered
- 7 *Okeanos Explorer* Cruises
- 10 non-*Okeanos Explorer* Cruises

Expedition Content Added
- ~275 content essays
- ~900 images
- ~65 videos

SOCIAL MEDIA

Facebook Followers ~145,000

Instagram Followers ~72,200

Twitter Followers ~188,300

YouTube Subscribers ~85,700

PUBLIC OUTREACH

Ship Tour Attendees ~60

In-Person Event Attendees ~8,600

Live Interaction Attendees ~320

Media Mentions ~590

EDUCATION

Educator Professional Development Workshops 30

Educators Trained 672

Estimated Number of Students Reached 81,000+

Listserv/Newsletter Subscribers 6,800+

OER Education Facebook Followers ~1,200

Teacher at Sea 1

watch time as discoveries streamed live from expeditions aboard *Okeanos Explorer* to the OER YouTube channel.

Combining efforts on https://oceanexplorer.noaa.gov/ with OER social media platforms allowed scientists, resource managers, students, members of the general public, and others to actively experience ocean exploration, expanding available expertise, cultivating the next generation of ocean explorers, and engaging the public in exploration activities.

MEDIA AND OUTREACH

In 2019, the https://oceanexplorer.noaa.gov/ website and OER social media accounts helped to generate buzz about exploration activities. These efforts caught the eyes of media outlets, resulting in more than 590 OER-related news reports filed in print, radio, television, and online media, including the Associated Press, NPR, CNN, ABC, *The Washington Post*, *The New York Times*, *National Geographic*, the *Daily Mail*, *Newsweek*, Gizmodo, and *Smithsonian* magazine. Top stories included the accidental discovery of a shipwreck during *Okeanos Explorer's* shakedown mission (page 65), the recorded first sighting of a giant squid in US waters, and rare footage of sharks feeding on a swordfish fall (page 67).

OER engaged more than 8,900 people through in-person and telepresence-enabled events associated with 2019 *Okeanos Explorer* expeditions. Live telepresence interactions were conducted with a wide range of groups and institutions, including the Santa Barbara Museum of Natural History Sea Center, North Carolina Aquariums, the University of New Hampshire's Center for Coastal and Ocean Mapping/Joint Hydrographic Center, Mystic Aquarium, the New England Aquarium (Figure 1), and Harbor Branch Oceanographic Institute. Additionally, the ship was open for touring during a port call in Dartmouth, Nova Scotia, Canada (Figure 2).

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

EDUCATION

The year 2019 was highly engaging for ocean explorers. The OER Education Team provided a number of products to highlight important work and discoveries for educators and students, including webinars, teacher professional development workshops, live interactions, and inspiring highlight videos.

The year began with 45 participants from 22 states and four countries engaging with the education team and two expedition science leads for the first OER Year in Review webinar for educators. This webinar shared exploration highlights from the Gulf of Mexico, along the southeast US continental margin, and off of Puerto Rico and the US Virgin Islands. Additionally, in June, more than 75 educators gathered for an exciting webinar focused on the Journey into Midnight: Light and Life Below the Twilight Zone expedition with world-renowned explorer Edie Widder.

It was also a dynamic year for educator professional development offerings. As one of 30 professional development workshops OER supported across the country, OER Education Alliance Partners at the Hawai´i Institute of Marine Biology and Waikīkī Aquarium, both part of the University of Hawai'i at Mānoa, hosted a workshop in April 2019 for educators in American Samoa in cooperation with National Marine Sanctuary of American Samoa and the Tauese P.F. Sunia Ocean Center. Through the workshop,

FIGURE 1. During the Deep Connections 2019 expedition, a live interaction between the *Okeanos Explorer* team and New England Aquarium drew a crowd of over 160. *Image credit: New England Aquarium*

FIGURE 2. Global Foundation for Ocean Exploration Engineer Dan Rogers gives visitors a close-up look at ROV *Deep Discoverer* and its technological features during ship tours held in Dartmouth, Nova Scotia.

FIGURE 3. Participants at an educator professional development workshop at the EcoExploratorio show off their certificates. *Image credit: NOAA OER, EcoExploratorio*

25 Samoan educators participated in hands-on STEM activities and became familiar with a multitude of resources to engage their students in the world of ocean exploration, both locally and beyond.

OER's reach was further expanded by developing a full OER Education Alliance Partnership with the EcoExploratorio Science Museum in Puerto Rico. There, 38 educators participated in a winter workshop, with more workshops planned for the future (Figure 3).

In an effort to increase engagement opportunities for students, OER partnered with a team at the Inner Space Center at the University of Rhode Island Graduate School of Oceanography to develop a program offering live interactions directly from the ISC into schools across the country. This effort reached 240 kindergarten to college students and piloted a quality method to broaden OER's reach beyond interactions directly with *Okeanos Explorer* (Figure 4). One participating teacher shared: "I'm being flooded with comments from the staff about how wonderful the presentation was and how enthralled the kids were! Thank you so much for…the opportunity. We are a small school with many kids who don't get too many opportunities and this was amazing!"

In 2019, new video efforts highlighted the excitement of ocean exploration. During the Windows to the Deep 2019 expedition, through a partnership with Silvergate Media and using their animated underwater adventurers the Octonauts, OER released a behind-the-scenes look at *Okeanos Explorer* (Figure 5). Octo-Cadets (children typically age three and up) watched the video online to see first hand exploration aboard a state-of- the-art vessel. And, in collaboration with NOAA Ocean Today, OER created a video showcasing some of the most exciting deep-sea discoveries made throughout the year. The 2019 Deep Dive Greatest Hits was released as part of Ocean Today's Every Full Moon video series, featuring some of the amazing underwater discoveries made by *Okeanos Explorer,* E/V *Nautilus*, and R/V *Point Sur*, including never-before-seen feeding frenzies and ferocious tugs-of-war on the seafloor as well as an attack by a giant squid.

FIGURE 4. OER Education Program Manager Susan Haynes talks to 120 K–6 students in Massachusetts via the Inner Space Center at the University of Rhode Island. *Image credit: Inner Space Center*

FIGURE 5. OER Senior Education Specialist Debi Blaney and NOAA Ship *Okeanos Explorer* Commanding Officer Eric Johnson visit with the Octonauts on the ship's bridge. *Image credit: Art Howard, GFOE*

Additionally, as engagement partnerships between OER, the Ocean Exploration Trust, and the Schmidt Ocean Institute continue to grow, the first tri-ship exploration findings publication for educators, *Ocean Exploration Driven Forward through Partnerships*, was developed. All three organizations now provide this product as a resource for educators, and there are plans for regular updates.

In the international arena, OER participated in the 7th European Marine Science Educator Association (EMSEA) conference hosted by ExpoLab (part of the Ciencia Viva Science Centre Network) on São Miguel Island, Azores, and delivered a presentation about the ASPIRE campaign and OER education products. The conference was well attended with representatives from 19 countries and laid an educational foundation for OER exploration of the Mid-Atlantic Ridge.

Demonstrating NOAA's Commitment to Diversity, Equity, and Inclusion

By Catalina Martinez, Mashkoor Malik, Susan Haynes, Elizabeth Lobecker, Kasey Cantwell, and Shannon Hoy

NOAA's Office of Ocean Exploration and Research continues to demonstrate a strong commitment to diversity, equity, and inclusion by participating in NOAA-wide recruitment and retention efforts, by helping with initiatives to improve the workplace climate, and through intentional efforts to reach a more diverse audience, a need identified by a recent external review of the OER Education Program. OER is also informed through membership in the NOAA Diversity and Professional Advancement Working Group (DPA WG) that was created in 2014 to address the issues and challenges associated with diversifying the NOAA workforce.

In collaboration with the NOAA Office of Education, OER is working with the Ocean Discovery Institute (ODI) in San Diego to determine how best to engage students and educators who come from diverse, under-resourced communities. As part of ODI's rolling Scientist in Residence (SIR) program where students interact with scientists who represent the cultural and ethnic diversity of their City Heights community, OER Regional Program Manager Catalina Martinez spent six weeks with ODI's newly opened Living Lab (Figure 1). She participated in several initiatives, including engaging with City Heights teachers and ODI students and personnel to assess barriers to accessing ocean science content, educational opportunities, and career paths. Throughout the residency, Catalina mentored students, participated in career development efforts, and hosted weekly ocean exploration education sessions. Live programming from NOAA Ship *Okeanos Explorer* was also successfully piloted through the Inner Space Center located at the University of Rhode Island during two ODI Living Lab events held in the summer of 2019.

FIGURE 1. NOAA OER Regional Program Manager Catalina Martinez (fourth from right) working with Ocean Discovery Institute (ODI) Science Empowering Students (SES) in the ODI Living Lab. SES pairs high school mentors with middle school students and scientist mentors to address scientific questions. This group was measuring length and weight of fish as part of a seal prey study led by Stephanie Nehasil, a PhD candidate at University of California San Diego, in collaboration with NOAA Fisheries. Students were investigating how changes in sea surface temperature may be affecting the nutritional quality of California sea lion prey species, such as fish and squid. Stephanie will incorporate these data into models that examine the relationship between changes in sea surface temperature, the nutritional quality of prey, and sea lion pup production.

Working with teams across NOAA, OER personnel helped to increase the agency's presence at important conferences for engagement with groups historically and consistently underrepresented in STEM, such as the Society for Advancement of Chicanos/Hispanics and Native Americans in Science (SACNAS), the American Indian Science and Engineering Society (AISES), Inclusive SciComm, the National Conference on Race and Ethnicity (NCORE), and the Society for Women in Marine Science (SWMS). This year, OER personnel also participated with broader geoscience diversity initiatives through the American Geophysical Union (AGU) to engage in dialogue around challenging topics through panel discussions, film screenings (Figure 2), and facilitated workshops. OER also contributed to NOAA's Diversity Hiring Event designed to showcase diverse career opportunities in NOAA, with the goal of using special hiring authorities to recruit individuals from groups underrepresented in the agency workforce.

Working with NOAA's Office of Inclusion and Civil Rights and the Department of Commerce (DOC) Office of

FIGURE 2. A panel discussion followed a screening of URI Professor of Journalism/Media Kendall Moore's documentary film titled "Can We Talk 2: Difficult Conversations with Underrepresented People of Color: Sense of Belonging and White Allies in STEM" at the 2019 AGU Fall Meeting in San Francisco. Moore is at the podium, and panelists, who were also in the film, from left to right, are: Vernon Morris (Howard University), Aradhna Tripati (UCLA), Brandon Jones (NSF), and Catalina Martinez (NOAA OER). The film received a standing ovation. *Image credit: Kadidia Thiero, Significant Opportunities in Atmospheric Research and Science, Boulder, CO*

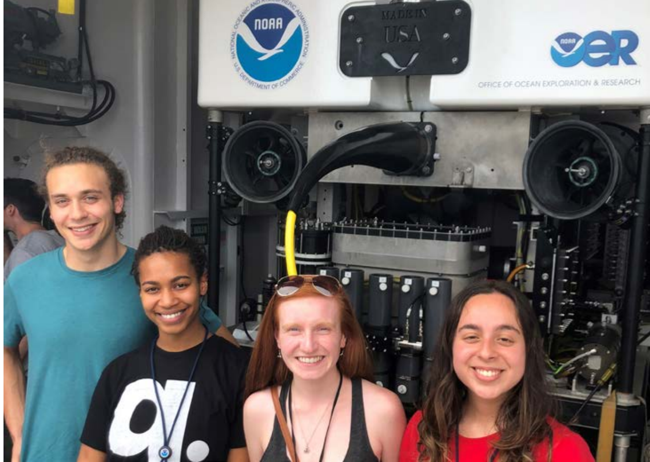


FIGURE 3. From left, Herbert Leavitt (2019 NOAA OER Hollings scholar), Kristyn Wilkerson (2019 EPP/MSI scholar), Laura Anthony (2018 Hollings scholar), and Paola Santiago (2019 NOAA OER EPP/MSI scholar) stand in front of ROV *Deep Discoverer* aboard NOAA Ship *Okeanos Explorer*.

FIGURE 4. More than 25% of the mission and crew team aboard NOAA Ship *Okeanos Explorer* for the Windows to the Deep 2019 expedition were women, including the commanding officer, executive officer, operations officer, expedition coordinator, mapping lead, and science leads. This is the first time this has happened onboard the ship, and it is a rarity among oceanographic research vessels. Seven of the women in this photo are also early career.

