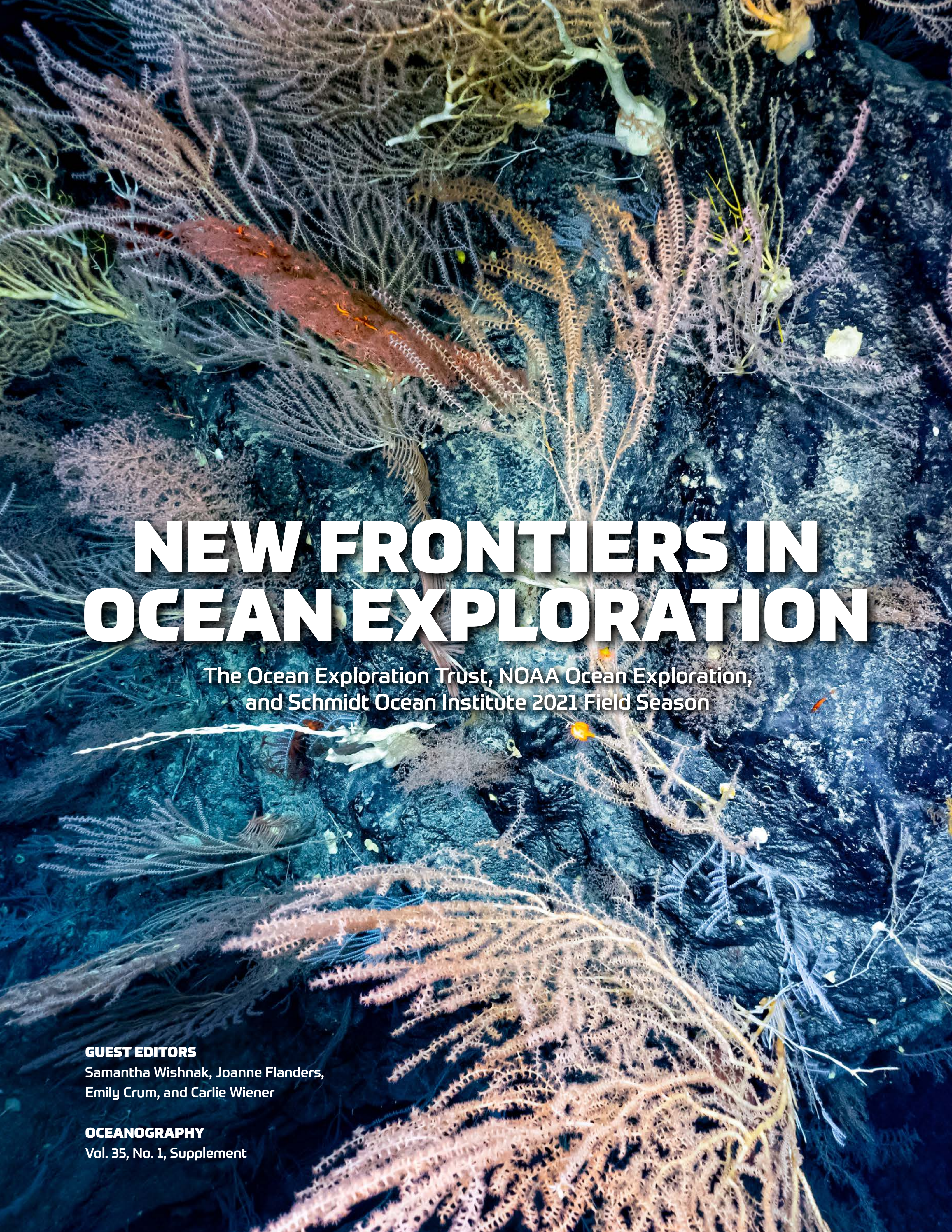

NEW FRONTIERS IN OCEAN EXPLORATION

The Ocean Exploration Trust, NOAA Ocean Exploration, and Schmidt Ocean Institute 2021 Field Season

GUEST EDITORS
Samantha Wishnak, Joanne Flanders, Emily Crum, and Carlie Wiener

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ON THE COVER

A diversity of deepwater coral species was imaged on Ha‘aheo Seamount during E/V *Nautilus* expedition Lu‘uaeaāhikiikapapakū (NA134) in Papahānaumokuākea Marine National Monument. *Image credit: Ocean Exploration Trust*

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BELOW

A squat lobster perches atop a bubblegum coral on San Juan Seamount in the Southern California Borderland. The image was taken by remotely operated vehicle *SuBastian* as researchers investigated several sites where marine minerals are known (or expected) to occur, while assessing the biological communities living among the mineral substrates. *Image credit: ROV* SuBastian/ *Schmidt Ocean Institute*

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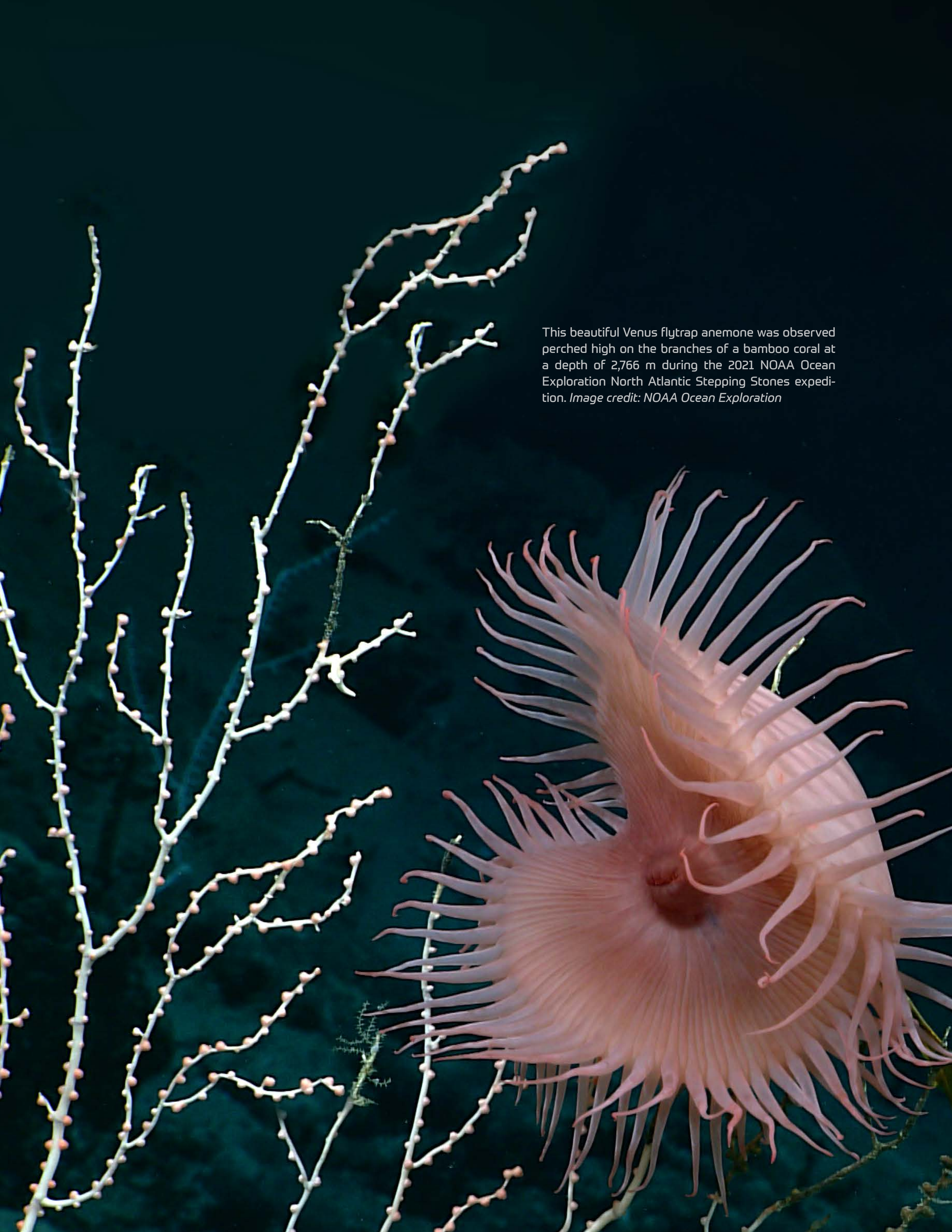


This beautiful Venus flytrap anemone was observed perched high on the branches of a bamboo coral at a depth of 2,766 m during the 2021 NOAA Ocean Exploration North Atlantic Stepping Stones expedition. *Image credit: NOAA Ocean Exploration*

INTRODUCTION

By Samantha Wishnak, Genene Fisher, and Carlie Wiener

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

Expedition programs in 2021 featured exploration of two ocean basins, with *Nautilus* off the west coast of the United States and British Columbia, and out to the Central Pacific; *Okeanos Explorer* in the North Atlantic; and *Falkor* leaving the Pacific to return to the Atlantic Ocean. All three organizations continued to develop shipboard and shoreside collaborations to adapt to conducting operations at sea during the evolving COVID-19 pandemic. The pages that follow contain expedition summaries, including initial results, highlights of new scientific programs and education and outreach initiatives, and previews of future exploration plans.

The first expeditions of the 2021 *Nautilus* season centered on the west coast of North America, featuring oxygen minimum zones off southern California (pages 26–27), methane seeps on the Cascadia margin (pages 28–29), and continued work with University of Victoria's Ocean Networks Canada (ONC) to support its offshore cabled observatory (pages 30–31). As *Nautilus* neared the end of the ONC expedition, the remotely operated vehicles (ROVs) *Hercules* and *Argus* became detached from the vessel, and thanks to the incredible support of the oceanographic community, we were able to quickly mount a recovery mission (pages 32–33). Next, *Nautilus* hosted the first NOAA Ocean Exploration Cooperative Institute (OECI) technology demonstration, which focused on advancing the efficiency and effectiveness of vehicle technology and engineering for ocean exploration (pages 34–35 and 62–63). *Nautilus* then mapped its way to Hawai'i to begin a multi-year emphasis on exploring the US Exclusive Economic Zone (EEZ) in the Central Pacific. Two expeditions within and near Papahānaumokuākea Marine National Monument (PMNM) included ROV surveys on seamount chains to document coral and sponge communities and to lay the groundwork for 2022 surveys (pages 36–39). During the field season, several expeditions mapped large swaths of seafloor to fill gaps in existing bathymetric data, supporting OECI goals as well as those of national and international collaborations to map the entire global seafloor by 2030 (pages 24–25). The OET section of the supplement includes detailed summaries of *Nautilus* shipboard technologies (pages 8–15), specimen collection highlights (pages 16–17), and early findings from several expeditions. In preparation for our work within PMNM, OET expanded its suite of education and outreach offerings and collaborated with local partners to co-develop meaningful outreach and education opportunities that incorporate Hawaiian culture and worldview into *Nautilus* expeditions (pages 18–21). In addition to the E/V *Nautilus* field season, OET also partnered with the University of New Hampshire and the NOAA Office of National Marine Sanctuaries to conduct an inland expedition at Thunder Bay National Marine Sanctuary located in Lake Huron (pages 40–41).