Civil Rights, OER had a banner year supporting efforts to create a more inclusive and equitable workplace culture. Contributing to important initiatives such as the first-ever DOC First Generation Professionals Summit and NOAA's Third Annual Diversity and Inclusion Summit, OER is helping to create an organizational climate conducive to the success of all individuals.

Since its inception in 2001, OER has hosted 16 John A. Knauss Marine Policy Fellows, two Ernest F. Hollings Undergraduate Scholars, and three NOAA Educational Partnership Program (EPP) Undergraduate Scholars from minority serving institutions (MSI) (Figure 3). Tailored programs were developed for each individual by OER staff, and many interns and fellows have been hired into federal and contract positions within OER and other NOAA offices. The *Okeanos Explorer* mapping team has also provided specialized training to more than 130 Explorers-in-Training (EiTs), 14 of whom were selected through the EPP/MSI program. All receive a variety of onshore and at-sea experiences, enhancing their academic and career trajectories through development of unique skill sets and access to a professional network, field experiences, and exposure to diverse careers they may never have considered otherwise. Because these gateway opportunities can be life changing for students fortunate enough to be selected, OER continues to partner with the NOAA Office of Education to help identify and remove barriers to entry for underrepresented minority groups, developing best practices that can ultimately translate across many agencies, academic institutions, and industries.

One of the advantages of telepresence-enabled exploration is that it helps to remove some of the barriers to participation (funding for sea time, limited berths, prior experience requirements, to name a few) and provides access to data and information to anyone with an Internet connection in real time. Additionally, OER strives to be inclusive in the selection process for the at-sea team, specifically recruiting individuals with diverse backgrounds, early career scientists, and those from groups underrepresented in STEM fields. In 2019, all but one of the *Okeanos Explorer* science leads were women, half were early career, and one was a scientist from an underrepresented group (Figure 4). We see these expeditions as opportunities to engage with and give voice to the next generation of explorers, a group that we hope will soon become as diverse as our nation.

Sponsored Projects

The NOAA Office of Ocean Exploration and Research

Introduction

By Nathalie Valette-Silver, Stephen R. Hammond, Frank Cantelas, Chris Beaverson, Adrienne Copeland, Katharine Egan, Amanda N. Netburn, Margot Bohan, Yvette Jefferson, and Joyce Woodford

NOAA's Office of Ocean Exploration and Research is the only federal program dedicated to exploring the deep ocean, closing gaps in our basic understanding of US deep waters and seafloor, and delivering ocean information needed to strengthen the economy, health, and security of our nation. To accomplish its mission, OER conducts ocean exploration expeditions and campaigns using NOAA Ship *Okeanos Explorer* and a variety of other ships, engages in formal partnerships as well as national and international alliances, and sponsors ocean exploration and technology innovation and development projects. Sponsored projects include competitive grants, cooperative agreements, and unsolicited projects that align with NOAA and OER missions.

In fiscal year 2019, OER published a Federal Funding Opportunity (FY19 FFO) that invited proposals for exploration in ocean waters under US jurisdiction, including the US EEZ and areas mapped by, or of interest to, the US Extended Continental Shelf (ECS) project. Important marine habitats as well as potential living and nonliving resources within the EEZ and ECS are neither fully explored nor characterized. Funded FY19 FFO grants are addressing these knowledge gaps and, in doing so, are providing information that will help support the nation's Blue Economy.

FY19 FFO projects focused on (1) discovery of microorganisms, sponges, corals, and other organisms with biopharmaceutical or biotechnical potential; (2) acquisition of baseline ocean environmental information to better inform decision-making where future ocean energy development or critical mineral extraction may occur; and (3) finding and characterizing shipwrecks and submerged cultural resources that played a role in America's historical ocean-based economy. In FY19, OER funded eight such FFO projects (Figure 1) and three technology projects through the National Oceanographic Partnership Program competition.

NOAA's Cooperative Institute for Ocean Exploration, Research, and Technology (CIOERT) continued to conduct exploration and research focused on OER's priorities. FY19–FY20 will mark the end of a highly successful 10-year OER/CIOERT collaboration that led to major marine biology discoveries, including new species and habitats and the development of instruments that advanced ocean exploration.

Also in 2019, through a competitive process, NOAA selected the University of Rhode Island to host an exploration-focused cooperative institute. In this Ocean Exploration Cooperative Institute (OECI), URI will lead a consortium of four graduate degree-granting institutions, one ocean exploration nonprofit, and several task-specific partners to support and enhance core NOAA Ocean Exploration priorities. Significantly, OECI aims to leverage science, technology, and outreach/education capacities that do not currently exist within NOAA. An OECI priority is to transition away from the current methods of deep ocean exploration by developing and deploying smaller and less expensive ROVs and AUVs.

Finally, during FY19, ongoing grants continued to support marine science discoveries as well as ocean exploration technology innovations. Highlights from selected seagoing projects conducted during fiscal year 2019 follow.

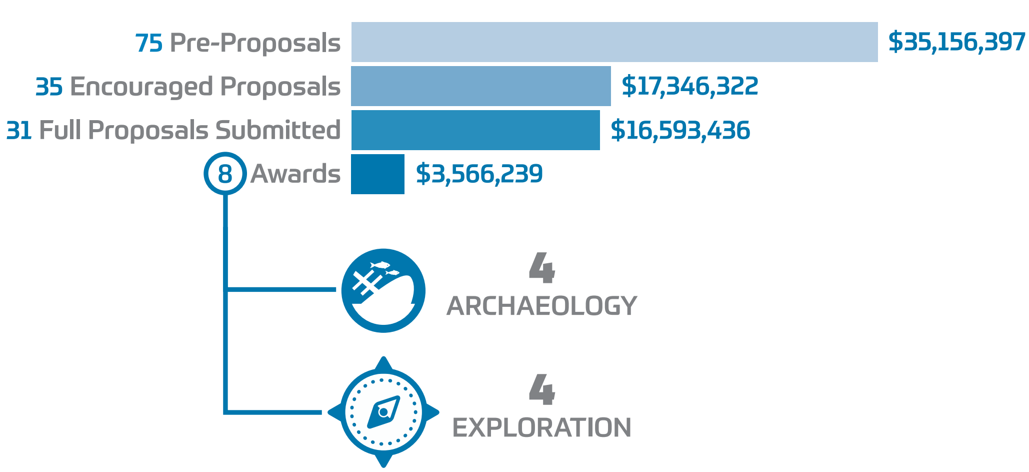


FIGURE 1. FY19 FFO grant projects statistics. *Image credit: Matthew King, NOAA OER*

Cooperative Institute for Ocean Exploration, Research, and Technology

By Joshua Voss and Shirley Pomponi

NOAA's Cooperative Institute for Ocean Exploration, Research, and Technology (CIOERT) is led by Florida Atlantic University's (FAU) Harbor Branch Oceanographic Institute in partnership with NOAA's Office of Ocean Exploration and Research, University of North Carolina Wilmington (UNCW), University of Miami, and SRI International. CIOERT's vision is to transform the way we explore our ocean basins through novel approaches and technology. Disciplined innovation is applied to continually improve, extend, and strengthen NOAA's exploration, research, and operational capabilities. CIOERT serves OER strategic priorities in three theme areas: (1) exploration of continental shelf edge frontiers, (2) research on vulnerable coral and sponge ecosystems, and (3) development of advanced underwater technologies.

In 2019, CIOERT's efforts to explore and characterize mesophotic coral reef ecosystems via ROV and technical diving (Figure 1) continued with four research cruises. Chief Scientists Joshua Voss and John Reed led a team of 20 researchers and graduate students from FAU Harbor Branch and the UNCW Undersea Vehicles Program (UVP) aboard R/V *F.G. Walton Smith* to explore the Florida Keys National Marine Sanctuary (FKNMS) and the Pulley Ridge Habitat Area of Particular Concern (HAPC). The expedition completed 18 ROV dives and conducted benthic surveys designed to assess potential hard bottom habitats at mesophotic depths that had recently been identified by NOAA multibeam mapping in the region. Large areas of mesophotic coral habitat were confirmed near the Key Largo Management Area outside of the current marine protected areas. Stony coral, soft coral, black coral, and sponge samples were also collected from both shallow and mesophotic depths in the Upper Keys, Lower Keys, and Dry Tortugas to assess genetic connectivity across the region. Finally, given the current dramatic outbreak of stony coral tissue loss disease in South Florida and the wider Caribbean, the surveys also assessed coral health status. Fortunately, no tissue loss disease was observed among mesophotic corals in the region (Figure 2). The results of this expedition will provide key information and data as FKNMS implements its Restoration Blueprint.

FIGURE 1. Technical divers prepare to deploy during CIOERT's Florida Keys National Marine Sanctuary expedition. *Image credit: Voss Lab, CIOERT, FAU Harbor Branch*

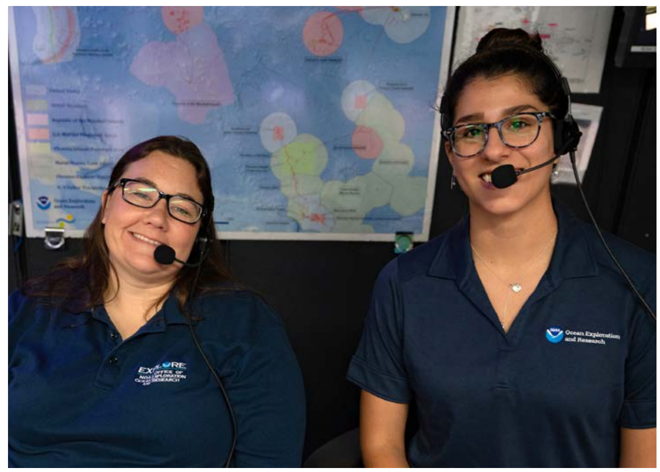
CIOERT researchers John Reed and Stephanie Farrington completed their eighth expedition with NOAA Fisheries and the UNCW UVP team aboard NOAA Ship *Pisces* in June 2019. Benthic and fish communities in marine protected areas from Florida to the Carolinas were explored and characterized during 33 ROV dives, and multibeam mapping was completed in seven areas including inside the Oculina Bank HAPC. These cruises were designed to identify key mesophotic reef resources and habitats in the southeast US region and to provide data and information that supports management decisions by NOAA and the South Atlantic Fishery Management Council.

CIOERT-supported graduate students Alexis Sturm and Ryan Eckert successfully completed an expedition aboard M/V *Caribbean Kraken* to assess shallow and mesophotic

FIGURE 2. Alacranes Reef demonstrated impressive coral cover and no active coral disease during CIOERT's July 2019 expedition. *Image credit: Voss Lab, CIOERT, FAU Harbor Branch*

FIGURE 3. Samples collected by ROV from the extensive coral communities in the Flower Garden Banks National Marine Sanctuary during the telepresence expedition will be used to assess genetic connectivity across the northwest Gulf of Mexico and tropical western Atlantic. *Image credit: GFOE*

FIGURE 4. Stephanie Farrington from FAU Harbor Branch and Kimberly Galvez from CIOERT partner University of Miami prepare for a live interaction with FAU Harbor Branch Oceanographic Institute during the 2019 Southeastern US Deep-sea Exploration.



coral reef connectivity in the southern Gulf of Mexico. The expedition focused on two unique coral reef ecosystems, Alacranes Reef and Bajos del Norte, that may contribute coral and sponge larvae to downstream coral ecosystems in Flower Garden Banks and the Florida Keys (Figure 2). A Mexican National Protected Area and UNESCO Biosphere Reserve, Alacranes Reef is situated at the edge of Campeche Bank 140 km to the north of the Yucatán Peninsula. Bajos del Norte is a relatively uncharacterized site near the Yucatán Channel that may be important for coral reef connectivity given its location near the conjunction of the Caribbean Sea and the Gulf of Mexico.

With support from the NOAA Office of National Marine Sanctuaries, FAU Harbor Branch partnered with the Global Foundation for Ocean Exploration, Flower Garden Banks National Marine Sanctuary (FGBNMS), Boston University, and the New York City College of Technology during a telepresence-enabled expedition in the northwest Gulf of Mexico (Figure 3). The mission was the first to use GFOE's portable satellite communications system, which allowed high-resolution video from ROV *Yogi* to be streamed in real time and enabled diverse opportunities for live interactions and community engagement. Samples of sponges, stony corals, and black corals were also collected to expand CIOERT's genetic connectivity research objectives. The expedition focused on banks currently under consideration in the proposed expansion of FGBNMS, providing compelling data and images to support this important management objective.

CIOERT researchers served as key contributors during NOAA Ship *Okeanos Explorer*'s 2019 Southeastern US Deep-sea Exploration expedition. Stephanie Farrington served as the expedition's biology science lead (Figure 4), and Shirley Pomponi, Cris Diaz, and John Reed anchored a team of faculty and graduate students who participated daily from FAU Harbor Branch's Exploration Command Center. The expedition provided multiple telepresence outreach opportunities for college and high school students, including very successful live interactions with the *Okeanos Explorer*.

CIOERT has also made strides in advancing technologies related to the Blue Economy. Using an amino acid-optimized nutrient medium, Shirley Pomponi and her colleagues at FAU Harbor Branch and Wageningen University & Research (Netherlands) have demonstrated a substantial increase in both the rate and number of cell divisions in nine marine sponge species. These results form the basis for developing marine invertebrate cell models to better understand early animal evolution and predict the impact of climate change on coral reef community ecology. Sponge cell lines can also be used to scale-up the production of sponge-derived chemicals for clinical trials and develop new drugs to combat cancer and other diseases.

Exploration of Gulf of Alaska Seamounts

By Katrin Iken

In July 2019, scientists from the University of Alaska Fairbanks led an expedition on R/V *Sikuliaq* to explore the seamounts in the northern Gulf of Alaska. This basin contains a chain of about 35 seamounts of volcanic origin that rise between 1,000 m and 3,500 m above the seafloor but whose summits typically reach only within 600–900 m of the sea surface. Seamounts in general interact with the surrounding deep-sea system by altering the deep water-column structure, which affects mixing and nutrient concentrations as well as the exchange of biota. These conditions can contribute to high biodiversity.

During 2019, we used the innovative imagery and specific sampling capacity of ROV *Global Explorer* (Oceaneering International) to examine the pelagic and benthic systems on the summits and deep slopes of Giacomini and Quinn Seamounts. We observed that both seamounts harbored vastly different communities on the deep slopes (2,500 m) compared with the summits. Deep slope fauna on both seamounts were less diverse and less abundant than summit fauna. Large glass sponges, sea cucumbers, and crabs were most common on the Giacomini slope. Similarly, the benthic community at the deep slope of Quinn seamount was almost barren, with only the occasional sea cucumbers and crabs.

Though only about 70 km apart, the benthic summit communities of Giacomini and Quinn Seamounts were distinct. Giacomini exhibited a much more diverse and dense coral fauna (Figure 1) that provided habitat for many associated taxa such as crabs and brittle stars (Figure 2). In contrast, the Quinn summit was rich in sea cucumbers, sea stars, and crabs as well as occasional corals. One reason for this observation could be that Quinn's summit is deeper (900 m) than Giacomini (650 m), but it could also indicate the isolation of the seamount summits and lack of propagule exchange, possibly due to circulation isolating rather than connecting seamount summits. Fish were consistently, although not always frequently, observed. Grenadiers (Macrouridae) were most common at deeper slope locations while rockfish (*Sebastes*) were most common on seamount summits. Observations of the strikingly patterned deep-sea sole on the summits (Figure 3) were noteworthy. The observation of several cusk eels (Ophidiidae) on the seamount slopes adds to the sparse record of this group in Alaska.

FIGURE 1. A rich assemblage of corals, anemones, sponges, and sea cucumbers on the top of Giacomini Seamount. Corals provide good vantage points for brittle stars and shrimp to capture food particles and prey. *Image credit: NOAA-UAF-Global Explorer*

FIGURE 2. Deep-sea corals provide excellent habitat for associated species such as king crab and brittle stars. *Image credit: NOAA-UAF-Global Explorer*

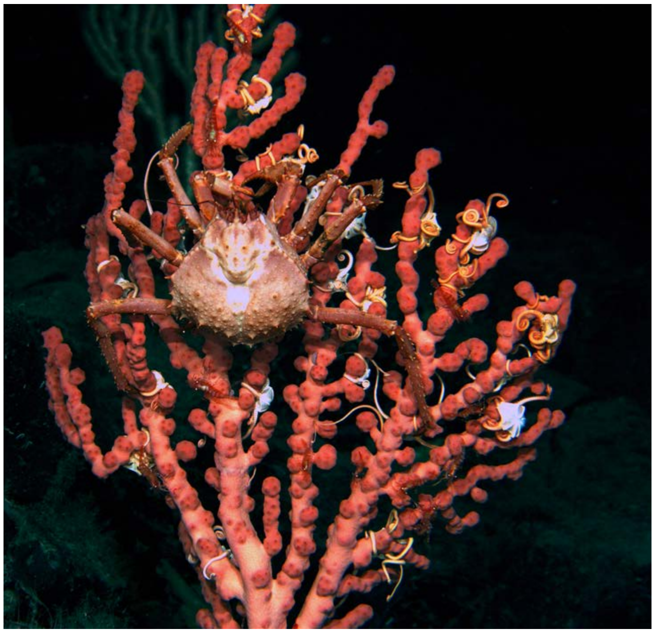


FIGURE 3. Deep-sea sole (*Embassichthys bathybius*) are widely distributed across Alaskan waters, including on seamounts, but stand out with their stark black-white coloration and size (~30 cm). *Image credit: NOAA-UAF-Global Explorer*

Exploring for a Biogeographic Boundary Along the Emperor Seamount Chain: A Multidisciplinary Approach

By John R. Smith, Les Watling, Natalie Summers, E. Brendan Roark, Nicole Morgan, Becca Lensing, Scott C. France, Henrietta Dulai, Glenn S. Carter, Sarah Bingo, and Amy Baco-Taylor

The bathyal zone (800–3,500 m depth) is the least well-known depth zone in the ocean, yet it harbors considerable deep-sea coral and sponge diversity. The significant difference in bathyal fauna between the Aleutians and Hawai'i led us to propose that a transition occurs somewhere along the Hawaiian-Emperor seamount chain, the only continuous geomorphic feature between these two areas that can host bathyal benthos. However, water mass data implied there was no difference in temperature and salinity at bathyal depths anywhere along the chain. We suggested that currents moving east to west through the 500 km wide gap between Nintoku and Koko Seamounts would act as a "current wall," limiting the ability of larvae to emigrate either north or south.

A 32-day multidisciplinary expedition was mounted in July–August 2019 with biologists joining chemical, physical, and geological oceanographers to address this issue and provide additional baseline data from this remote region. In addition to a trial dive at Hess Rise, we conducted 10 ROV dives on seven Emperor seamounts, from Suiko in the north to Koko in the south, using the Schmidt Ocean Institute's R/V *Falkor* and ROV *SuBastian* (e.g., Figures 1 and 2). Dive depths ranged from 2,400 m to 1,800 m and 1,000 m to 1,200 m and were live-streamed with narration by the onboard scientists (32,500 views, 51 hours posted).

Over 230 specimens were collected, including 82 octocorals, 22 sponges, and 126 other invertebrates. Animals were identified and recorded from the video images on each dive to estimate the frequency and distribution of taxa. Hydrographic samples were taken to understand the longer-term history of local water mass characteristics and their variability. Geological samples (31) were also acquired for geochemical analysis and dating to fill some gaps in this little-visited part of the Hawaiian-Emperor chain. Acoustic Doppler current profiler surveys were conducted to characterize the velocity structure of the current regime. Additionally, a comprehensive marine geophysical program, consisting of gravimeter and magnetometer measurements and >20,000 km^2 of multibeam bathymetric surveys, was carried out to guide study site selection, provide project context, and aid future missions and studies.

We consistently found species with known northern distributions until we dove near the southern end of the gap where the octocorals and sponges were characteristic of the central Pacific fauna that was regularly observed during NOAA's Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE). Many of the animals observed on the northern Emperor seamounts had not been seen before and are likely new species that may not be related to those from the Aleutian Ridge. From the perspective of our biogeographic objectives, the cruise was a huge success. However, we must now explain how such a boundary can be created and persist. For that, we await the analyses of numerous water, current, and fossil coral samples acquired on the cruise.

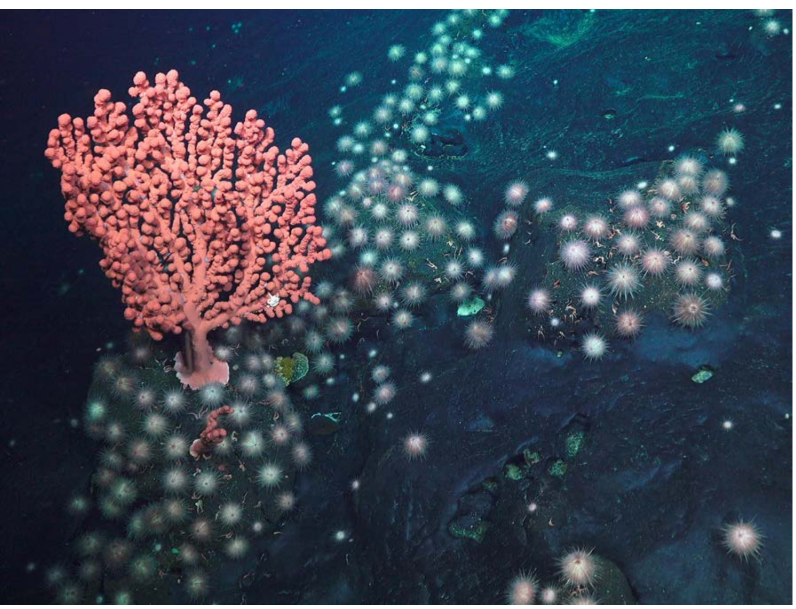


FIGURE 1. *Paragorgia arborea* (bubblegum coral) and regular urchins were observed on polymetallic crust substrate at Suiko Seamount (1,350 m depth). *Image credit: Schmidt Ocean Institute*

FIGURE 2. A community of bubblegum (red) and red tree (orange) coral, regular urchins, a large vase sponge *Rossellidae* (center, white), and clusters of an unknown hydroid (gray) were found growing on volcanic substrate at Jingu Seamount (1,396 m depth). *Image credit: Schmidt Ocean Institute*

Search for Life Under Ice Overcomes Challenges to Explore Arctic Vents

By Christopher R. German

A multinational team of 36 researchers set sail on the Norwegian icebreaker *Kronprins Haakon* on September 19, 2019, from Svalbard, Norway, as part of the Hot Vents in an Ice-Covered Ocean (HACON) expedition to investigate biogeographical connections and biogeochemical interactions in this remote ocean.

Deploying the hybrid ROV/AUV *Nereid Under Ice* (*NUI*) developed by Woods Hole Oceanographic Institution (Figure 1), the scientists wanted to investigate competing hypotheses concerning the genetics of hydrothermal vent fauna at the Arctic Ocean's Gakkel Ridge. Would the fauna show genetic similarities to vent fauna in the Norwegian-Greenland Sea or to chemosynthetic fauna from the far side of the Arctic near the Aleutians, or were they entirely new species?

To answer these questions, WHOI upgraded *NUI* to reach 5,000 m depth and gave it an ability to switch between AUV (survey vehicle) and ROV (seafloor imaging and sampling) modes during under-ice dives.

Despite technical challenges with *NUI*, and difficult ice conditions, the team was able to deploy a towed video camera from the Alfred Wegener Institute for Polar and Marine Research (Germany) to collect high-resolution digital images of the Aurora vent site, revealing two active black smokers and a diversity of vent fauna (Figure 2). Continuing away from the vents, these same surveys imaged a wide variety of habitats, from soft sediments surrounding rocky outcrops colonized by glass sponges and associated fauna to mysterious sinkholes and basalt mounds sometimes coated in fine or coarse rust-colored sediments and sometimes overlain by extensive sulfide mounds.

FIGURE 1. The WHOI-developed *Nereid Under Ice* (*NUI*) hybrid autonomous vehicle is ready to dive into the Arctic Ocean during the Hot Vents in an Ice-Covered Ocean (HACON) expedition. *Image credit: Stefan Buenz, Norges Artiske Universitet*

As the cruise ended, the team was able to dive *NUI* to ~4,000 m depth beneath the >90% ice cover that was closing in over the site and collect the first-ever samples of the glass sponge species that represent the dominant benthic fauna along Gakkel Ridge. These new samples will be critical to answering whether there is a viable pathway for gene flow of vent-endemic fauna into the Arctic from other ocean basins.

Despite the challenges of working in such a high-risk environment, the WHOI/Jet Propulsion Lab team have already begun making plans for a return trip to the Gakkel Ridge site with their international colleagues—ideally as early as summer 2021.