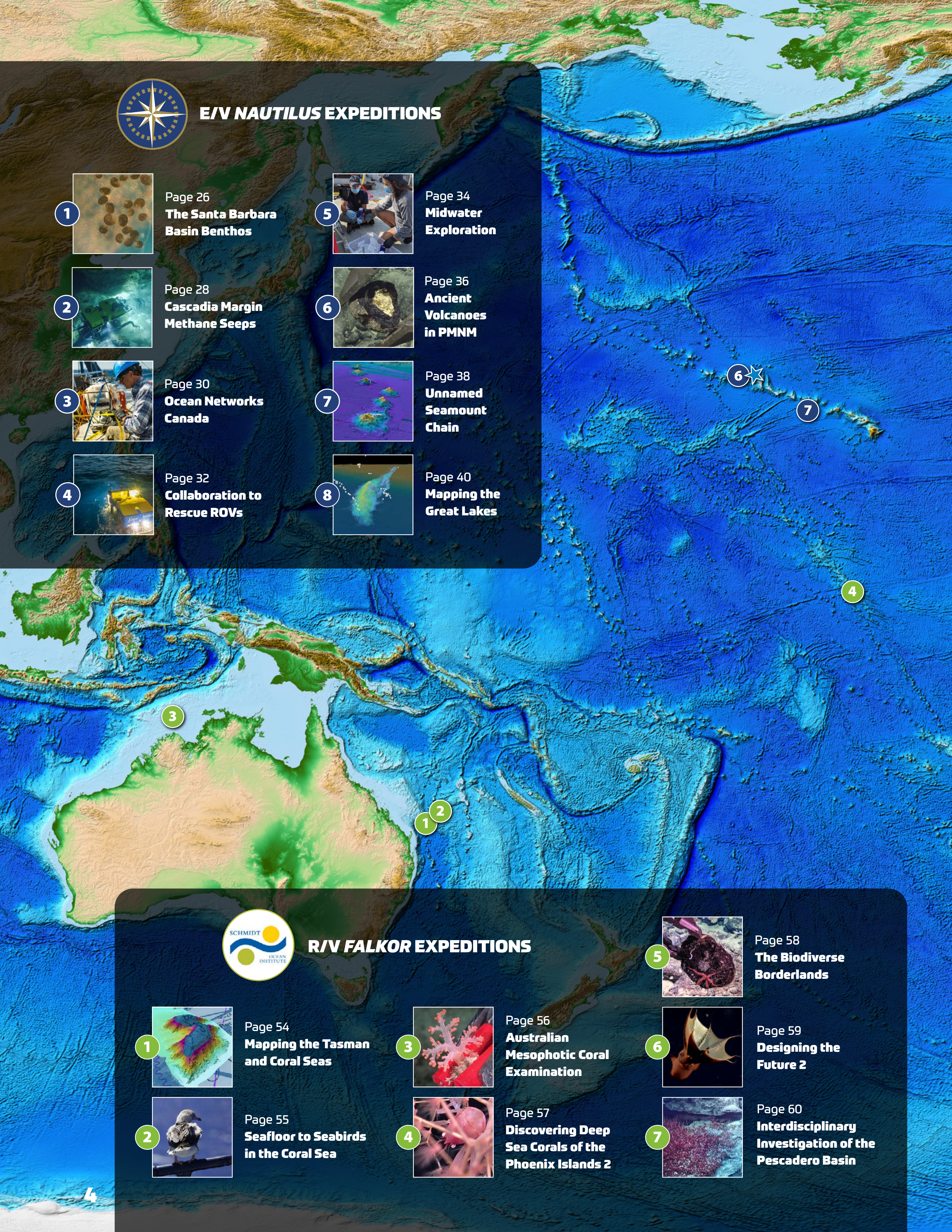
The second section of this supplement features NOAA Ocean Exploration's 2021 season, with the pace and efficiency of mapping operations increasing, and *Okeanos Explorer* becoming the first ship in the world to receive a complete upgrade to Kongsberg's new EM 304 multibeam sonar (page 44). Season highlights include the exploration of Blake Plateau off the coast of the southeastern United States (page 44), when NOAA Ocean Exploration marked the mapping of 2,000,000 km^2 of seafloor since *Okeanos Explorer* was commissioned in 2008. A pilot project to process mapping data in the cloud created an environment in which simultaneous work on data could occur from anywhere in the world (page 44). Highlights from the North Atlantic Stepping Stones expedition are presented (page 46), and there is an overview of ROV operations and how they inform exploration, as well as a brief description of discoveries, including the first visual confirmation of ferromanganese nodule fields in the New England Seamount Chain (page 46). NOAA Ocean Exploration moved on to investigate the Blake Spur where rich sponge gardens were revealed (page 46), before discovering and exploring SS *Bloody Marsh*, a World War II-era oil tanker sunk off the coast of South Carolina by a German U-boat (page 46). NOAA Ocean Exploration support for advancing technology is featured, describing emerging tools such as 'omics as well as testing and deployment of two autonomous sensor platforms. An update on *DriX*, a technology the OECI is developing, is included. An overview of maritime heritage work highlights the discovery, with "reasonable certainty," of US Revenue Cutter *Bear* following a nearly two-decade search for this historically significant ship of exploration (page 48). This section of the supplement concludes with a summary of NOAA Ocean Exploration's expanded diversity and inclusivity efforts during the year (page 49) before turning to outreach and education endeavors that included a "brand refresh," a new education website, and an expansion of internship opportunities (page 50).

In 2021, Schmidt Ocean Institute's research vessel *Falkor* traveled across the Pacific, then made its way back to the Atlantic to prepare for passing the baton to the newly acquired research vessel *Falkor (too)* and marking a new era of oceanographic research and evolution for the institute. The final section of the supplement reviews an extraordinary year for SOI activities, including the seven expeditions that took place in Australian waters and beyond, as well as the institute's Artist-at-Sea program and growing partnerships activities (pages 52–61).

A key part of all three organizational missions is sharing research and expeditions with students, educators, and the general public through collaborations that allow all partners to amplify their work. OECI, a consortium of five organizations that work together to advance ocean exploration technology and training in concert with NOAA Ocean Exploration, moved forward into its third year with operations and educational outreach (pages 62–63). Over the last two years, NOAA Ocean Exploration, the Ocean Exploration Trust, and Schmidt Ocean Institute collaborated to build a single online hub for ocean science and exploration-themed educational resources, which launched in summer 2021 (pages 64–65). Collaborating across the ocean exploration field, the Inner Space Center at the University of Rhode Island supports professional development, online learning, and live event programming (pages 66–67).

Looking ahead at 2022, the Ocean Exploration Trust will continue to build upon partnerships and research from E/V *Nautilus* within the Central Pacific, particularly Papahānaumokuākea Marine National Monument and the Pacific Remote Islands Marine National Monument. During summer 2022, NOAA Ocean Exploration's *Okeanos Explorer* will work along the Mid-Atlantic Ridge and then transit to the Panama Canal, crossing into the Pacific in August to begin exploration off the US West Coast. The year will bring a sea change for Schmidt Ocean Institute, with delivery of *Falkor (too)* in fall 2022. We all look forward to continuing to explore the ocean and to connecting diverse communities with the deepest parts of our planet (pages 68–69).

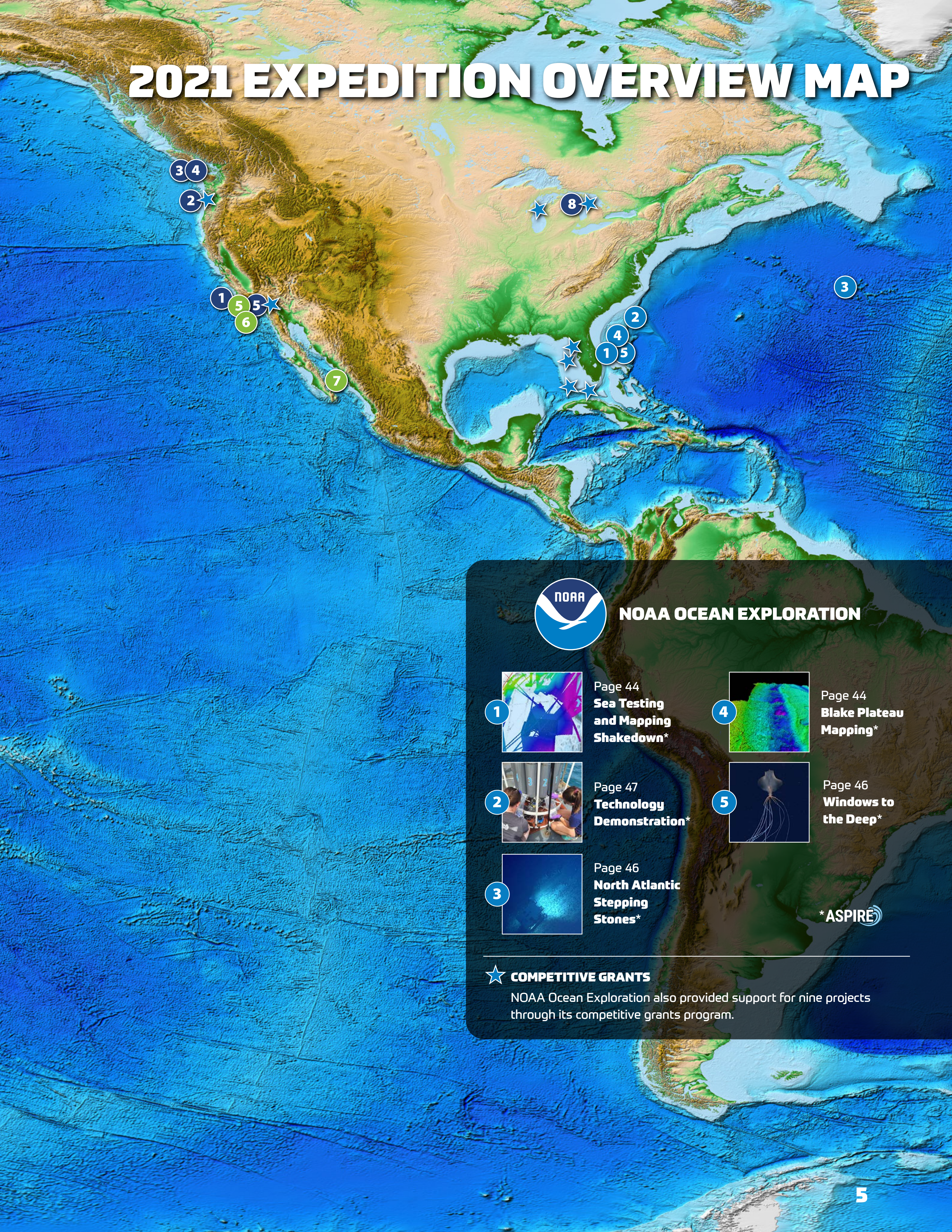
Hemicorallium sp., an octocoral in the precious coral family Coralliidae, observed in Papahānaumokuākea Marine National Monument during E/V *Nautilus* expedition NA134. *Image credit: OET*