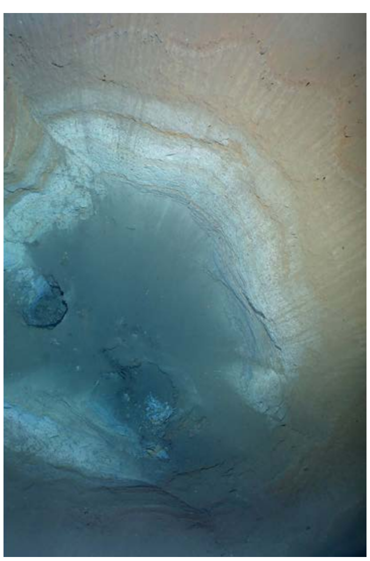
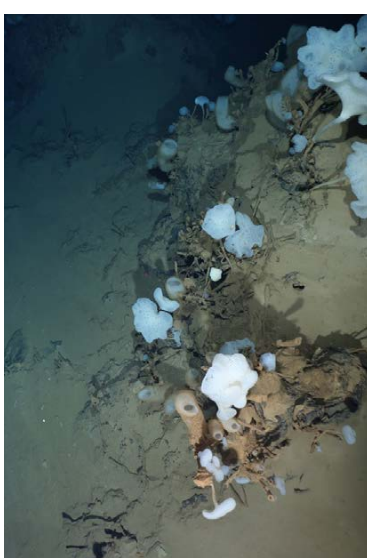
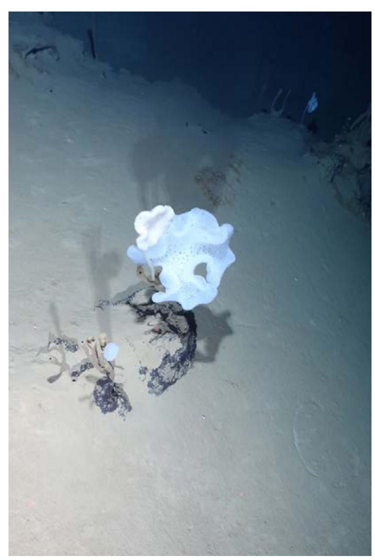





FIGURE 2. Images from Aurora Seamount explored by HACON. *Image credit: Eva Ramirez-Llodra, Norwegian Institute for Water Research*

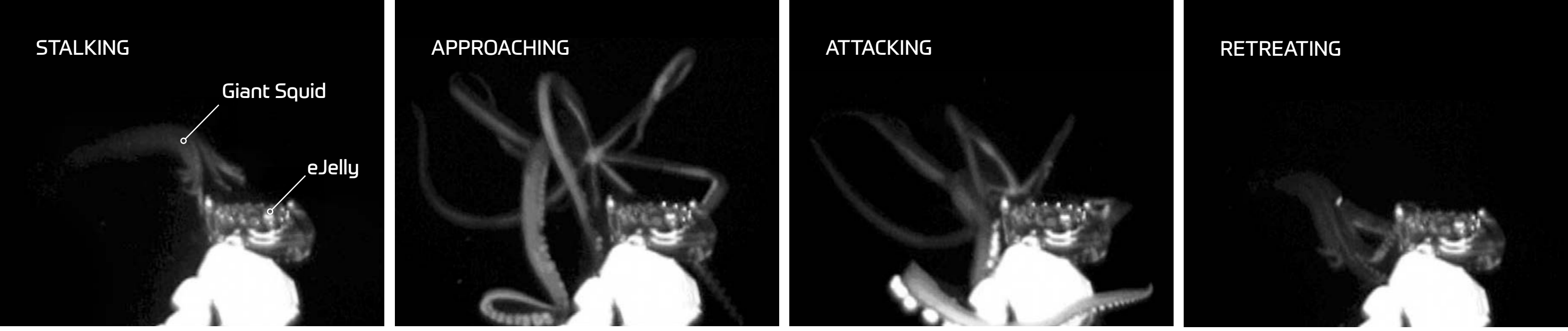


FIGURE 1. Images of the giant squid *Architeuthis dux,* filmed under near-infrared light using the *Medusa* camera system at ~700 m depth, showing the animal's approach to, attack of, and retreat from a simulated bioluminescent target. *Image credit: Edith Widder, Ocean Research & Conservation Association and Nathan Robinson, Cape Eleuthera Institute*

Journey into Midnight By Sönke Johnsen

"Journey into Midnight" was two-week research cruise on R/V *Point Sur* that explored biodiversity, vision, bioluminescence, and biophotonics in the northeast Gulf of Mexico. The science crew consisted of six co-PIs and their labs, plus a teacher-at-sea and a professional photographer. Working mostly at depths of 1,000–2,000 m, we completed 12 ROV dives, six *Medusa* (a drifting stealth camera system) deployments that collected 160 hours of video, and 15 midwater trawls. Significantly, we captured footage of a juvenile specimen of the giant squid *Architeuthis dux* (Figure 1). The second in situ footage of this squid ever and the first in US waters, it both generated intense national and international media coverage and demonstrated the value of stealth technology for deep-sea research. In addition, we discovered and measured what may be the blackest natural surface known—the skin of the deep-sea anglerfish *Oneirodes*. This skin, which is currently being assessed using electron microscopy and complex optical modeling methods, is as black as the blackest known technological substances and may provide insight into how to design these important materials. We also filmed one of the most impressive bioluminescent displays known, that of the threadfin dragonfish *Echiostoma barbatum*, showing that it emits light even from the tips of its fin rays.

Development of Innovative Techniques for Exploring Novel Submarine Springs on the Gulf of Mexico Outer Continental Shelf

By Emily R. Hall, Jim Culter, Jordon Beckler, Martial Talliefert, Frank Stewart, and Chris Smith

Studies of offshore submerged sinkhole and spring features (blue holes) have been limited, as they frequently exceed normal scuba limits, reaching depths of >130 m, and have openings too small for many submersibles to access. These blue holes host several commercially important and regulated fish species as well as protected species, and they are ecological hotspots with respect to species composition and diversity. To overcome the technological limitations and explore the geological, physical, and chemical environments of blue holes and the resulting biological distribution, we assembled an innovative sensor and sampling suite. The principal objectives of the project were to (1) repurpose and repackage existing high-tech marine biogeochemical instrumentation to create a benthic lander appropriate for exploration of these environments (Figure 1); (2) develop a multi-day logistical plan for safely deploying the platform in conjunction with geochemical, genomic, and macrofauna surveys; (3) employ this plan in the exploration of two blue holes at depths >100 m and develop a long-term plan for the systematic exploration of other blue holes on the West Florida Shelf; and (4) disseminate data and images through innovative means designed to captivate the public and garner future interest from scientists.

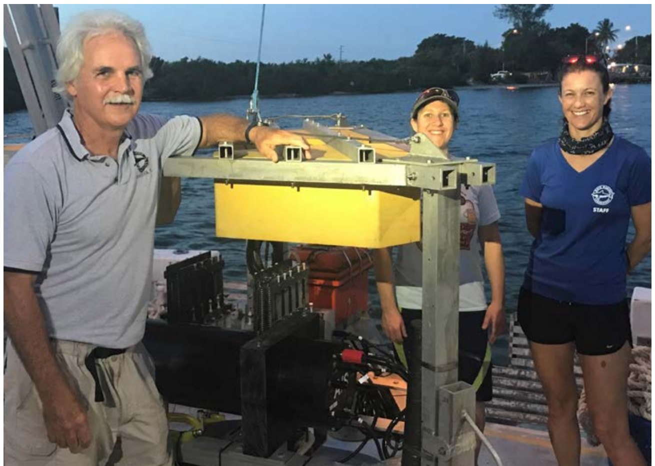


FIGURE 1. From the left, Jim Culter (co-PI from Mote Marine Laboratory), Nastassia Putin (postdoc from Georgia Tech), and Emily Hall (PI from Mote Marine Laboratory) stand around the benthic lander prior to deployment. *Image credit: Mote Marine Laboratory*

Microbial Stowaways: Exploring Shipwreck Microbiomes in the Deep Gulf of Mexico

By Leila Hamdan

During June–July 2019, an expedition to the northern Gulf of Mexico explored, for the first time, two wooden-hulled shipwrecks and began the study of microbial stowaways living on and around them to learn how shipwrecks shape microbial biodiversity in the deep sea. The University of Southern Mississippi (USM), in collaboration with the Bureau of Ocean Energy Management and the Naval Research Laboratory, led the expedition. The shipwrecks investigated were site 15711 at approximately 530 m depth in the Viosca Knoll lease area and site 15470 at approximately 1,800 m depth in the Mississippi Canyon lease area.

Deployed from R/V *Point Sur*, ROV *Odysseus* collected high-resolution images of diagnostic artifacts and hull construction features of the two nineteenth-century wooden-hulled sailing vessels to inform archaeological interpretations (Figures 1 and 2). Video and photos are being analyzed to develop archaeological site plans, vessel age estimations, and baseline characterizations. Digital imagery is being used to develop 3D photogrammetric models. The ROV collected sediment push cores for studies of microbiome composition, biodiversity and richness, and porewater geochemistry. Sediments are being examined to determine whether the shipwrecks enhance microbial biodiversity of the seabed. These data will be used in conjunction with machine learning to geospatially predict microbial assemblages around shipwrecks from the current study and from previous works. In addition, microbial recruitment experiment arrays were placed on the seafloor near the shipwrecks to study dispersal of microbial "stowaways" into the surrounding environment (Figure 3).

In December 2019, after four months on the seafloor, all microbiome recruitment arrays were recovered using an instrumented lander outfitted with an acoustic release. During the fieldwork, USM's Marine Education Center hosted an Ocean Science and Technology Camp (OSTC). The OSTC delivered an ocean science career-focused experience to 20 high school students from across the nation. Camp participants met with the research team and ship crew to learn about the lives and careers of marine scientists and engineers. The camp culminated with a live telepresence event during the exploration of site 15711.

The Microbial Stowaways project involves scientists from marine archaeology and microbial ecology. This collaboration is the first to address how shipwrecks impact the distribution of microbiomes across space and time.

FIGURE 1. Stern of shipwreck site 15470 with draft mark visible. *Image captured by ROV Odysseus, courtesy of Microbial Stowaways*

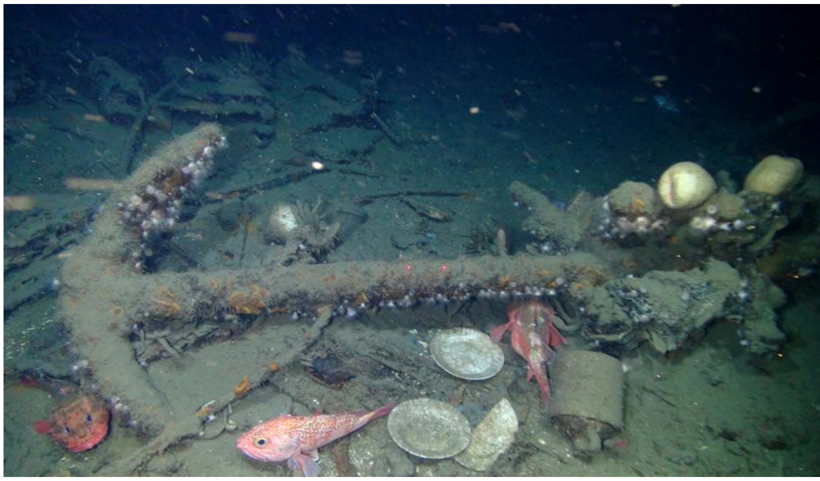


FIGURE 2. Image of the newly found anchor at shipwreck site 15711. *Image captured by ROV Odysseus, courtesy of Microbial Stowaways*

FIGURE 3. Leila Hamdan stands in front of the microbiome recruitment experiment array and lander. *Image credit: Justyna Hampel, The University of Southern Mississippi*

Submerged Paleolandscapes of the Northwestern Gulf of Mexico

By Amanda Evans

For two weeks in late May and early April, 2019, a team of marine archaeologists and marine geophysicists explored the outer continental shelf in the northwestern Gulf of Mexico for evidence of paleolandscapes submerged by rising seas since the Last Glacial Maximum. The team used a chirp sub-bottom profiler and a parametric sonar to record the seafloor and underlying strata (Figure 1). Building from previous exploration and survey work, the team targeted a 606 km^2 area (Figure 2), looking for evidence of paleovalleys buried below the modern seafloor. A total of 670 survey line kilometers were transited during the cruise; in addition to subbottom and parametric sonar data, the team collected magnetometer data for seafloor hazards identification and bathymetry data for correlation with sea level curves. The team is in the process of analyzing the collected data and selecting locations for vibracoring, to be conducted in spring of 2020. The data will result in a better map of the paleolandscape and a better understanding of the environments that were available to human populations when this portion of the continental shelf was exposed as dry land.