E/V *NAUTILUS* EXPEDITIONS

R/V *FALKOR* EXPEDITIONS

2021 EXPEDITION OVERVIEW MAP



NOAA OCEAN EXPLORATION

1 Page 44 **Sea Testing and Mapping Shakedown***

2 Page 47 **Technology Demonstration***

3 Page 46 **North Atlantic Stepping Stones***

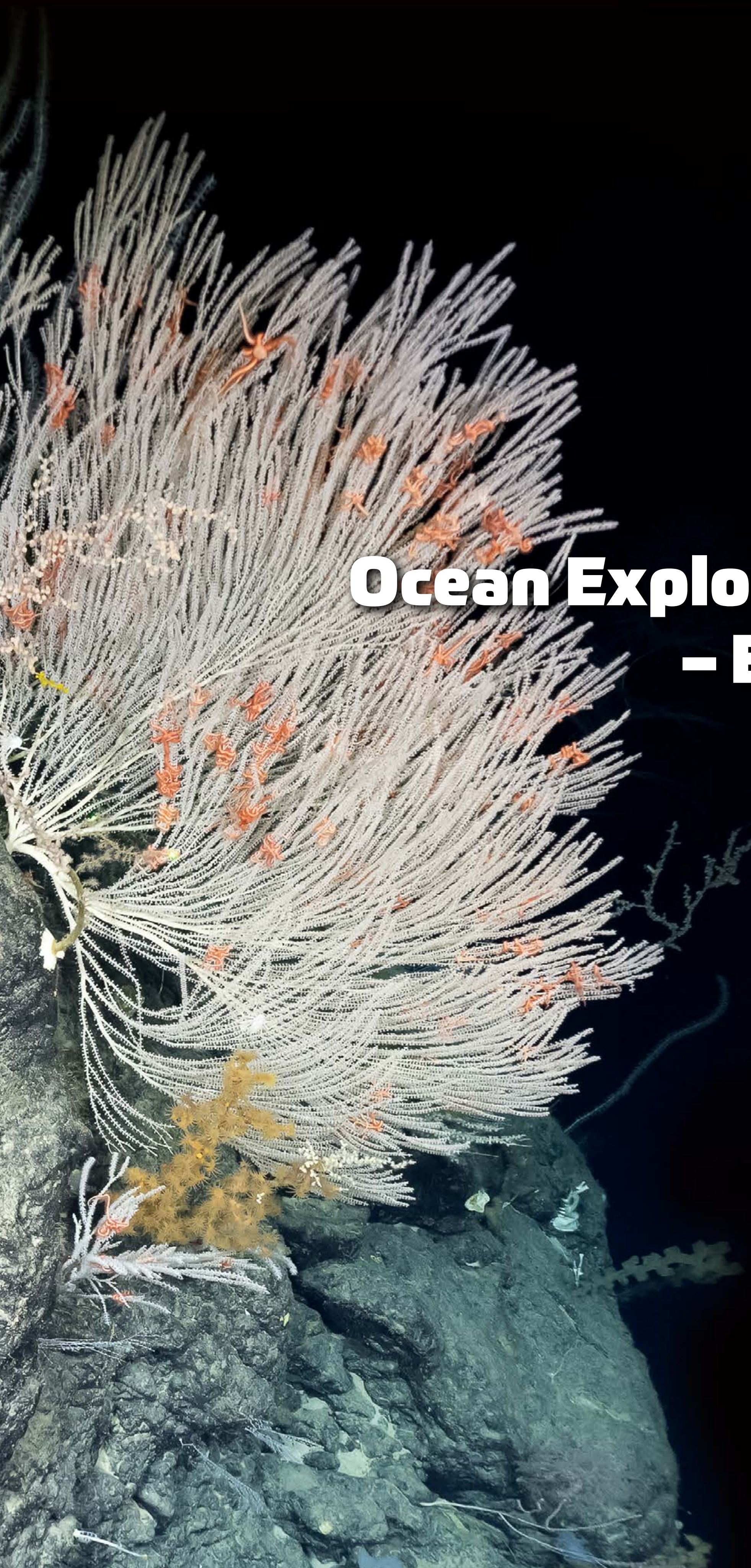
4 Page 44 **Blake Plateau Mapping***

5 Page 46 **Windows to the Deep***

*ASPIRE

★ **COMPETITIVE GRANTS**

NOAA Ocean Exploration also provided support for nine projects through its competitive grants program.



PART 1

Ocean Exploration Trust – E/V *Nautilus*

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

TECHNOLOGY

E/V *Nautilus*

Exploration Vessel (E/V) *Nautilus* is an efficient 68-meter ship, with berthing for 17 permanent crew members in addition to 33 berths for members of the rotating Corps of Exploration. The ship is equipped with a Kongsberg EM 302 multibeam echosounder and two remotely operated vehicles (ROVs), *Hercules* and *Argus*. *Nautilus* has a data lab and newly renovated 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. 68.23 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. Four 6.1-meter (20-foot) vans

COMPLEMENT. 17 crew; 33 science and operations

FLAG. St. Vincent and the Grenadines

ADDITIONAL EQUIPMENT

- Dynacon 369i ROV winch with 7,000 meters (23,000 feet) of 1.73 centimeter (0.681 inch) diameter electro-optic Rochester 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; crane and 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 stabilized Sea Tel 9711 uplink antenna capable of C- and Ku-band operation of up to 20 Mbps (C-band circular or linear)

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

CAMERAS. 23 high-definition cameras: aft port, amid and starboard (pan/zoom/tilt), transom, bow, Command Center (7), wet lab, ROV hangar, winch hold (6)

COMMUNICATIONS
- Ship-wide RTS Odin intercom system for shipboard communications and connection with shoreside participants
- Software audio connection for global participants using VLink multi-platform intercom client (Mac, Windows, Android, iOS); telephone interface is available through a Rhode Island exchange for real-time collaboration between scientists ashore and on the ship
- Full Internet connectivity from shipboard LAN and wifi
- KVH TracPhone-v7 for redundant bridge communication, providing telephone and IP service

DATA PROCESSING & VISUALIZATION LAB

AREA. 44.5 square meters (480 square feet)

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

RACK ROOM

AREA. 17.3 square meters (185 square feet)

DATA STORAGE. 50 TB onboard 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. UHD Panasonic BGH1 studio camera; Sony A1 camera kit for topside video with live broadcast capacity via Teradek 500

PRODUCTION. 8-input video production switcher for live-produced interactions; full production editing workstation with ship-to-shore transmit capacity for remote production needs

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
- Panasonic MDF-C8V1 ULT –80°C/–86°C scientific freezer, 0.085 cubic meters (3 cubic feet)
- Two science refrigerators, approximately 0.57 cubic meters (20 cubic feet) each
- Science freezer, –20°C, 0.14 cubic meters (5 cubic feet)

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

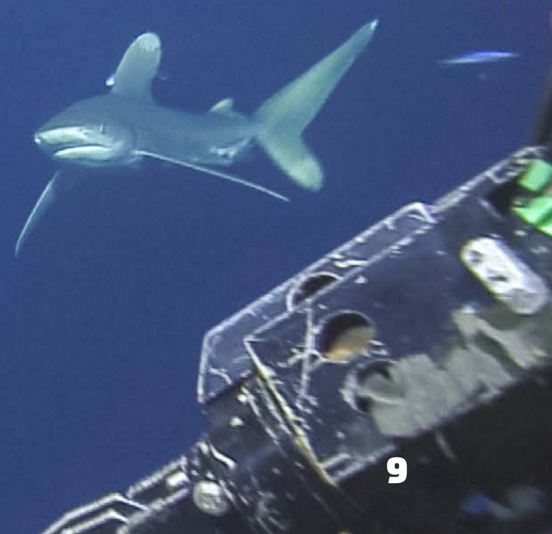
STORAGE. Storage for spares and other equipment

CONTROL, COMMAND, & OUTREACH VANS

AREA. 43 square meters (476 square feet)

WORKSTATIONS. Twelve; typical configuration for ROV operations: two to four scientists, data logger, pilot and copilot, navigator, video engineer, educator

VIDEO RECORDING AND STORAGE. Two Cinedeck ZX85 video recorders that capture ROV footage in two simultaneous codecs, two Blackmagic Hyperdeck uncompressed 4K recorders, two AJA KiPro Go recorders, 2x LTO-6 archive media drives, 2x LTO-8 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, including gas seeps, and creating bathymetric maps for ROV dive planning and situational awareness. 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 up to 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. 1%–5% water depth (e.g., 10–50 meters [33–164 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 (3.5/15 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 echosounding 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 SYSTEMS

SYSTEM. Sonardyne Ranger 2 with Lodestar GyroUSBL transceiver deployed from the moonpool for USBL tracking of ROVs *Hercules* and *Argus*

RANGE. Up to 7,000 meters (22,966 feet)

POSITIONING ACCURACY. 0.5% of slant range

OPERATIONAL COVERAGE. ±90°

OPERATING FREQUENCY. 19–34 kHz

TARGETS TRACKED. *Hercules*, *Argus*, and two additional transponders are available. More targets can be tracked with the addition of compatible Sonardyne transponders

SYSTEM. TrackLink 5000MA system for backup 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

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, 4x 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. 30 meters/minute (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

USBL NAVIGATION. Sonardyne Ranger 2

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

ALTIMETER. Benthos PSA-916

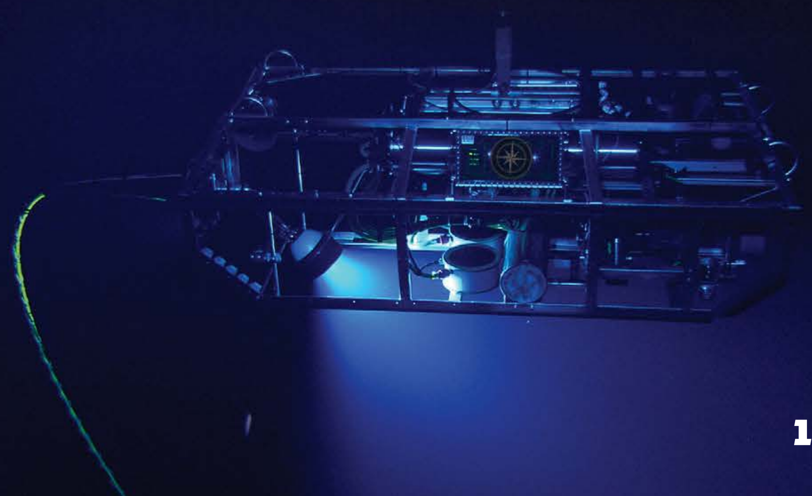
FORWARD-LOOKING SONAR. Mesotech 1071, 300 kHz, 0.5–100 meter (1.6–328.1 foot) range typical

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

SCIENTIFIC INSTRUMENT SUPPORT

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

DIGITAL DATA CHANNELS. Ethernet



Remotely Operated Vehicle *Hercules*

Since it was first launched in 2003, ROV *Hercules* has been working in tandem with ROV *Argus* to explore the geology, biology, archaeology, and chemistry of the deep sea. *Hercules* is equipped with a high-definition video camera, several LED lights, two manipulator arms, and a variety of oceanographic sensors and samplers. A suite of high-resolution mapping tools is available for use upon request. *Hercules* can deliver up to 113 kg (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, tunable from 400 kHz to 1,000 kHz; range to 200 m (656 feet) at 450 kHz; range resolution up to 3.75 mm (0.15 inch)
- TriTech Super SeaKing V7 scanning sonar, 325 kHz and 675 kHz; range 0.4–300 meters (1.3–984 feet); range resolution 0.015 m (0.05 feet)

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. Fifteen 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

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

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
- Kongsberg M3 multibeam sonar
- Norbit wideband mulitbeam sonar - forward or downward facing
- 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 (7 feet long × 3.28 feet wide × 3.94 feet tall)

WEIGHT. 1,000 kilograms (2,200 pounds) in air; 771 kilograms (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) SeaLite LSL-1000 sphere lights

VEHICLE SENSORS & NAVIGATION

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

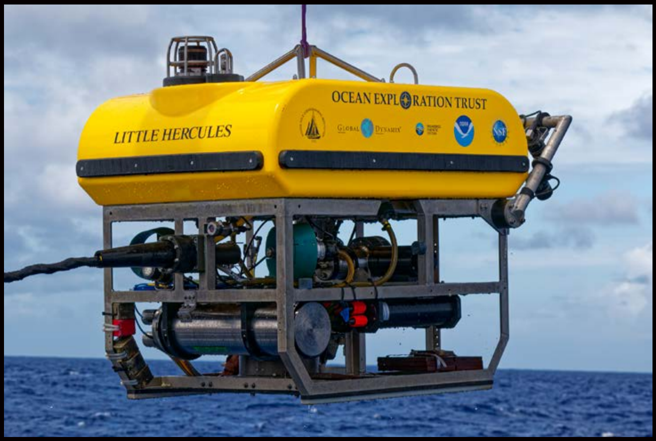
ALTIMETER. Valeport VA500 500 kHz altimeter

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

SCIENTIFIC INSTRUMENT SUPPORT

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

DIGITAL DATA CHANNELS. Ethernet, RS-232



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 (4.59 feet long × 3.28 feet wide × 3.93 feet tall)

WEIGHT. 400 kilograms (900 pounds) in air;
45.36 kilograms (100 pounds) 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 or ultra high definition
- Two mini utility cameras (fixed mounted), 480 line NTSC format

LIGHTING. Four Deepsea Power & Light LED sphere lights

Remotely Operated Vehicle *Little Hercules*

VEHICLE SENSORS & NAVIGATION

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

ALTIMETER. Valeport VA500 500 kHz altimeter

FORWARD-LOOKING SONAR. Kongsberg Mesotech 1071 scanning sonar, 675 kHz, 1–200 meter (3–656 feet) range typical

SCIENTIFIC INSTRUMENT SUPPORT

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

DIGITAL DATA CHANNELS
- RS-232 serial
- Ethernet: 10/100/1,000 mbps links available

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

2021 TECHNOLOGY COLLABORATIONS

- OREGON STATE UNIVERSITY. Sexton still camera
- UNIVERSITY OF RHODE ISLAND. Norbit wideband multibeam sonar

FROM SEEPS TO SEAMOUNTS

E/V *Nautilus* Expedition Samples in 2021

By Steven Auscavitch, Lila Ardor Bellucci, Tamara Baumberger, Elizabeth Miller, Christopher Kelley, and Nicole Raineault

Continued efforts by the Ocean Exploration Trust staff, contractors, and partners to engage the Scientist Ashore community resulted in an increased quantity and diversity of samples collected by E/V *Nautilus* in 2021. Season-wide, over 450 sample collections were recovered, including biological voucher specimens, sediment cores, rocks and crusts, and eDNA extracts. Scientists Ashore were able to connect and participate via the integrated OET Science Portal that allowed more comprehensive interaction with watch standers on board *Nautilus* using collaborative tools. Building on the success of the 2020 season's collaborative sampling effort, a sample request tracker was employed for collections in the Papahānaumokuākea Marine National Monument (PMNM) and the Exclusive Economic Zone (EEZ) surrounding Hawai'i to maximize the availability of sampling products to the scientific community and to minimize disturbance of monument biological, geological, and cultural resources. From these areas, 132 rock samples and cores totaling over 650 kg of material were collected and sent to the Marine Geological Samples Laboratory at the University of Rhode Island Graduate School of Oceanography for curation. In addition, 166 biological samples were deposited at the Museum of Comparative Zoology at Harvard University to facilitate scientific studies of biodiversity in these regions.