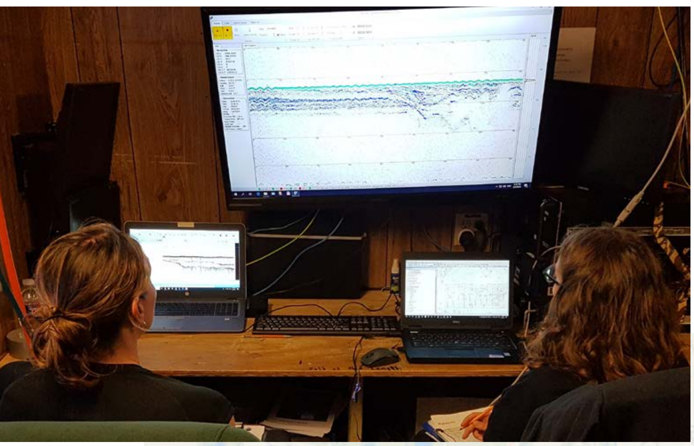
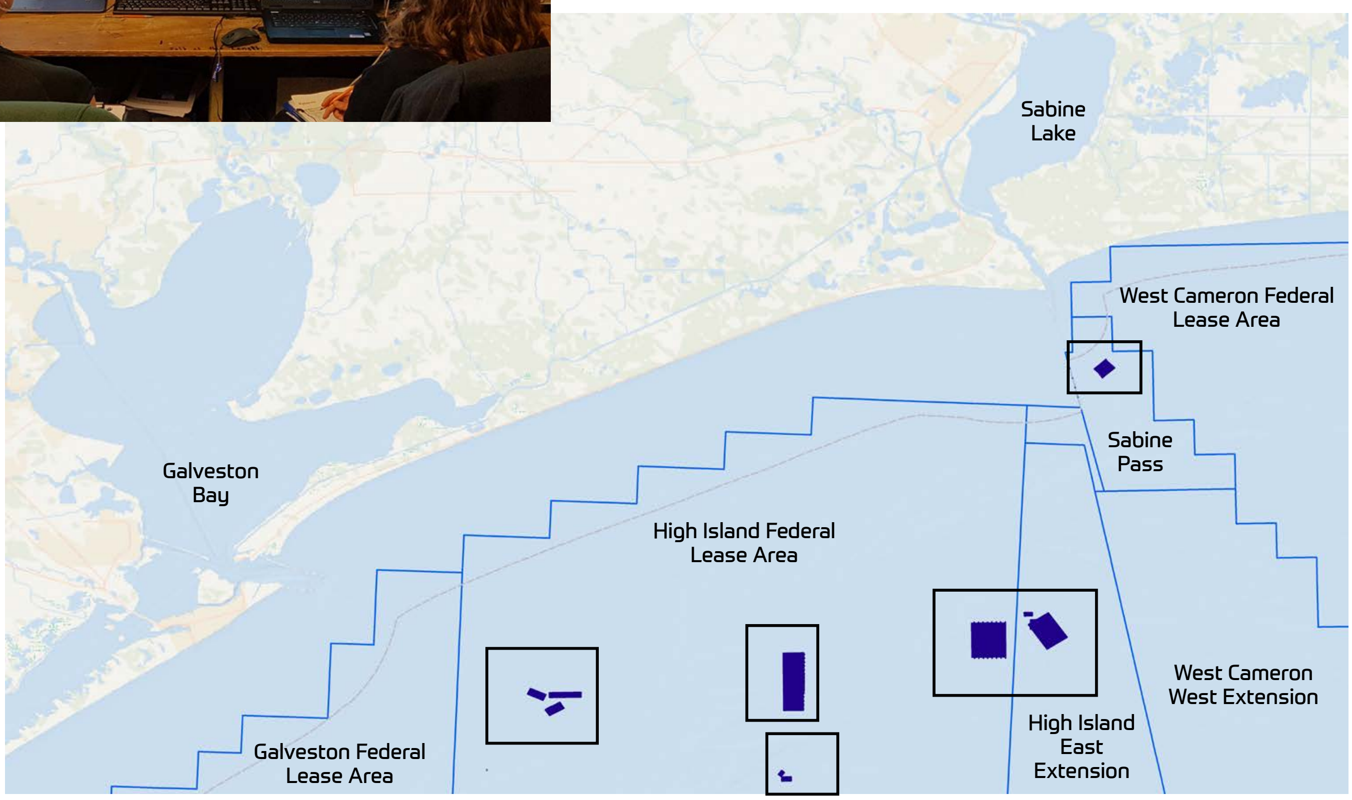


FIGURE 1. Amanda Evans (left) and Megan Metcalfe (right) monitor the parametric sonar during survey operations. *Image credit: Megan Metcalfe, Wessex Archaeology, UK*

FIGURE 2. A map showing the five general areas surveyed (black boxes) in the Gulf of Mexico, offshore Texas and Louisiana. The dark blue within the boxes is the actual survey lines completed.



Update on Co-Exploration: A Toolbox for Subsea Data Processing and Real-Time Information Interaction Over Acoustic Communications

By Carl L. Kaiser and Laura Lindzey

We are developing a suite of tools designed to significantly improve human-robot interactions in deep-sea exploration. This "co-exploration" combines onboard data processing, machine learning, heuristic anomaly detection, and a GIS-based user interface (Figure 1) to provide information in real time that previously required vehicle recovery.

Co-exploration is a collaboration between robot and human. Traditionally, the robot has all of the data but no context, and the human has all of the context but no data. For example, when searching for chemical anomalies, rather than transmitting all oxidation-reduction potential data to the user, the AUV sends only the magnitude and location of the largest anomalies. The human explorer then sends a request to the AUV to collect additional data from those sites such as bathymetry, photos, and other chemical data while converting data into information, for example, using unsupervised machine learning to classify seafloor types.

In the short term, co-exploration will lead to more efficient use of ship time, while in the long term, it will reduce risk from long-duration, shore-launched missions. Both will greatly speed the pace of discovery.

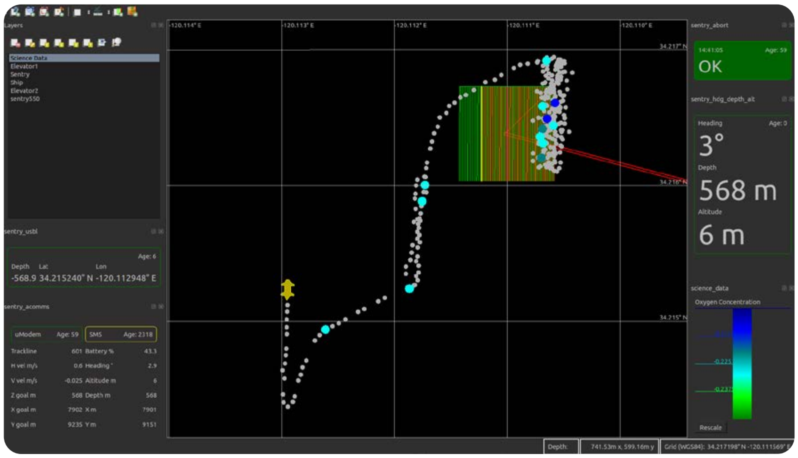


FIGURE 1. Early example of real-time chemical data being displayed in the GIS-based user interface. *Image credit: WHOI*

Improving Navigation for Long Endurance Underwater Robots

By Michael V. Jakuba, James W. Partan, and Christopher Dolan

With funding from the National Science Foundation and NOAA, we are developing a one-way travel-time inverted ultra-short baseline (OWTTIUSBL) acoustic navigation system intended for very low power operation on autonomous gliders and other vehicles. The system will allow arrays of autonomous vehicles to navigate in deep water with a precision significantly better than that achieved using periodic GPS fixes when at the surface along with dead-reckoning (Figure 1). In summer 2019, we installed a test article containing a prototype version of the system on ROV *Deep Discoverer* aboard NOAA Ship *Okeanos Explorer* and spent three dives collecting performance data at various depths, relative orientations, layback distances, and two source frequencies. The test article contained a Micro Modem-based system (the intended final embodiment) as well as a high rate data-acquisition system designed to collect raw passband data from a second array also mounted on the device. These data are currently being analyzed.

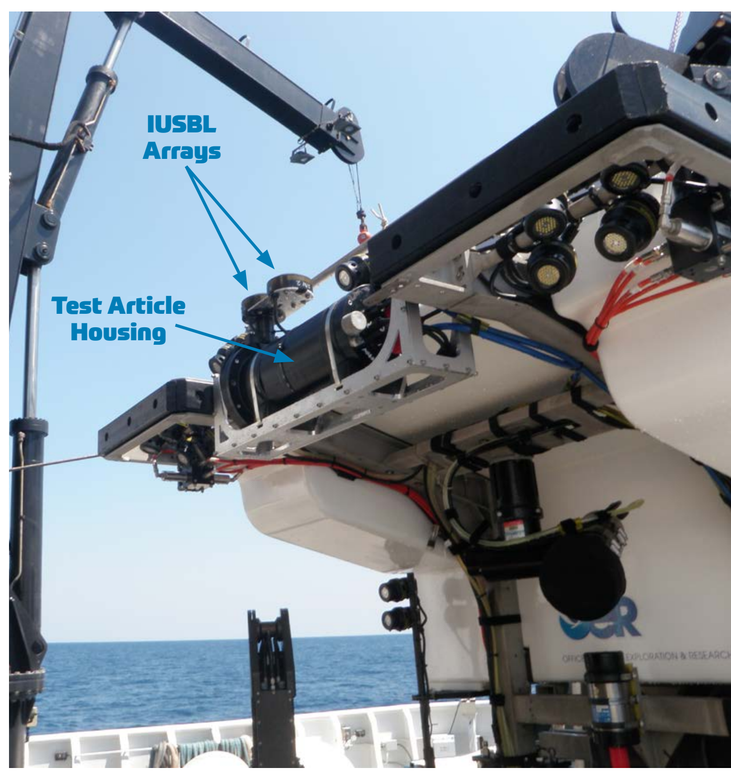


FIGURE 1. The OWTTIUSBL test article installed in the "brow" of ROV *Deep Discoverer*. *Image credit: M. Jakuba, WHOI*

The remotely operated vehicle (ROV) *SuBastian* obtains push cores in a seep-associated habitat off the coast of Oregon in Astoria Canyon, June 14, 2019.

PART 3

Schmidt Ocean Institute – R/V *Falkor*

Exploration and Innovation at Sea: The Schmidt Ocean Institute 2019 Field Season

By Carlie Wiener, Shannon McClish, Logan Mock-Bunting, and Jyotika Virmani

Schmidt Ocean Institute (SOI) continues to support innovative technology and research to better characterize and protect the deep, remote regions of the global ocean. Understanding these waters is more important than ever before, as our ocean and climate are changing rapidly. While exploring new realms and supporting important science, SOI tracks and broadly shares findings from this research-based work that has wide-ranging societal impacts. We at SOI believe successful ocean exploration involves emphasizing the importance of ocean health and connecting everyone to ocean science. Through remote exchanges, exhibits, and ship-to-shore connections, as well as Student Opportunities and Artists-At-Sea programs, institutions, classrooms, and homes all over the world have become part of the SOI research team.

In 2019, SOI collaborated with experts around the world to complete 11 expeditions aboard the research vessel *Falkor*. Each expedition brought impactful new scientific tools to address critical questions that challenge our ability to understand the ocean. Advancements in technology led to new breakthroughs, literally from top to bottom, from the role of the sea surface microlayer in the ocean's heat budget to characterization of novel benthic ecosystems. The 2019 expeditions featured coordinated technology—using an integrated framework of robotics, precise observations, software, and data—to allow scientists to study the ocean in new regions and on new temporal and spatial scales. Based on the belief that the development and application of new technology is essential to understanding dynamic ocean systems, long-term development goes into each SOI robotic system, sensor, and method before it is applied at sea on *Falkor*. The important contributions to enhancing knowledge of the ocean that took place aboard *Falkor* in 2019 will lead to better ocean policies and management.