CASCADIA MARGIN SEEP ECOSYSTEMS – Tamara Baumberger and Lila Ardor Bellucci

Over the past decade, the number of known active methane seeps along the Cascadia margin has increased dramatically from fewer than 100 to more than 1,000 (Merle et al., 2021). To better understand their influence on the biogeochemistry and ecology of the region, 34 of these sites have now been characterized by E/V *Nautilus* ROVs, and an additional five have been visited by R/V *Falkor*'s ROV *SuBastian*. Working with NOAA Ocean Exploration and OET, cruise NA128 investigated diverse seep sites within six regions along the Cascadia margin off the US Pacific Northwest coast to identify relationships among depth, geological setting, chemical composition, methane output, and the biological community supported. Over 150 bulk samples of gas, methane hydrate, seawater, sediment, rock, and fauna were collected from actively seeping sites, and they were subsampled for a wide range of analyses that are currently underway. Sampling spanned diverse habitats, including bacterial mats, clam beds, tubeworm bushes, background sediments, and the overlying water column (Figure 1). Analysis of these sample collections will increase understanding of the sources and fates of the gas exiting the seafloor, sediment biogeochemistry, microbial and macrofaunal communities in seep-driven ecosystems, and seep-related hard ground formation. An extensive multibeam sonar data set collected by *Nautilus* provides more constraints on the number of seeps at the Cascadia margin and improves methane flux estimates. The detailed maps constructed from this data set allow more in-depth analysis of seafloor structures. Importantly, the data collected along the Cascadia margin will provide a baseline for studies that inform fisheries management decisions, coastal carbon cycles, climate models, and knowledge of the natural resources and hazards along active margins, all of which have wide-ranging implications for the Blue Economy.

FIGURE 1. Samples of vesicomyid clams collected from a seep site off the Cascadia margin during NA128.

SPONGES IN THE PAPAHĀNAUMOKUĀKEA MARINE NATIONAL MONUMENT – Christopher Kelley

Direct collections of sponges from Papahānaumokuākea Marine National Monument yielded insights into potential new sponge species dwelling in this fully protected marine conservation area. In all, 13 sponge specimens were collected during expedition NA134: 12 glass sponges (Hexactinellida) and one demosponge (Demospongiae). The spicules of 11 of these sponges were examined microscopically and photographed on shore following bleach digestion of small aliquots from each specimen (Figure 2). Hexactinellid specimens included three members of the family Farreidae, two in the genus *Farrea*, and one that could only be identified as being a farreid. Other hexactinellid specimens included three pheronematids, all probably in the genus *Poliopogon*; two euplectellids, one a new species in the genus *Hertwigia* and another that is likely a new species in the subfamily Corbitellinae; and two euretids, one a new species in the genus *Periphragella* and the other a new species in the genus *Heterorete*. One of the *Poliopogon* sp. that was bright yellow when collected was also believed to be dying. The lone demosponge was one of the 11 specimens examined microscopically and was determined to be in the genus *Poecillastra*. Two other hexactinellid specimens were not examined microscopically but are believed to be another pheronematid in the genus *Poliopogon* and the other in the family Rossellidae. The current plan is to submit new species descriptions for the *Periphragella* sp. and the *Heterorete* sp. after additional examination this year.

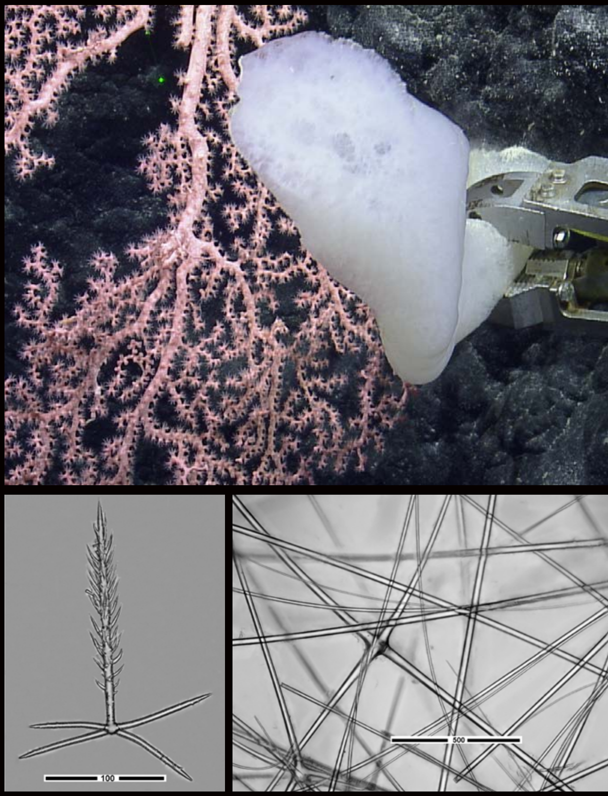


FIGURE 2. Spicule microscopy and in situ imagery for specimen NA134-063, a pheronematid glass sponge in the genus *Poliopogon*. *Image credit: C. Kelley*

DEEP-SEA FOOD WEBS – Elizabeth Miller

Sea cucumbers are abundant and important members of deep-sea communities that consume low-quality detrital material and make it available for higher trophic levels. They have a variety of strategies for surviving on detritus, but the potential role played by their gut microbiomes remains largely unstudied. Symbioses between animals and microbial communities residing in their guts have been widely documented, especially for animals that consume low-quality food. In 2021, seven deposit-feeding sea cucumbers were collected between 500 m and 4,000 m depth around the Hawaiian Islands and across the Papahānaumokuākea Marine National Monument during expeditions NA134 and NA135 (Figure 3). To determine the influence of gut microbiota on their diets, the specimens will be dissected to isolate their gut contents from their body tissues. Gut microbial communities will be characterized using 16S rRNA sequencing, and stable isotope analysis will be used to quantify microbial reworking and processing along the length of the animals' gut tracts. The use of stable isotopes will also indicate what types of organic material, detrital versus microbial, are utilized by sea cucumbers at different depths. As food supply and quality decline with depth, we expect to find that gut communities are increasingly utilized to break down detritus. Deeper-living sea cucumbers may also directly consume their gut bacteria as an additional food source. Obtaining specimens across a wide depth range will permit direct examination of how these animal-microbe symbioses vary as a result of environmental conditions.

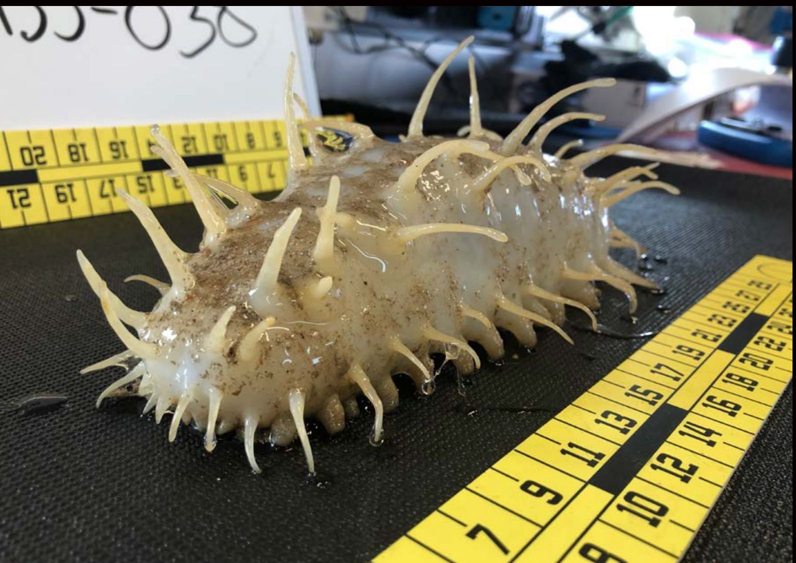


FIGURE 3. A sea cucumber (*Oneirophanta* sp.) collected during NA134 in Papahānaumokuākea Marine National Monument.

Building Community from Ship to Shore Through Ocean Exploration

By Megan Cook, Samantha Wishnak, Kelly Moran, Jonathan Fiely, Jamie Zaccaria, Jacob Ottaviani, Madison Dapcevich, and Emily Ballard

As OET continued to safely conduct at-sea operations amidst the ongoing pandemic, the 2021 E/V *Nautilus* expedition season had a very successful year in education and outreach with the return of our signature programs, including at-sea experiences for educators and students and interactive streaming experiences with the onboard expedition teams. Additionally, we continued to leverage new programs that were developed as a necessity for remote engagement pivots, including a social media live event series (Figure 1) and the expansion of direct ship-to-shore classroom connections.

Celebrating Ocean Exploration Together with Live Streaming and Digital Outreach

Across 10 expeditions and five months, global audiences and learners of all ages joined *Nautilus* in the Eastern Pacific Ocean from California to Canada and in the Central Pacific throughout the Hawaiian Islands and Papahānaumokuākea Marine National Monument. Live exploration streamed from the seafloor onto NautilusLive.org, the online home of the Corps of Exploration, where viewers could dive deeply into the backgrounds and experiences of our role model team, learn about technologies, and enjoy recent discovery highlights. During the 2021 field season, Nautilus Live brought together curious minds for more than 287,000 hours of live stream viewing and received over 19,700 questions submitted to the onboard expedition teams by public audiences online.

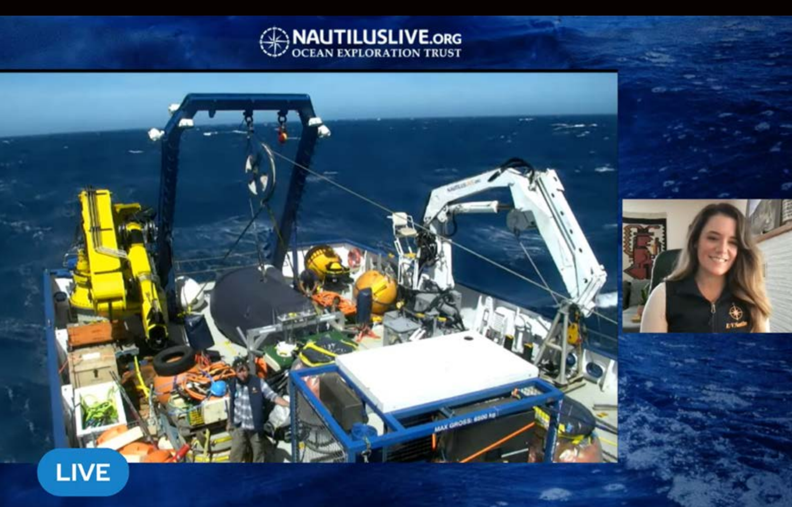


FIGURE 1. Live events introduced audiences to at-sea role models and upcoming expedition objectives in a fun, casual setting perfect for fielding questions from at-home learners and interested fans of ocean exploration.

Building on the momentum of a social media event series that began in 2020, our team produced 14 events this year for YouTube and Facebook audiences via a *Next on Nautilus* series that previewed expedition science and introduced 39 key expedition personnel in a casual format. Supported by the University of Rhode Island's Inner Space Center, this series has tallied over 93,000 views since April 2021.

As ocean exploration discoveries gain broad public attention, our catalog of nearly 15 years of discoveries continues to inspire audiences. Our media library received over 9.1 million views this year and tallied nearly 600,000 viewing hours of ocean discoveries and STEM career content.

Social media platforms continue to be one of the most direct ways to reach young audiences and offer real-time glimpses behind the scenes of shipboard operations. Our social media outreach is a key part of how we share new discoveries and interact with the public and the press around the world. Instagram followers grew by nearly 12%, and YouTube subscribers increased by 10% in 2021. The Corps of Exploration is active in our social media presence including through Instagram Story takeovers, which offer fun and personal introductions to the various roles required for the success of our team. Fourteen team members hosted Instagram takeovers this year, including our first ʻŌlelo Hawaiʻi (Hawaiian language) takeover, generating content that remains discoverable across the platform. Social media remains one of our fastest-growing methods for sharing ocean stories with our 700,000+ followers.

Our return to Papahānaumokuākea Marine National Monument garnered considerable interest from local Hawaiian news stations and national media intrigued by the richly diverse coral and sponge reefs observed by the team, as well as sightings like a small pink *Chaunacops* anglerfish. Ongoing research involving data collected through OET field programs continues to be featured in online news publications, with headlines that include: "Microbial Predators at Hydrothermal Vents Play Important

FIGURE 2. Science Communication Fellow Maynard Okereke, also known as Hip Hop M.D., combines science, music, and entertainment to bring STEM elements into everyday pop culture to inspire diverse minority and youth involvement in STEM fields. Alongside other Fellows hosting ship-to-shore interactions and engaging global audiences is live streaming ROV dives, Maynard created media including this TikTok introduction to shipboard life that reached thousands of learners.

Role in Deep-Sea Carbon Cycling" *(SciTech Daily)*, "NASA tests mixed reality, scientific know-how and mission operations for exploration" *(PhysOrg)*, and "The Drone Boat of 'Shipwreck Alley'" *(The Verge)*. Footage collected during *Nautilus* expeditions is actively licensed for use by national and international production companies; museums and aquariums; professional development events; and academic film makers, including BBC Natural History Unit, Plimsoll Productions for Netflix, Field Museum, NASA's Jet Propulsion Laboratory, and Monterey Bay Aquarium for a new deep-sea exhibit. This year, we also celebrated the release of the National Geographic-published biography and biopic of OET founder Robert Ballard's long and successful career in ocean exploration.

The unexpected mid-season ROV recovery aided by the University of Washington's R/V *Thomas Thompson* and Woods Hole Oceanographic Institution's ROV *Jason* was a triumph of teamwork. It served as a powerful reminder of the connections the Nautilus Live community has to our work as dedicated viewers poured out their support, especially in response to the live streaming of the recovery and a short recap video of the recovery efforts. Interaction with our audience during this challenging time reflects the deep investment the public has in the platform and team aboard *Nautilus:*

> "Exploration at its finest and you're bringing us along with you. THANK YOU SO MUCH!!!! Love hearing about the stuff we're seeing on screen too. People are jumping in (the stream) all the time so every grenadier, ghost shrimp, or sea cuke could be someone's first!"
> "We are family. With the live feeds we are allowed to become part of *Nautilus* and we celebrate with you and mourn with you when things go wrong. We try to teach our kids how to handle themselves during tough times."
> "You guys are amazing. The way you do science communication for the public is really inspiring. I'm 26 and feeling a bit lost, but marine biology has always been a passion. The realization that underwater fungi exist might just be the thing that pushes me to go back to uni and get that degree!"

Return of At-Sea Programs

After a yearlong COVID-19 hiatus, OET's Science Communication Fellowship (SCF) program once again welcomed educators back aboard *Nautilus*. SCFs are formal and informal educators who join the Nautilus Exploration Program as communicators to share the excitement of exploration and research with students and public audiences in their communities and around the world. The SCF includes science communication training; experience sailing two to three weeks as expedition storytelling moderators; a cohort-based year-long professional collaboration with OET, STEM professionals, and fellow educators; and the development of a STEM lesson or outreach materials for their learners as a culminating deliverable.

Fellows use their unique platforms and outlets—from school assemblies to journalism to original art to TikTok—to reach those in their networks and invite learners to join in the ocean exploration process, immerse in STEM subjects, and envision possibilities for their own or their students' careers (Figure 2). This year the program included 11 SCFs from seven states that had originally been accepted into the 2020 cohort and were deferred due impacts of the pandemic on our at-sea expedition staffing. Reflecting our focus on providing professional development experiences to educators with reach in underserved communities, this cohort included seven educators who teach at Title-1 schools or serve audiences historically marginalized from STEM as well as four educators of color.

This at-sea program provides professional experiences among STEM professionals and develops educators' understanding and confidence in interpreting cutting-edge science for students. A participant summarized their learning this way: "Through my at sea experience aboard E/V *Nautilus* I was able better appreciate and understand the importance of many topics such as the interrelationships between Earth's global systems in the ocean, the need for protecting the nonrenewable ecosystems of the deep sea, the need to nurture the biocultural resources, among others. Experiencing first-hand exploration of the ocean and life at sea—sharing this experience with my students and teachers—will enrich my biology curriculum with ocean education for the rest of my life."

This year also brought back OET's Science & Engineering Internship Program (SEIP), providing at-sea experiences for nine college students and early career professionals from seven states and provinces. SEIP provides vocational training and real-world experience for students in community college through graduate programs studying ocean science, engineering, and video through internship positions that entail two to four weeks working aboard *Nautilus* as data loggers, seafloor mappers, navigators, ROV pilots, or video engineers (Figure 3).

These internships are modeled to expand students' learning, teamwork, and communication skills as they work alongside a wide array of scientists, engineers, students, and educators who also serve as role models for other learners in educational outreach activities. Six women joined this workforce development program this season.

Reaching Learners in Classrooms and Beyond

In an effort to begin expanding the accessibility of ocean exploration content available to educators and classrooms, we launched Spanish language translations of all of OET's online STEM lessons, bringing 30 national standards-aligned, inquiry-based, hands-on, deep-sea lessons to native speakers and language learning audiences. All media produced this year, along with the top 150 most-viewed Nautilus Live videos were captioned in English and Spanish.

Eager to reach learners both in and out of the classroom, OET partnered with Tumble Science Podcast for Kids to create the How to Become an Ocean Explorer podcast episode featuring Corps of Exploration role model Tayloranne Smith. This podcast tallied over 40,000 listens in the first three months, and its audience continues to grow (Figure 4).

Alongside these efforts, we continue to develop new resources for learning in classrooms, at home with family, and remotely. These include engaging animations, new lessons focused on the intersection of science and creativity through art, and videos that take students into the roles of explorers at sea. In parallel with a suite of over 100 educational resources available on Nautilus Live, on World Ocean Day the team was proud to launch the Deep Ocean Education project website, developed with support from the National Marine Sanctuary Foundation and partners NOAA Ocean Exploration and Schmidt Ocean Institute as a one-stop-shop for the best deep-sea educational resources.

Ship-to-Shore Engagement

Interest in real-time dialog with STEM professionals continues to grow as classrooms and communities explore careers and seek role models who provide representation in spaces students may not yet envision themselves. OET's live ship-to-shore interactions connect K–12 classrooms, universities, museums, science centers, and out-of-school programs with opportunities to learn about ocean exploration and direct questions to the at-sea team located in a newly constructed onboard broadcast studio, where views into the *Nautilus* ROV control room allow viewers to witness active exploration. The new studio's capabilities include shipboard camera and underwater stream video switching, video playback, and the ability to conduct live interactions from other workspaces around the vessel (Figure 5).

Throughout the season, OET used social media and leveraged partnerships to publicly advertise ship-to-shore interaction programs as openly available worldwide. We expanded our reach to the largest level in the last five years and conducted 341 live ship-to-shore interactions that reached over 13,900 students in 38 states and US territories and 11 other countries. Beyond streaming into conferences and community events, 253 programs connected directly with K–12 classrooms, and another 35 linked the team with community college and college courses. These connections remain one of OET's most dynamic and popular ways to engage students with professionals essential to an expedition and, as such, are a key component of the role modeling

FIGURE 3. Ocean Science Intern Kainalu Steward assists with sample documentation and processing.

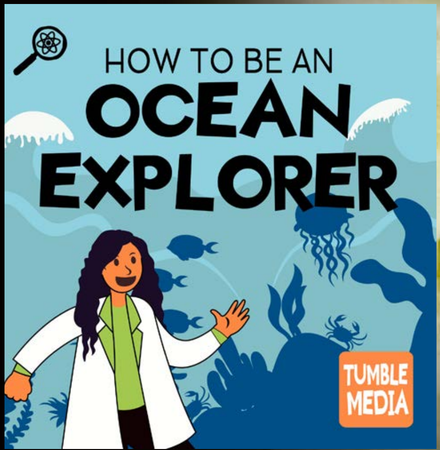


FIGURE 4. Find the How to Become an Ocean Explorer podcast from Tumble Science Podcast for Kids wherever you get your podcasts.

FIGURE 5. Ship-to-shore interactions connect communities and classrooms with explorer role models like scientist Adrienne Shumlich (left) and Ocean Science Intern Moronke Harris (right).

aspects of OET's program. Throughout the season, over 60% of the 150+ expedition team members aboard *Nautilus* participated as hosts for at least one classroom connection.

This variety of education programs is possible through the support of the Office of Naval Research, the National Marine Sanctuary Foundation, the Ocean Exploration Cooperative Institute via NOAA Ocean Exploration, CITGO, and private donors.

Advancing JEDI Across Oceans and Deepening Relationships in the Pacific

OET is committed to the important work of advancing justice, equity, diversity, and inclusion (JEDI), and fostering an anti-racist culture within our organization and throughout the oceanographic community. Following staff-led JEDI priority setting for the organization, OET refined policies and practices to improve the safety and well-being of all team members, particularly those with identities historically marginalized in ocean exploration and STEM. OET has implemented changes in staff hiring practices, increased stipends for at-sea roles, and directed funding to reduce other barriers through reworking travel policies and reimbursements. Understanding we have blind spots as a predominantly white workplace, OET has also hired a diversity, equity, and inclusion strategist to lead an independent assessment of our at-sea fellowship and internship programs' planning and implementation focused on increasing identity-based mentorship competency and reducing barriers for participants with identities historically marginalized from STEM.

As our operations shift to expeditions in the Central Pacific for the years ahead, our team is mindful of the harms perpetrated throughout large-ocean states in the name of science and is committed to working intentionally to be grounded in cultural humility, and to ensure that expeditions conducted aboard E/V *Nautilus* will reflect collaborative approaches inclusive of Pacific Islanders' worldview. Our team had the honor to work closely with the Papahānaumokuākea Marine National Monument staff along with the Office of Hawaiian Affairs-facilitated Papahānaumokuākea Native Hawaiian Cultural Working Group (CWG) in the nine months ahead of expeditions to build relationships and hear priorities for Native Hawaiian community education and outreach as well as future collaboration.

FIGURE 6. ʻŌlelo Hawaiʻi live ship-to-shore interactions brought the Hawaiian language into ocean exploration expeditions alongside culturally based names celebrating ocean exploration.

To support the vibrant resurgence of ʻŌlelo Hawaiʻi and incorporate Hawaiian immersion schools with expeditions, members of our team, the NOAA Office of National Marine Sanctuaries, and the CWG collaborated on creating Hawaiian names for expeditions as well as an original mele (chant). The teams also worked together on a shared Hawaiian vocabulary for science and technology terms commonly used on the expedition to normalize the language on a modern ocean exploration expedition.