An unmanned aerial vehicle passes overhead, collecting data on the sea surface below. In the water, a Surface Processes Instrument Platform collects detailed in situ measurements of ocean surface dynamics.

COSTA RICAN DEEP-SEA CONNECTIONS

Led by Erik Cordes, Temple University, and collaborators from the University of Rhode Island, Costa Rica Marine Institute, Universidad de Costa Rica, Scripps Institution of Oceanography, and the California Institute of Technology

A multidisciplinary team delved into never-before-seen seamount sites during pioneering exploration around the Isla del Coco National Park, a UNESCO World Heritage Center in Costa Rica. The expedition made some exciting discoveries, including identification of at least four new species of deep-sea corals and six other animals that are new to science. The finding of these novel deep-sea coral species led to a call to protect these specialized ecosystems. The survey results will support the effort to create a new marine protected area from the mainland to Isla del Coco, ensuring that these corals are not impacted by fishing or potential mining activities. Some of the largest trash aggregations seen by the science party were found and imaged here at 3,000 m depth. The footage of this unfortunate finding is now being used to illuminate the impact of marine trash, including an international deep-sea trash campaign showing that just because you cannot see it does not mean it is not there. This expedition marks the first surveys of seven of the seamounts in the area. The science team combined sampling, chemical sensor data, photographic profiling, and water column sampling for a complete characterization and greater understanding of each of these seamount communities.

A scene documented by ROV *SuBastian* reveals corals, sponges, squat lobsters, a crinoid, anemone, and more. This expedition was the first time that seven seamounts (including Isla del Coco) in the area have been surveyed. The results of these surveys, including the description of the deep-sea coral communities they host, will help support the effort to create a new marine protected area around these seamounts to ensure that they are not impacted by fishing or potential mining activities.

"One of the great things about being on an expedition like this is we have a chance to find new species. It shows you how little you know and provides insights into new deep-sea life."

– Greg Rouse, Scripps Institution of Oceanography

Samantha Joye, Zachary Marinelli, Andy Montgomery, and Rachael Karns inspect the latest rocks that arrived on deck from ROV *SuBastian*'s sampling.

MICROBIAL MYSTERIES: SEARCHING FOR MICROBIAL COMMUNITY STRUCTURE

Led by Samantha Joye, University of Georgia, and collaborators from Max Planck Institute for Marine Microbiology, Harvard University, Coastal Carolina University, University of North Carolina at Chapel Hill, and the Universidad Nacional Autónoma de México

The science team discovered a hydrothermal field at 2,000 m depth while exploring the Gulf of California, where towering mineral structures 23 m high serve as biological hotspots for marine life. These newly discovered geological formations revealed a previously unknown feature—flanges angled downward that act as pooling sites for discharged fluids and create the illusion of a mirror for those observing the superheated (366°C) fluids beneath them. The minerals collected across these features are laden with metals, and the fluids sampled are highly sulfidic, yet teeming with biodiversity. An unprecedented study conducted on this expedition used advanced technology, including new jumbo-osmo samplers for in situ fluid collection, 4K deep-sea underwater cameras, and radiation tracking devices, as well as sediment and fluid samplers mounted on SOI's ROV *SuBastian*. The data collected advance the knowledge of biological cycling of methane in the water column and in sediments. Additionally, the suite of tools allowed scientists to study microbial and biochemical processes across a gradient of fluid flux regimes and water depths in the Gulf of California. The knowledge gleaned will be applicable to oceanic environments around the globe and will allow scientists to identify and frame exciting new questions.

"This is an amazing natural laboratory to document incredible organisms and better understand how they survive in extremely challenging environments."

– Samantha Joye, University of Georgia

A wide view landscape of oil hydrothermal chimneys. Researchers are interested in the types of novel microbes that might be processing (consuming) this oil.

SEEKING SPACE ROCKS

Led by Marc Fries, NASA Johnson Space Center, and collaborators from NASA Goddard Space Flight Center, Rice University, Harvard University, and NOAA Olympic Coast National Marine Sanctuary

A successful three-day search for meteorites that fell into the ocean on March 7, 2018, took place in the Olympic Coast National Marine Sanctuary. During this ROV *SuBastian* sea trial, the science team searched the seafloor with a "cosmic dustpan," a special scoop that was designed and fabricated by SOI's lead mechanical engineer, Jason Williams. Although meteorites exhibit several unique characteristics that are not found in rocks originating on Earth, finding them is very challenging. After the samples were analyzed, the science team identified a one cubic millimeter, unmelted meteorite fragment. Despite its tiny size, the scientists were able to measure the oxygen isotope content of the unmelted material. Based on this "fingerprinting," the meteorite appears to be an unusual, metal-rich type called mesosiderite, or silicated iron meteorite, but further measurements are still needed to confirm. If confirmed as a mesosiderite, this will be the eighth "meteorite fall" of this type seen to date and one of 261 found in total (out of over 63,000 known individual falls). Analysis of the recovered material is currently underway.

Ralph Harvey and Betsy Pugel search for meteorite fragments by sieving seafloor mud collected in ROV *SuBastian*'s Bio-Box.

USGS scientist Nancy Prouty (right) points to a feature in a sample of carbonate recovered from the seafloor of Astoria Canyon held by British Geological Survey scientist Diana Sahy.

METHANE HYDRATES AT THE EDGE OF STABILITY

Led by Carolyn Ruppel, US Geological Survey, and collaborators from the US Geological Survey, University of Rochester, University of North Carolina Chapel Hill, British Geological Survey, and GEOMAR

An international science team completed the methane hydrates expedition focused on the geology, ecology, physics, and chemistry of the US Pacific Northwest margin cold seeps, where methane and other gases are emitted from the seafloor. This research addressed critical knowledge gaps about gas hydrate degradation as well as the timing and triggers for seep emissions. The team deployed novel technology during the expedition, including two types of technologically innovative landers, one with in situ incubation chambers for determining the rates of microbial methane oxidation in the water column (designed by Christopher Martens, University of North Carolina) and others with capabilities for measuring the size, shape, number, and rise velocity of gas bubbles as they emerged from the seafloor (designed by Jens Greinert, GEOMAR). The in situ measurements gathered with the landers could provide unprecedented information about the destruction of methane by microbial processes at the actual depths and temperatures where these microbes live. Using ROV *SuBastian*, the researchers also acquired samples to measure the composition of seep gases (Tamara Baumberger, NOAA Pacific Marine Environmental Laboratory) and determine the age of rocks formed by microbial processes related to the methane emissions (Diana Sahy, British Geological Survey). Extensive mapping with R/V *Falkor*'s multibeam system revealed new water column gas plumes that could be traced to seafloor seeps, highlighting their role in injecting carbon and other nutrients into the ocean. This expedition is among the first cold seep studies to simultaneously collect a wide range of data at seep sites.

Numerous Charitometridae crinoids cling to a steep cliff face, with small cup corals and Stylasteridae hydrocorals behind them.

DEEP CORAL DIVERSITY AT EMPEROR SEAMOUNTS

Led by Les Watling, University of Hawai'i, and collaborators from the University of Hawai'i, Texas A&M University, and Florida State University

This expedition comprised the first complete assessment of coral diversity across the Emperor Seamount Chain Main Gap, with scientists examining the location where North Pacific intermediate and deep waters cross these seamounts. The researchers found a surprisingly abrupt shift in deep coral species over a distance of 160 to 200 km. Radioisotopes and CTD data were used to track water masses and allow scientists to identify environmental effects that contributed to the observed faunal shift. These findings have implications for determining how many protected areas are needed in deep waters, particularly in this active region, which is vulnerable due to coral harvesting, deep-sea fishing, and potential mining. Octocorals provide essential habitat for deep-sea fish and other organisms, and their now-known distribution will be used to better inform resource managers in updating policy to protect the different regions of coral. Several new coral species were also discovered, including a new type of bamboo coral.

"If the deep sea is all one big unit, then you can put a few protected areas wherever convenient and that would take care of it, but if it is, in fact, divided up into a bunch of biogeographic units then it is important to have a protected area in each one."

– Les Watling, University of Hawai'i

NECKER RIDGE: BRIDGE OR BARRIER?

Led by Amy-Baco Taylor, Florida State University, and collaborators from Texas A&M University and Scripps Institution of Oceanography

The Bridge or Barrier expedition identified coral diversity along Necker Ridge, a key geologic feature between central and western Pacific seamounts and the Hawaiian Ridge. The data retrieved will provide a better understanding of seamount communities and the connection between Pacific deep-sea ecosystems that could soon face impacts from human activity such as cobalt-rich, manganese crust mining. This baseline characterization of the biological diversity and surrounding ecosystem is critical in order to understand the effects that mining endeavors would have on ocean ecosystems. Since the expedition, the team has catalogued and archived the collected specimens and started geochemistry measurements to characterize the modern water column and create paleoceanographic reconstructions. Additionally, the team is looking at deep-sea coral distributions in relation to ocean pH and total alkalinity in order to reconstruct past changes in ocean pH and nutrient changes over decades.

Coral species were rarely seen in flat, sediment-covered areas, whereas high coral abundance was observed in steep areas with rocky substrate and strong currents.

In the control room, Co-Principal Investigator Kakani Katija (MBARI) describes the complex maneuvers that must be undertaken in order to collect the best data.

"While I cannot begin to convey what it feels like to watch a live feed of a siphonophore dance across the monitors of R/V *Falkor*, I am beginning to think about how art, design, engineering, and science can be used to enhance our understanding of organisms we may never be able encounter firsthand."

– Alyson Ogasian, Artist-at-Sea Participant

DESIGNING THE FUTURE

Led by Brennan Phillips, University of Rhode Island, and collaborators from Monterey Bay Aquarium Research Institute (MBARI), Harvard University/Wyss Institute, and the City University of New York Baruch College

This expedition was the first part of a technology development project for an in situ species sampling tool that enables rapid characterization of deep-sea organisms. Species sampling is an essential tool for oceanographers, but current sampling methods are detrimental to many deep-sea species, inhibiting our ability to explore biodiversity and investigate physiological questions. The engineering team tested new robotic sampling systems on ROV *SuBastian* and integrated MBARI's DeepPIV (particle image velocimetry) system to provide visual perspectives of fluids moving through organisms, a revolutionary achievement in midwater oceanic exploration. Collectively, these new technological breakthroughs are now being integrated into the ROV for rapid specimen characterization. Over the course of six ROV dives, MBARI's DeepPIV system scanned deep-sea jellyfish, ctenophores, siphonophores, and glass sponges. A new soft robotic gripping system developed by University of Rhode Island and Harvard University researchers and tried on ROV *SuBastian* is designed to gently pick up delicate single-celled organisms that can be very challenging to collect. Artist-at-Sea participant Alyson Ogasian collaborated with the team to integrate her three-dimensional printed designs into some of the experimental deep-sea cameras. The new technology will be fully implemented in a *Falkor* science expedition in 2020.

Jennifer Keating-McCullough (NOAA/PIFSC/JIMAR) monitors the acoustics from R/V *Falkor*'s hydrophone. These real-time audio signals allow scientists to listen for any marine mammals in the area.