The team also hosted live ship-to-shore interactions in ʻŌlelo Hawaiʻi for local students, supported by a paid onboard CWG representative who served as a Hawaiian language correspondent and cultural liaison for the expedition. Together, partners shared promotional flyers in Hawaiian language through Department of Education, charter and kula kaiapuni (Hawaiian immersion school) networks. As a result, during expeditions in and around Papahānaumokuākea Marine National Monument, the team hosted 26 live Q&A sessions with Hawaiʻi schools, and 38% of those connections reached learners at Hawaiian language immersion schools (Figure 6).

Our team looks forward to building upon these relationships and supporting Native Hawaiian and Pacific Islander leadership in the future of exploration. We are committed to including, amplifying, and making space for more Black, Indigenous, Latinx, Asian, Pacific Islander, Native Hawaiian LGBTQIA+, and historically marginalized voices in the deep sea and STEM communities, leveraging our education, outreach, and exploration programs.

Nautilus Field Season Overview By Allison Fundis

As you will read in the articles in this section of the *Oceanography* supplement, 2021 proved to be an important year for the Ocean Exploration Trust. Significant improvements were made in how we conduct scientific ocean exploration, how we engage the public and next generation, and how we build collaborations and partnerships to ensure our work and expeditions are planned and implemented ethically. While there were many high points to the six-month-long 2021 E/V *Nautilus* field program, it was not without its challenges. Implementing seagoing expeditions during an evolving pandemic remained demanding, and we had to conduct an unforeseen rapid recovery mission to retrieve ROVs *Hercules* and *Argus* from the seafloor in the middle of the season. Despite the challenges, we came out on the other side even more appreciative of our team members, with an unwavering dedication to OET's mission and for our many partners and collaborators across the ocean sciences community.

Between the end of our 2020 field season in November and the start of the 2021 field season in June, we made major enhancements to E/V *Nautilus* to ensure the ship is equipped to serve as a capable platform for the complex multi-vehicle expeditions we are undertaking as part of our work with our Ocean Exploration Cooperative Institute (OECI) partners and NOAA Ocean Exploration. We lengthened the stern of the ship by 4 m to gain additional aft deck space and to accommodate the integration of a new crane for autonomous vehicle deployments from the starboard side of the ship while retaining our existing crane for port-side deployments. We also added new two new cabins, allowing us to provide opportunities for more people to join *Nautilus* expeditions for years to come.

Over the course of the 2021 field season, E/V *Nautilus* spent 148 days at sea, mapped over 107,000 km^2 of seafloor, conducted 60 ROV dives, provided at-sea opportunities for 20 interns and educators participating in our education programs, and conducted over 340 live ship-to-shore broadcasts in English and ʻŌlelo Hawaiʻi that connected over 13,000 students onshore to the role models within the Corps of Exploration aboard *Nautilus*. In addition to the *Nautilus* field season, OET also partnered with the University of New Hampshire and NOAA Office of National Marine Sanctuaries to conduct an inland expedition at Thunder Bay National Marine Sanctuary located in Lake Huron within the Great Lakes.

The first expedition of the E/V *Nautilus* season brought researchers from Woods Hole Oceanographic Institution and Harvard University aboard to explore oxygen minimum zones off the coast of southern California. The research objectives of the expedition focused on microscopic foraminifera living within the sediment, as well as a deployment of the Autonomous Biogeochemical Instrument for

2021 At a Glance

10	Cruises
148	Days
60	ROV Dives
648	ROV Hours in Water (27 Days)
450	Samples Collected (1,053 Subsamples)
107,000	Square Kilometers Mapped

in situ Studies (ABISS), a prototype for a wireless seafloor sampling tool for studies of microbial activity and conducting measurements of environmental data (pages 26–27).

Nautilus then proceeded north toward Oregon, mapping the seafloor along the way to fill in gaps in existing seafloor bathymetric data within the US Exclusive Economic Zone (EEZ), supporting goals of the OECI as well as national goals to map deep waters within the US EEZ by 2030 and the international collaborative goals of Seabed 2030.

Nautilus then returned to the Cascadia margin, where over 3,500 methane seeps have been discovered since a 2016 *Nautilus* expedition to the same region and subsequent expeditions led by others to explore the active subduction zone off the Washington/ and Oregon coasts. The 2021 expedition focused on several previously unexplored regions along the margin that had yet to be visually surveyed in addition to investigating a helium anomaly that was noted at a previously explored methane seep site in 2016 and again in 2018 (pages 28–29).

Continuing north to British Columbia, OET partnered with Ocean Networks Canada (ONC) for a sixth time to provide support in maintaining and deploying instruments and equipment that are part of its 8,000 km offshore cabled observatory. In addition to supporting the engineering aspects of the observatory, E/V *Nautilus* and the ROVs were also used to assist ONC with their science objectives at all of their research sites across the Juan de Fuca Plate, including tectonically active subduction zones, methane seeps, hydrothermal vents, and the abyssal plain (pages 30–31).

As we neared the end of the ONC expedition, there was an unexpected failure in the termination to our ROVs, and they became detached from the vessel with no way for us to recover them at their approximately 2,200 m depth. With the incredible support of the broader ocean science community—notably University of Washington (UW), Woods Hole Oceanographic Institution (WHOI), the US National Science Foundation, and UNOLS—we were able to mount a recovery mission just six days after the incident. With assistance from UW's R/V *Thomas G. Thompson* and WHOI's ROV *Jason*, the ROVs were returned to *Nautilus* (pages 32–33).

Fortuitously, the following planned expedition was a mapping-focused expedition that allowed our vehicle team to take needed time to assess the ROVs after their hiatus on the seafloor. The following expedition brought *Nautilus* back to southern California and continued to map gaps in seafloor bathymetric data while en route.

Next, E/V *Nautilus* hosted the first OECI technology demonstration focused on making advances in vehicle technology and engineering that allow for ocean exploration to be conducted more efficiently and more effectively. The 2021 OECI technology challenge included multi-vehicle operations with WHOI's *Mesobot* autonomous midwater vehicle, WHOI's hybrid ROV *Nereid Under Ice*, and OET's ROV *Argus*. An impressive suite of proof-of-concept tests was conducted that will ultimately lead to new concepts of operations for ocean exploration in the future, including tele-operation capabilities (pages 62–63).

E/V *Nautilus* then mapped its way to Hawaiʻi to begin what is likely to be a multi-year focus on exploring the US EEZ in the central Pacific. The first of these expeditions focused on mapping the Liliʻuokalani Seamounts within the Papahānaumokuākea Marine National Monument (PMNM). In preparation for a follow-on ROV expedition to the same region in 2022, OET collaborated with the NOAA Office of National Marine Sanctuaries and members of the PMNM Native Hawaiian Cultural Working Group to codevelop meaningful outreach and education opportunities with the intent to appropriately incorporate Hawaiian culture and worldview into *Nautilus* expeditions and to provide capacity to codevelop Hawaiian language materials and connections for language immersion schools (pages 36–37 and pages 18–21).

The following expedition returned to PMNM to conduct ROV surveys on a chain of seamounts to document the extent at which the region supports coral and sponge communities like others in the region (pages 36–37).

To round out the 2021 E/V *Nautilus* field season, we visited the unexplored and unnamed seamounts just outside of the southeastern PMNM boundary. This expedition focused on generating high-quality bathymetric maps and implementing ROV dives to conduct biodiversity surveys along the flanks of the seamounts and to collect geological samples so that the geochemistry and geological history of the region could be better understood (pages 38–39).

In 2022, *Nautilus* will continue to build on the successful 2021 field season to explore the central Pacific with our partners at NOAA Ocean Exploration, the OECI, NOAA Office of National Marine Sanctuaries, and most importantly, with our partners and friends who are local to the communities in which we are operating.

E/V *Nautilus* 2021 Mapping: US West Coast to Papahānaumokuākea Marine National Monument

By Lindsay Gee, Erin Heffron, Christopher Kelley, Emil Petruncio, Kate von Krusenstiern, Neah Baechler, Samantha Wishnak, Renato Kane, Annie Hartwell, John R. Smith, and Nicole Raineault

In 2021, E/V *Nautilus* expeditions covered broad areas of the northern and eastern Pacific, mapping the seafloor with the ship's multibeam sonar and sub-bottom profiler (Figure 1). Mapping provides the foundation for expeditions by modeling seafloor geomorphology in advance of exploratory ROV dives. New mapping data also contribute to a primary goal of the National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone (NOMEC, June 2020), add to the Global Multi-Resolution Topography (GMRT) data synthesis, and support the broader global goals of producing a complete global seabed model under the Nippon Foundation-GEBCO Seabed 2030 project (SB2030). The 2021 *Nautilus* mapping resulted in a total mapped area of 107,246 km^2 of seafloor, including 80,829 km^2 within the US Exclusive Economic Zone (EEZ), along 22,904 km of trackline.

During three expeditions conducted between July and September, *Nautilus* mapped along the US west coast EEZ. NA127, the first expedition, supported ROV dives in the Santa Barbara Basin, then filled gaps in coverage on the transit north to Astoria, Oregon, primarily focusing on mapping along the Cascadia deformation front to support the Expanding Pacific Research and Exploration of Submerged Systems (EXPRESS) research campaign (pages 26–27). The mapping added to coverage from 2020 and was completed on NA130 during the return south to San Pedro, California.

Mapping on expedition NA128 supported ROV dives by using multibeam water column data to confirm the location of methane seeps. Mapping also filled in coverage gaps on the Cascadia margin. In addition, a Norbit ultra compact wideband multibeam sonar was mounted on ROV *Hercules* to produce centimeter-scale seafloor maps (pages 28–29).

In October, *Nautilus* crossed the Pacific to Hawai'i, filling in gaps in bathymetry and also completing a gap-filling survey in the EEZ east of Hawai'i. The final three cruises of 2021 were conducted in and adjacent to Papahānaumokuākea Marine National Monument (PMNM). Mapping on two of the cruises was conducted primarily to support ROV operations but also completed or added to existing mapping of over 14 seamounts (pages 36–37 and 38–39).

The NA133 mapping expedition to Lili'uokalani Ridge (*Lu'uaeaahikiikalipolipo*) was the primary mapping cruise in 2021, constituting the first-ever mapping survey of that seamount chain (Figure 1 inset). Prior to the cruise, the only knowledge of bathymetry in this region had been estimates from satellite radar altimetry combined with sparse single-beam and multibeam sonar tracks. The seamount chain extends southward from Hess Rise into the outer PMNM and is thought to originate from a Cretaceous mantle plume (Garcia et al., 1987; Pringle and Dalrymple, 1993). The priority of this expedition was to map the seamounts within PMNM, although mapping also extended to the north to provide information on the extended geologic structure.

Full coverage mapping was completed on four seamounts inside the PMNM (Loudoun, King George, Nootka, Mercury) and a fifth seamount (Solide) was partially mapped. All except Nootka were found to be guyots (flat-topped seamounts) having summit depths between 583 m and 997 m, notably deeper than summits at nearby

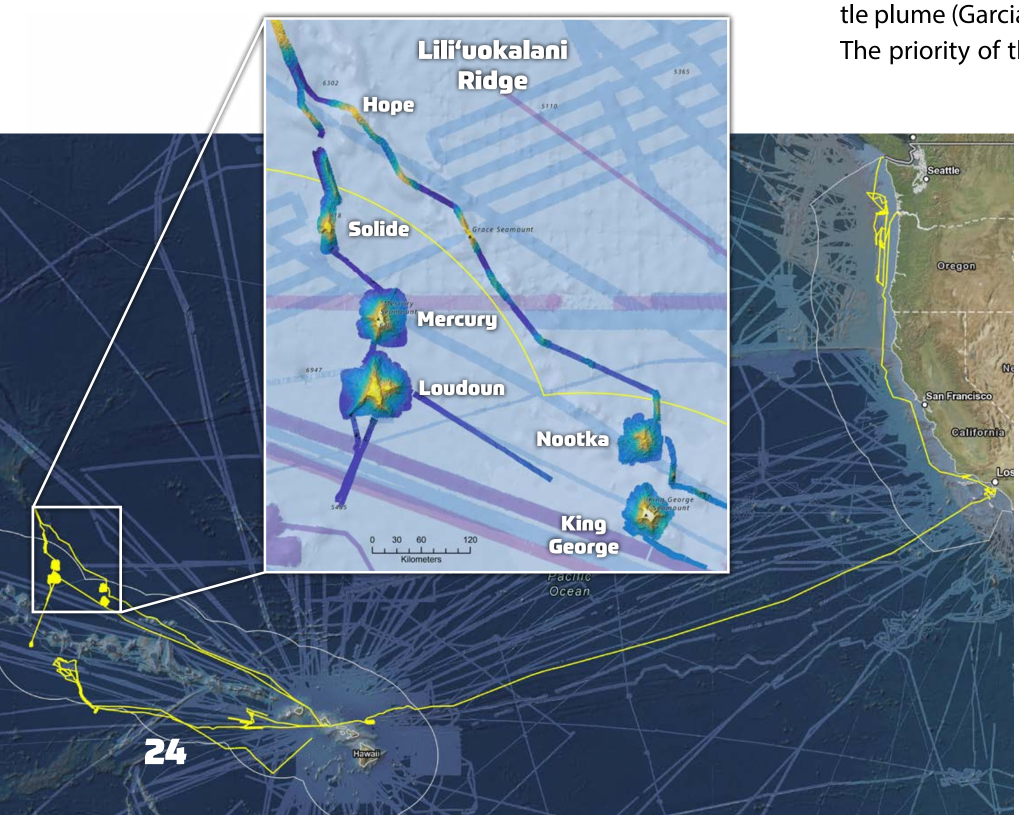


FIGURE 1. Nautilus 2021 mapping during expeditions NA126 to NA135 (yellow trackline). The inset shows coverage of seamounts mapped on Lili'uokalani Ridge during NA133.

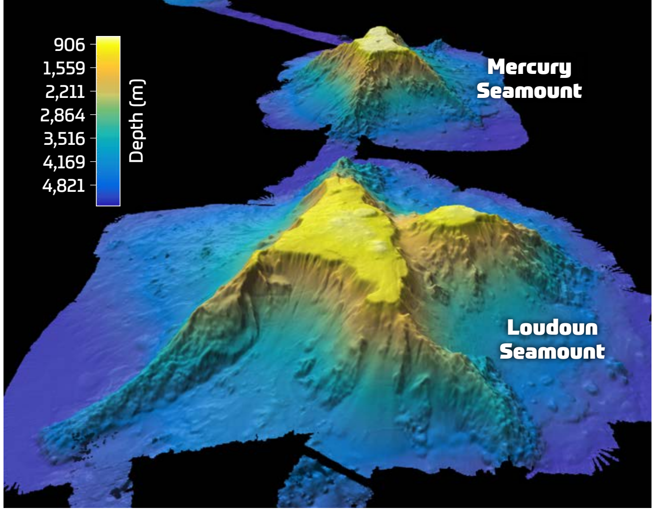
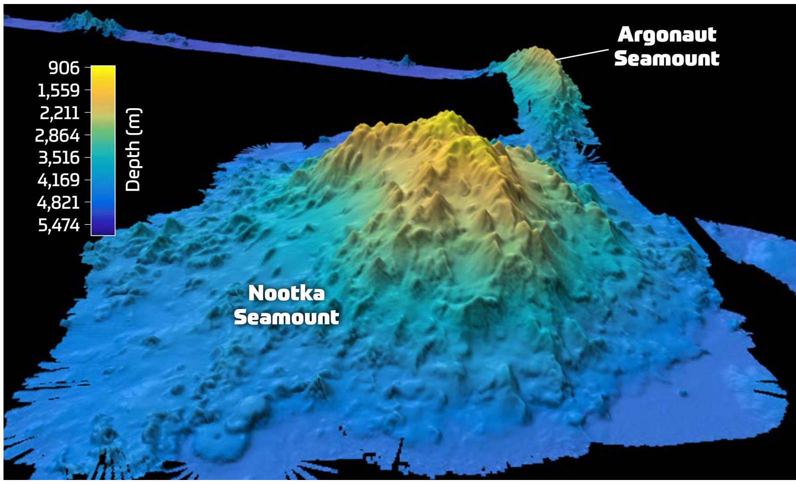


FIGURE 2. Multibeam bathymetry of Loudoun Seamount showing the flat summit typical of guyots. The smaller summit on the east side may indicate that a second volcano was involved in the creation of this seamount. Mercury Seamount is visible behind Loudoun. Bathymetry is vertically exaggerated 3x; the view is to the north.

FIGURE 3. Multibeam bathymetry of Nootka Seamount showing the large number of small volcanic cones and ridges covering the summit and flanks. The summit of Argonaut Seamount is visible just behind Nootka. Bathymetry is vertical exaggerated 3x; view is to the north.



Hawaiian ridge features. This depth difference suggests they were present on the seafloor prior to Hawaiian plume activity in this area of the Pacific Plate (Kelley et al., 2015).

The map of Loudoun Seamount reveals large and small adjacent summits separated by a deep section of seafloor (Figure 2). There is evidence of mass wasting particularly on the south side and along several smaller terraces within the main terrace on the guyot summit. These terraces may be remnants of reefs that "drowned" as the seamount subsided.

Nootka Seamount is conical in shape and has many small features (cones, mini-ridges, mounds) on its summit and flanks that extend to the surrounding seafloor (Figure 3). Some mounds on the east and west sides appear to be debris from flank failures. Others may be volcanic in origin, potentially resulting from shallower magma sources activated by tensional processes.

The morphologies of Mercury, King George, and Solide Seamounts are typical of guyots formed during the middle to Late Cretaceous. They have relatively unremarkable terraced summits with evidence of flank failures along the slopes. Notable features on all four guyots are rift zone ridges, which hold particular interest for ROV dives in 2022.

Additionally, water column backscatter around the summits of Loudoun and King George Seamounts indicated schools of fish, which could be indicative of abundant marine ecosystems to be examined in the future (Figure 4). The National Geographic Society's deep-sea camera system was deployed on King George Seamount near one of these areas where unidentified deep-sea rays and fish were preliminarily observed.

Most of the mapping north of the PMNM boundary occurred along the east fork of Lili'uokalani Ridge. Except for Hope Seamount, which appears to be a guyot, all of the other seamounts are ridge-like and have numerous small features similar to those on Nootka. This similarity suggests the east fork formed as a result of shallower tensional processes rather than a mantle plume and provides a prime target for ROV exploration and rock sampling in 2022.

Improvements to our mapping workflow implemented during the 2020 season streamlined the review of all 2021 multibeam data and allowed submission to the SB2030 data centers within weeks of the season's completion. The GMRT tiles produced on board have since been integrated in version 4 of the GMRT data synthesis, released in January 2022.

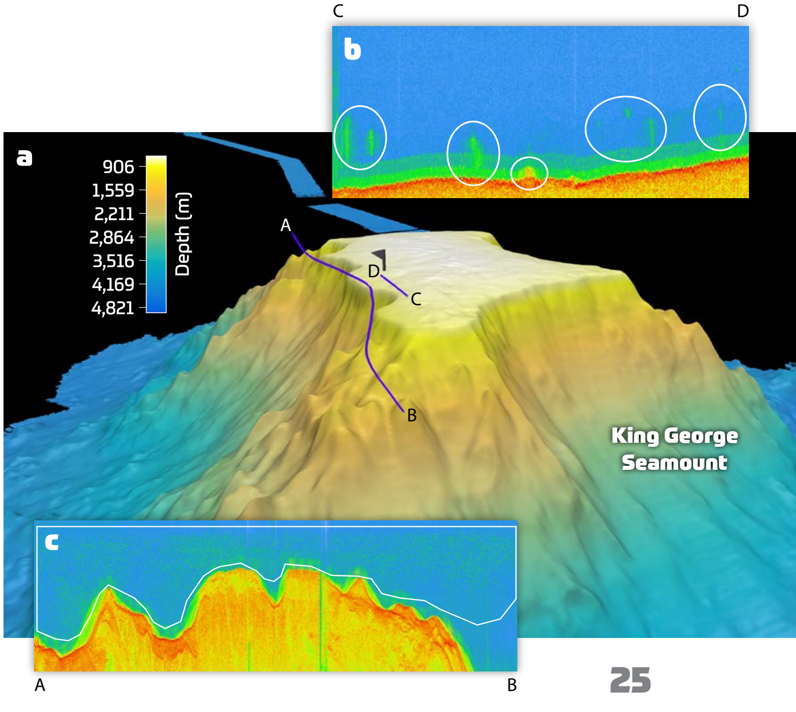


FIGURE 4. (a) Multibeam bathymetry of King George Guyot showing the location of the camera deployment (gray flag) and two multibeam tracklines. (b and c) Multibeam sonar water column data. White circles/polygon highlight targets in the water column interpreted as increased biological activity. During sonar data acquisition, an increase in water column targets and overall scattering in the water column, interpreted as an increased presence of biological activity, was noted near the top edges of guyots.

Probing the Santa Barbara Basin Benthos

By Joan M. Bernhard, Virginia P. Edgcomb, Christopher C. Powers, Brooke Travis, Sarah Lott, David Yousavich, Karla Haiat, Nicole Raineault, and Peter Girguis

The Santa Barbara Basin, located between the California mainland and northern Channel Islands, exhibits a naturally occurring 120 m high barrier—a sill—on its western side that restricts water circulation between the basin and the open ocean, resulting in oxygen-depleted, or even anoxic, bottom waters. These typically low-oxygen concentrations greatly impact the local benthos so that only microbes (including protists) and a few species of small metazoans (animals) inhabit the basin's deepest parts. Where bioturbating metazoans are absent, the basin's sedimentary deposits remain layered (Figure 1a), recording thousands of years of the basin's oceanographic and climatic history.

The goal of our E/V *Nautilus* expedition was to obtain samples of the organisms that inhabit these low-oxygen sediments and to perform experiments on the seafloor to better understand how these organisms thrive in this seemingly inhospitable habitat. In some regards, the Santa Barbara Basin can be considered an analog for an "Ocean World" (i.e., another planet where life may exist; https://www.nasa.gov/specials/ocean-worlds/). The seafloor of the basin's deepest area is typically covered with a white bacterial mat largely composed of the colonial sulfide-oxidizing bacterium *Beggiatoa*. In July 2021, the seafloor mat was well developed and extensive (Figure 1a,b), while the overlying water was anoxic, (i.e., ROV *Hercules*' optode oxygen sensor detected no dissolved oxygen). Anoxic environments are anathema to most eukaryotic life, which typically relies on oxygen to respire.

Our prior Santa Barbara Basin studies demonstrated that its microbial mat sediments support particular foraminiferan protists, often in extremely high abundances (hundreds per cubic centimeter; Bernhard et al., 1997). Many of these foraminifera species have bacterial symbionts (Bernhard et al., 2000). However, the foraminiferan that dominates this mat-associated habitat has a different type of symbiont: chloroplasts stolen from planktonic diatoms (Grzymski et al., 2002; Gomaa et al., 2021). This is a "chloroplast conundrum" because this kleptoplastidic ("plastid-stealing") foraminiferal species, *Nonionella stella* (Figure 2), thrives far deeper than enough sunlight penetrates to support photosynthesis.