LISTENING FOR CRYPTIC WHALE SPECIES

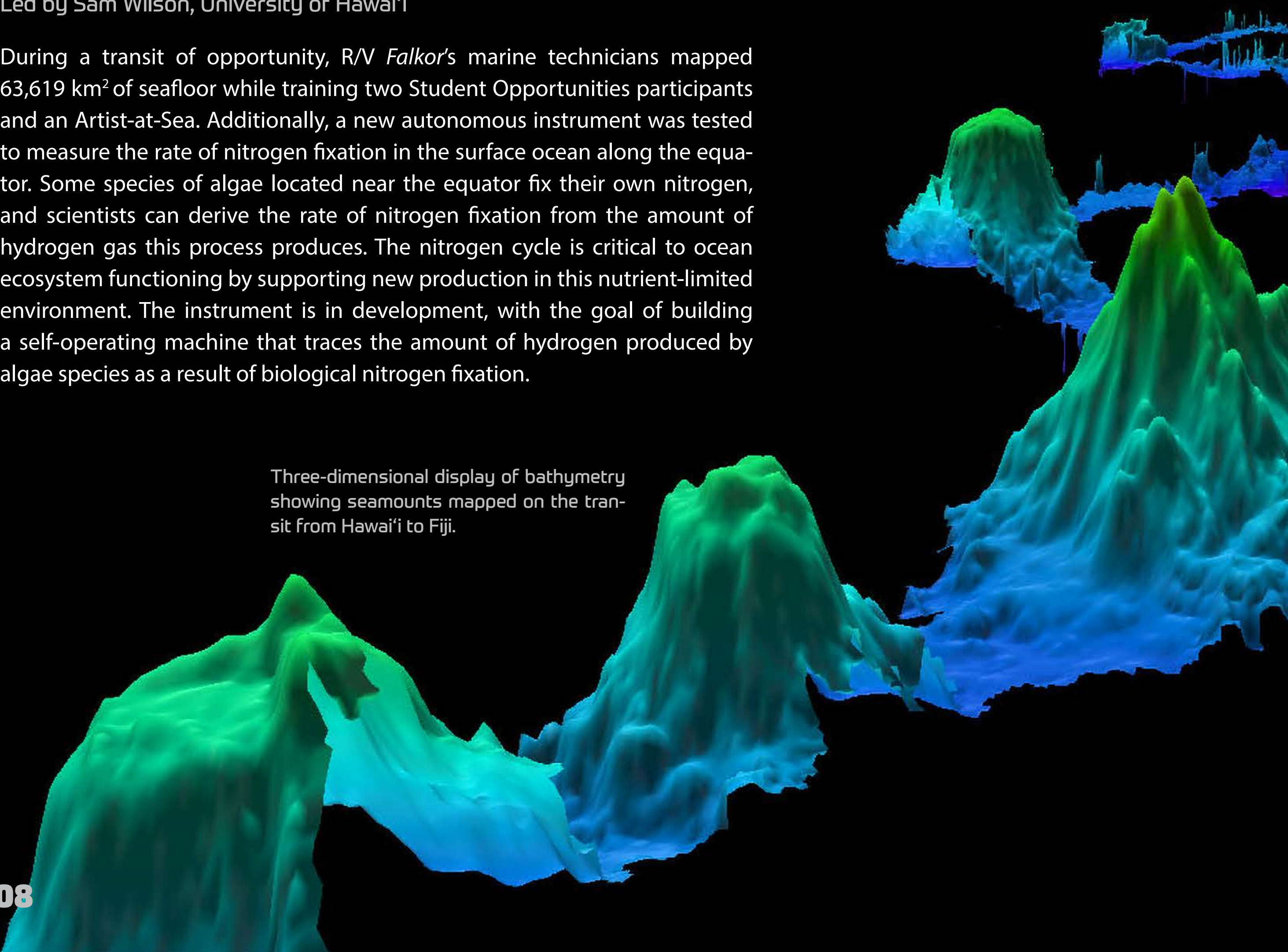
Led by Ann Allen, Cetacean Research Center at NOAA Pacific Island Fisheries Science Center, in collaboration with the University of Hawai'i

Beaked whales are some of the least understood mammal species due to their ability to dive to depths of over 2,000 m and spend very little time on the surface. Four species of beaked whales have been identified in Hawaiian waters, but only three species have ever been seen. The science team on this expedition used a combination of tools, including environmental DNA analysis and acoustics, for an unprecedented study of the elusive beaked whales. During the cruise, three Drifting Acoustic Spar Buoy Recorders (DASBRs) designed at NOAA were deployed at sites around the Hawaiian Islands. The acoustic data were coupled with continuous CTD sampling, permitting acoustic detection of the beaked whales for association with genetic information from water samples. The data are still being analyzed to provide knowledge of these whale communities that is essential for their protection and for reducing negative human impacts on their populations.

MAPPING THE GAPS

Led by Sam Wilson, University of Hawai'i

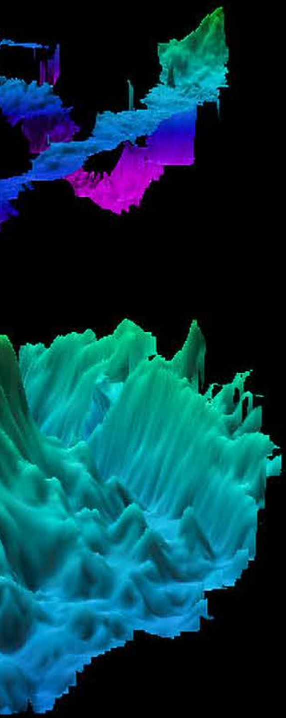
During a transit of opportunity, R/V *Falkor*'s marine technicians mapped 63,619 km^2 of seafloor while training two Student Opportunities participants and an Artist-at-Sea. Additionally, a new autonomous instrument was tested to measure the rate of nitrogen fixation in the surface ocean along the equator. Some species of algae located near the equator fix their own nitrogen, and scientists can derive the rate of nitrogen fixation from the amount of hydrogen gas this process produces. The nitrogen cycle is critical to ocean ecosystem functioning by supporting new production in this nutrient-limited environment. The instrument is in development, with the goal of building a self-operating machine that traces the amount of hydrogen produced by algae species as a result of biological nitrogen fixation.



Three-dimensional display of bathymetry showing seamounts mapped on the transit from Hawai'i to Fiji.

On the aft deck, Archel Benitez (Lead Deckhand) assists Adam Newell (Engineer/Pilot, L3 Latitude) with transporting one of the unmanned aerial vehicles from its transportation crate to the flight deck above.

Capable of flying for 12 hours, this L3 Harris HQ-90UAV unmanned aerial vehicle transitions into horizontal flight and vanishes into the distance after a graceful vertical launch.



AERIAL INVESTIGATION OF SEA SURFACE DYNAMICS

Led by Christopher Zappa, Lamont-Doherty Earth Observatory of Columbia University, in collaboration with Universität Oldenburg, NASA Goddard Space Flight Center, Georgia Institute of Technology, and Korea Polar Research Institute

An impressive coordinated array of unmanned aerial vehicles (UAVs) equipped with fully automated vertical takeoff and landing (VTOL) was used aboard R/V *Falkor* to study the sea surface microlayer during this expedition. This top layer of the ocean—less than 1 mm thick—mediates all interactions between the ocean and atmosphere. Understanding this gateway is essential for improving models of sea surface temperature and biogeochemical cycling. Building upon initial work done on *Falkor* in 2016, the team used highly accurate sensors on the aircraft to map the temperature and color of the ocean surface in high spatial and temporal resolution at image scales of 10 cm or less in near real time. The expanded observation abilities available on this expedition led to finding large rafts of pumice floating on the ocean surface and enormous blooms of *Trichodesmium* that extended kilometers into the horizon. Both the pumice and *Trichodesmium* patches showed clear evidence of near-surface ocean heating patterns. Over a period of five weeks, three aircraft were flown with four different payloads to study the surface skin layer of the ocean for over 240 hours, collecting 43 TB of data, and covering a distance of more than 19,000 km. The technology used will help future scientists to answer a multitude of urgent questions about ocean heat and carbon uptakes and their impacts on global temperatures, storms, and fisheries.

What's Next

By Alan P. Leonardi and Robert D. Ballard

Today's heightened interest in the global ocean is evidenced by governments recognizing the ocean's importance in supporting our environmental and economic security and the private sector's growing realization that the ocean provides important business opportunities. Philanthropy is advancing efforts to preserve this common heritage of humankind, and the public is increasingly aware of and interested in the value of the ocean in their daily lives. To say there is a modern-day ocean renaissance would be an understatement.

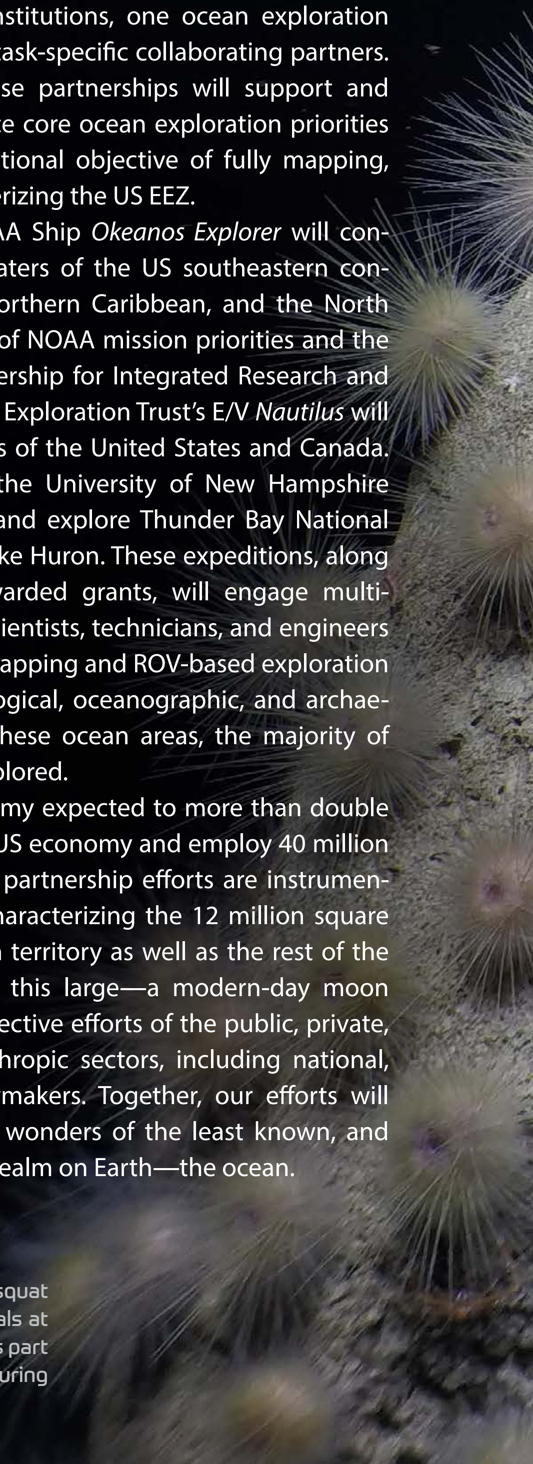
Throughout this supplement to *Oceanography*, we show how NOAA and its many partners focus on exploring and understanding our ocean for the benefit of humanity. We are advancing new technologies, establishing new public and private partnerships, and delivering deep ocean data to scientists and the public worldwide at unprecedented rates and resolutions. Together, these partnerships are mapping ocean bottom features at ever higher resolutions, discovering and documenting new species and geologic formations, demonstrating novel new ocean technologies capable of imaging and sensing the ocean at higher resolution or with more fidelity, and inspiring the next generation of ocean explorers, engineers, educators, and enthusiasts.

Policymakers are also expressing greater interest in ocean exploration and ocean science. The United States Congress has held hearings, and its members and staff have attended forums on ocean exploration. The President of the United States has issued a memorandum to all federal agencies prioritizing the mapping, exploration, and characterization of the US Exclusive Economic Zone. The White House has sponsored a Summit on Ocean Science and Technology Partnerships. And, international governmental and nongovernmental organizations continue to push for better understanding and sustainable use of the high seas. Throughout these efforts, the organizations highlighted in this supplement—and their many partners—are increasingly seen as valued and trusted partners by experts seeking to work with our scientists, engineers, and data specialists.

The national ocean exploration program continues to grow in other ways as well. New partnerships with private, not-for-profit, and philanthropic organizations such as Schmidt Ocean Institute, Ocean Infinity, OceanX, Caladan Oceanic, and Vulcan Incorporated are greatly expanding our abilities to explore and understand the deep ocean. NOAA recently established the Ocean Exploration Cooperative Institute, led by the University of Rhode Island and involving a unique consortium of four graduate degree-granting institutions, one ocean exploration nonprofit, and several task-specific collaborating partners. Working together, these partnerships will support and technologically enhance core ocean exploration priorities and help meet the national objective of fully mapping, exploring, and characterizing the US EEZ.

At sea in 2020, NOAA Ship *Okeanos Explorer* will conduct expeditions in waters of the US southeastern continental margin, the northern Caribbean, and the North Atlantic, all in support of NOAA mission priorities and the Atlantic Seafloor Partnership for Integrated Research and Exploration. The Ocean Exploration Trust's E/V *Nautilus* will explore the west coasts of the United States and Canada. OET and partners at the University of New Hampshire will continue to map and explore Thunder Bay National Marine Sanctuary in Lake Huron. These expeditions, along with competitively awarded grants, will engage multidisciplinary teams of scientists, technicians, and engineers to conduct undersea mapping and ROV-based exploration of the geological, biological, oceanographic, and archaeological resources of these ocean areas, the majority of which are largely unexplored.

With the Blue Economy expected to more than double its contribution to the US economy and employ 40 million people by 2030, these partnership efforts are instrumental to exploring and characterizing the 12 million square kilometers of US ocean territory as well as the rest of the ocean beyond. A task this large—a modern-day moon shot—requires the collective efforts of the public, private, academic, and philanthropic sectors, including national, state, and local policymakers. Together, our efforts will reveal the secrets and wonders of the least known, and likely most important, realm on Earth—the ocean.



Sea urchins dominate the top of the carbonate ridge, with some squat lobsters and *Enallopsammia* sp. and *Thouarella* sp. deep-sea corals at 383 m depth on the west side of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

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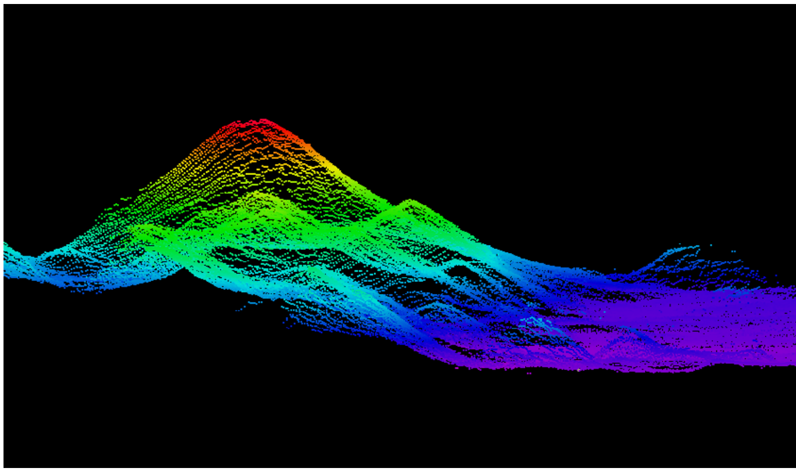
Image of a dumbo octopus (*Opisthoteuthis agassizii*). The dots are clear windows in the skin that may gather additional light. *Image credit: NOAA OER*



Raw point cloud of multibeam data collected by R/V *Falkor* on the transit from Hawaiʻi to Fiji (where permitted). Each point in the cloud represents a separate return (sound reflection) from one of the beams of *Falkor*'s echosounders. The blue and purple colors represent deeper parts of the seafloor, and the red represents shallower. *Image credit: Schmidt Ocean Institute.*

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A hermit crab was observed on an octocoral (tentatively identified as a plexaurid) during the R/V *Falkor* "Necker Ridge: Bridge or Barrier?" expedition that took place over September and October of 2019. *Image credit: Schmidt Ocean Institute*

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A goosefish (*Sladenia* sp.) was observed at 920 m depth perched on a seamount north of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

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At 970 m depth, a cusk eel swims above a seamount north of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

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A primnoid coral colony with seastar associates and a basket star imaged at 1,460 m depth on a seamount north of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

A *Chaceon* sp. crab imaged at 994 m depth under a ledge on a seamount north of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*

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In 2019, NOAA Ship *Okeanos Explorer* surpassed its 100th mission, mapping over 175,000 km^2 of seafloor and collecting more than 200 biological samples and 17 geological samples that are stored in publicly accessible repositories for further study by the scientific community. The year also brought unprecedented White House and congressional support to expand the scope and direction of NOAA's undersea mission, and a new Ocean Exploration Cooperative Institute was established that will leverage the expertise and synergy of public-private partnerships. Exploring the 12 million square kilometers of submerged US ocean territory will strengthen the economy, spur technology development, and inspire the next generation of scientists, engineers, and educators. We closed 2019 positioned to boldly move ahead with our partners to meet these objectives and advance the nation's ocean exploration program.

OER would like to acknowledge science writer Eric Niiler from Chevy Chase, Maryland, and OER graphic designer Matthew King for their expertise and creative contributions to this year's supplement.

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A colorful swallowtail bass (*Anthias woodsi*). *Image credit: NOAA OER*

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This octocoral and brittle star associate were documented during the Windows to the Deep 2019 expedition. *Image credit: NOAA OER*

A squat lobster was sampled at ~722 m depth using the suction sampler during the Windows to the Deep 2019 expedition. *Image credit: NOAA OER*

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Acronyms

ASPIRE.........................Atlantic Seafloor Partnership for Integrated Research and Exploration

ASV...............................Autonomous surface vehicle

AUV..............................Autonomous underwater vehicle

BEN..............................Bathymetric Explorer and Navigator

BOEM..........................Bureau of Ocean Energy Management

CAPSTONE.................Campaign to Address Pacific monument Science, Technology, and Ocean NEeds

CCOM..........................Center for Coastal and Ocean Mapping at the University of New Hampshire

CIOERT........................Cooperative Institute for Ocean Exploration, Research, and Technology

CTD..............................Conductivity, temperature, depth sensor

DAS..............................Distributed acoustic sensing

DEEP SEARCH...........Deep Sea Exploration to Advance Research on Coral/Canyon/Cold seep Habitats

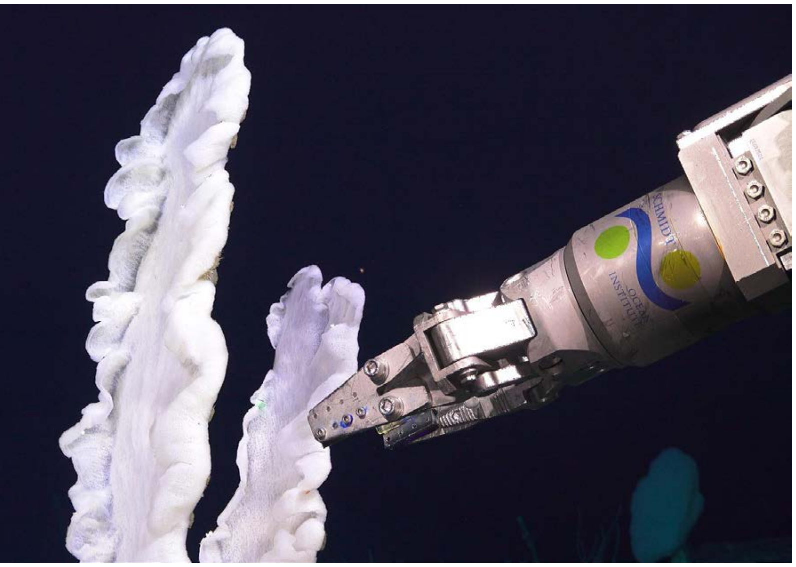
ECS...............................Extended Continental Shelf

eDNA...........................Environmental DNA

EEZ...............................Exclusive Economic Zone

EiT.................................Explorer-in-Training

E/V................................Exploration Vessel



ROV *SuBastian* takes a sample of a glass sponge (believed to be *Tretopleura* sp.) during the R/V *Falkor* "Necker Ridge: Bridge or Barrier?" expedition that took place over September and October of 2019. *Image credit: Schmidt Ocean Institute*

Photo of a ~50 cm long Tomopterid polychaete. These worms are covered almost entirely by scales known as elytra, which can be shed and regenerated as a means of defense in many species. The scales of some species are faintly bioluminescent, as this one appears to be. *Image credit: Schmidt Ocean Institute*

FAU...............................Florida Atlantic University

FGBNMS.....................Flower Garden Banks National Marine Sanctuary

FY..................................Fiscal Year

GEBCO........................General Bathymetric Chart of the Oceans

GIS................................Geographic information system

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

ISC................................Inner Space Center

MBNMS......................Monterey Bay National Marine Sanctuary

NCEI.............................NOAA National Centers for Environmental Information

NMS.............................National Marine Sanctuary

NOAA..........................National Oceanic and Atmospheric Administration

OER..............................NOAA Office of Ocean Exploration and Research

OET..............................Ocean Exploration Trust

ONC.............................Ocean Networks Canada

PRIMNM.....................Pacific Remote Islands Marine National Monument

ROV.............................Remotely operated vehicle

R/V................................Research Vessel

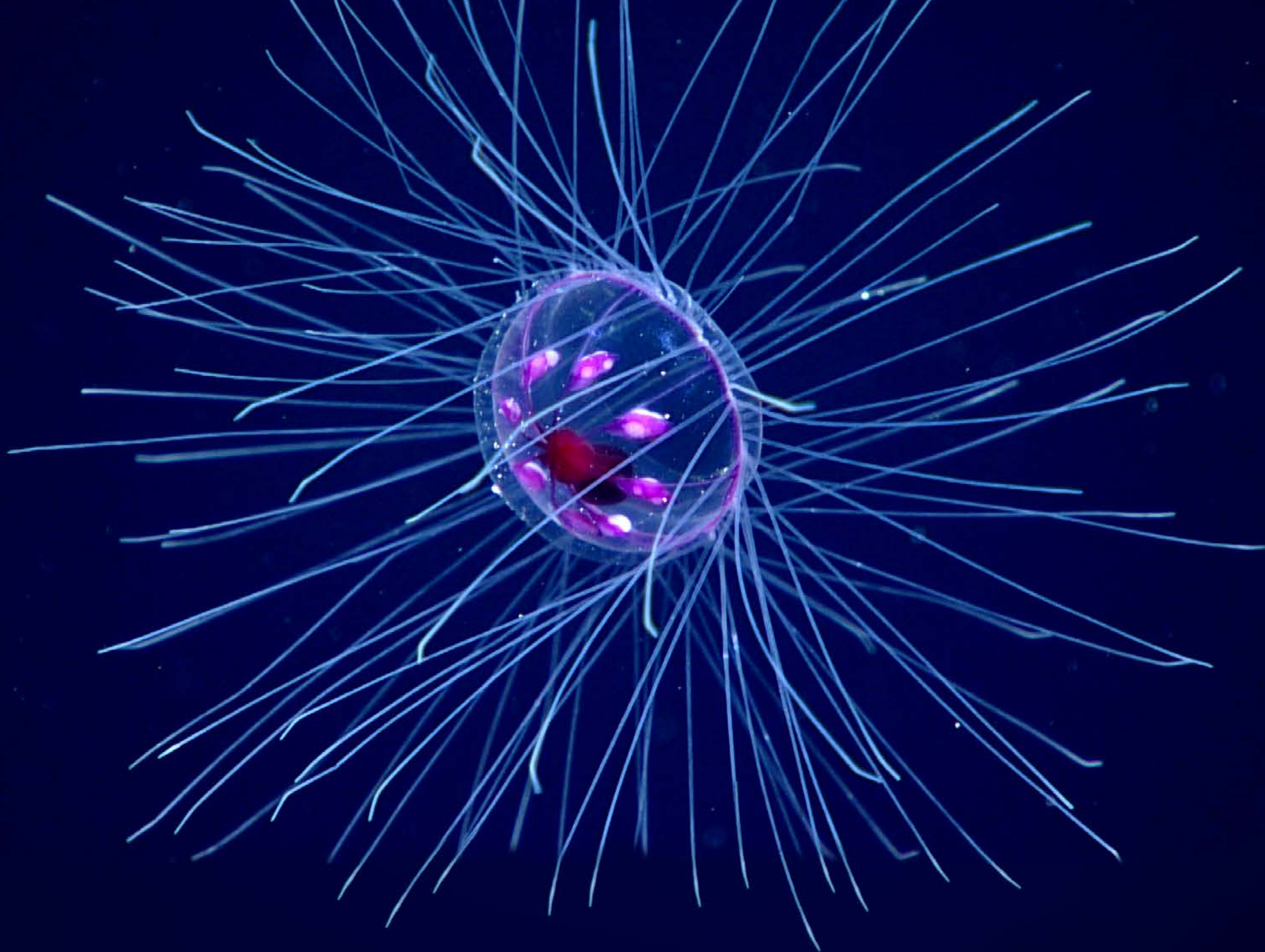
SOI................................Schmidt Ocean Institute

STEM............................Science, technology, engineering, and mathematics

URI................................University of Rhode Island

USGS............................United States Geological Survey

WHOI...........................Woods Hole Oceanographic Institution



This colorful jelly (*Crossota millsae*) put on quite a show for the lucky viewers who watched its water column acrobatics while it was feeding. *Image credit: NOAA OER*

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Paracalyptrophora sp. and a pink *Hemicorallium* sp. coral colony observed at 964 m depth on a seamount north of Jarvis Island, a US territory that is part of the Line Islands in the Pacific Ocean. The image was captured during E/V *Nautilus* expedition NA110. *Image credit: OET/WHOI MISO*