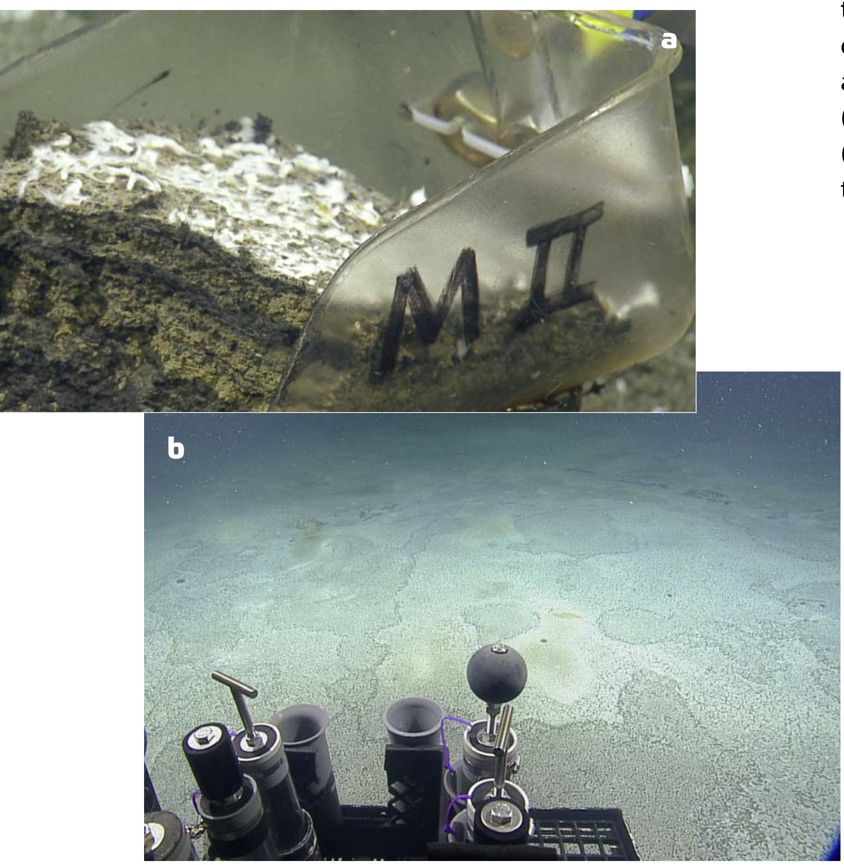


FIGURE 1. (a) Side view of a "scoop" of Santa Barbara Basin seafloor covered with white bacterial mat. Note the fine submillimeter-scale layers of sediment. (b) Overview of extensive bacterial mat imaged in July 2021.

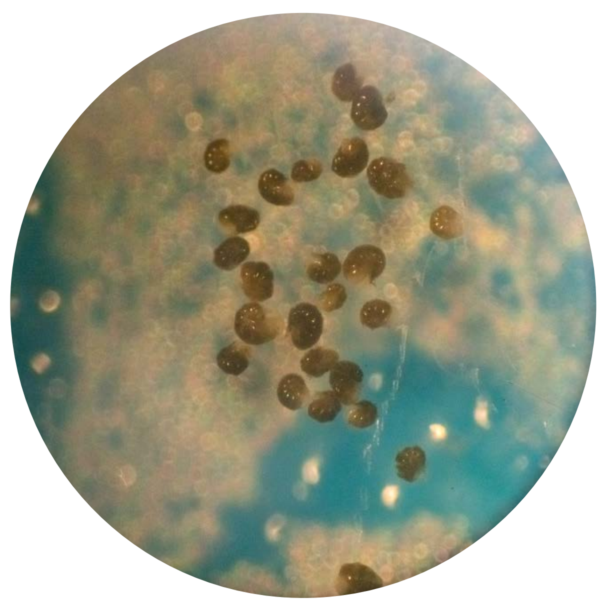


FIGURE 2. Twenty-five specimens of the kleptoplastidic foraminifer *Nonionella stella* as seen through a dissecting microscope, after their isolation from Santa Barbara Basin bacterial mat sediments. Note green coloration of foraminiferal cytoplasm. Each specimen is ~250 microns in diameter.

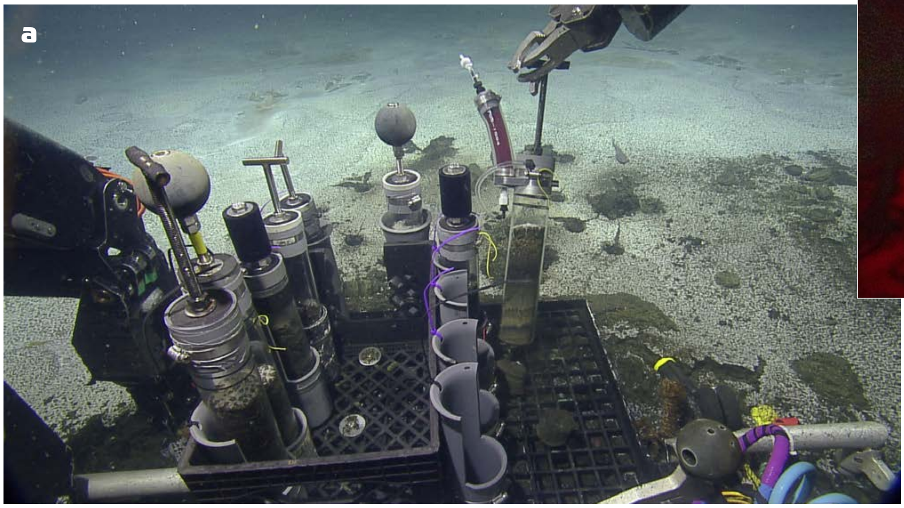


FIGURE 3. (a) *Hercules* places an injector push core into its holder on the front of the ROV. Once the push core was secured, the large diameter tube containing red liquid was squeezed to introduce preservative via capillary tubing. (b) Graduate student Christopher Powers and undergraduate Sarah Lott subsample a push core under red light.

ROV technologies were required to obtain foraminifera-laden sediments never exposed to sunlight to either preserve them in situ or to conduct incubation studies in situ, and to use a photosynthetically active radiation (PAR) sensor to measure the amount of incident sunlight where these foraminifera thrive. Our sampling efforts mainly involved targeted ROV push coring; some cores were positioned on the seafloor and left to incubate with chemically labeled compounds, and others were injected with a preservative (Figure 3a). The cores that were incubated on the seafloor were recovered on deck at dusk and subsampled under red light (Figure 3b).

In contrast, some of the expedition's research required collection of clams (*Lucinoma aequizonata*) that live on the oxygenated periphery of the Santa Barbara Basin. These clams depend on bacterial endosymbionts that live in their gills. Being infaunal (living within sediments), these bivalves are visible only by their characteristic double siphon pattern, which must be spotted by the ROV team so the clams can be scooped using the ROV arm.

One important objective of the expedition was a proof-of-concept deployment of the Harvard team's Autonomous Biogeochemical Instrument for in situ Studies (ABISS) lander. ABISS was placed at the deep, bacteria-mat-covered site shown in Figure 4, where oxygen was undetectable as measured by ROV *Hercules*' oxygen sensor. An array of oxygen and pH sensors, as well as osmotic fluid samplers for geochemical and microbiological studies, were mounted at varying positions on the lander, allowing the investigators to look at gradients in oxygen, pH, and the microbial community. Additionally, we deployed an experiment on ABISS to incubate sediments on the seafloor for longer than our one-day in situ push core incubations. Laminated sediments, which were collected via a *Hercules*-manipulated scoop (Figure 1a), were placed into a ~4 L box, the clear lid was secured, and the isotopic label was injected. After about one month, a release introduced a preservative into the box to stabilize the sediment until ABISS can be recovered in 2022.

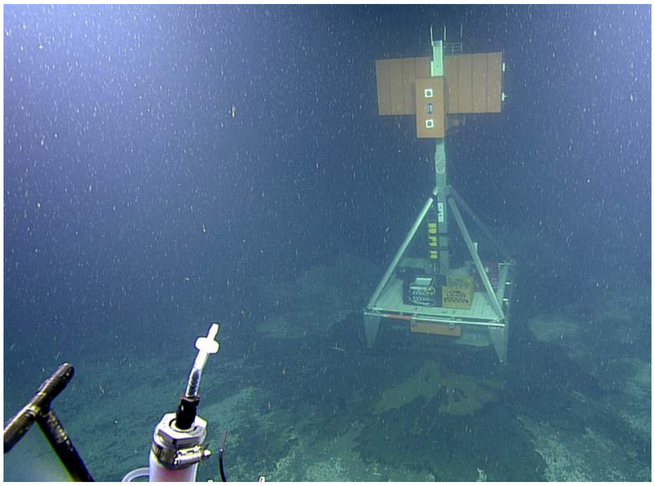


FIGURE 4. The Autonomous Biogeochemical Instrument for in situ Studies (ABISS) on the seafloor. The bacterial mat around the ABISS lander is disturbed in this image because *Hercules* operated close to it in order to load sediments into the biobox for the extended incubation experiment.

Genomic and (meta)transcriptomic analyses, among others, will be performed on the foraminifera. The clams will be used for lab-based experiments aimed at understanding rates of carbon transfer between host and symbiont. ABISS data will be analyzed to better understand the patterns of oxygen and pH changes over time.

Investigating Active Methane Seeps Along the Cascadia Margin

By Tamara Baumberger, Jeffrey Beeson, Susan Merle, Nathan Buck, Anson Antriasian, Kevin Roe, Shannon Brown, and Lila Ardor Bellucci

After postponement of the 2020 expedition season due to the COVID-19 pandemic, a multidisciplinary team of researchers set out in July 2021 on E/V *Nautilus* to further explore and characterize methane seeps along the Cascadia margin off the coasts of Oregon and Washington in the Northeast Pacific Ocean (Figure 1). With funding from NOAA Ocean Exploration, and in partnership with the NOAA Pacific Marine Environmental Laboratory (NOAA PMEL), Oregon State University, and the University of Washington, the 2021 project was building on two previous *Nautilus* expeditions to the Cascadia margin—NA072 in 2016 and NA095 in 2018.

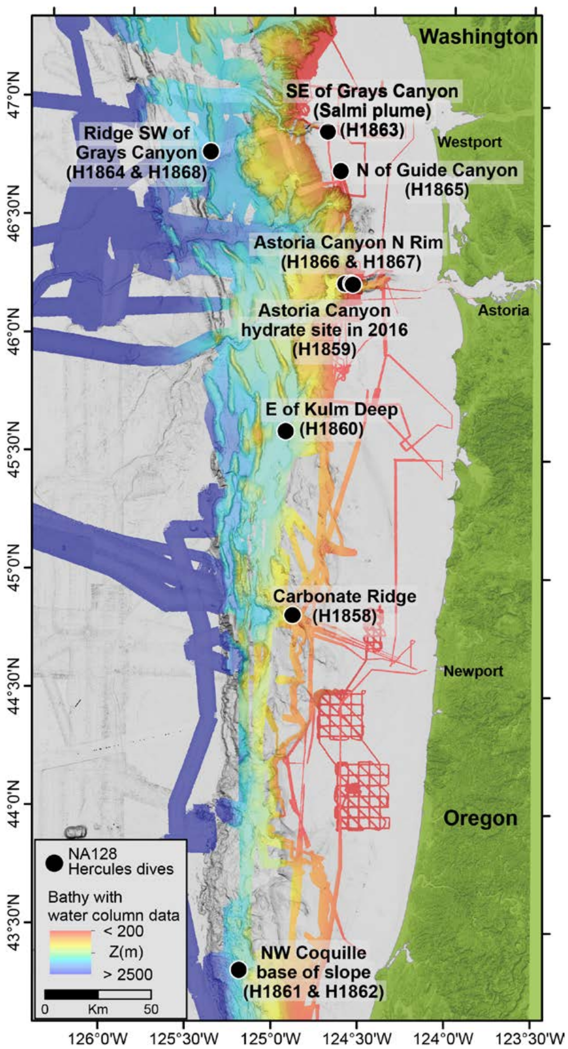


FIGURE 1. Locations of ROV *Hercules* dives along the Cascadia margin during cruise NA128.

Although many classic geological and geophysical studies of methane seeps and methane hydrates had been conducted along the Cascadia margin, and bubble streams had been reported by fishers over several decades, until 2016 the overall distribution and number of seeps was largely unexplored. During the 2016 E/V *Nautilus* expedition, multibeam sonar surveys located over 800 previously unknown bubble streams rising from the Cascadia margin between the Strait of Juan de Fuca and Cape Mendocino at depths between 104 m and 2,073 m; information collected during ROV *Hercules* dives helped to characterize 10 of these newly located seep sites.

The discovery of so many active seeps was a game changer. In the following years, NOAA PMEL and collaborators have conducted studies of several methane seeps along the Cascadia margin using a range of research vessels. By early 2020, nearly 3,500 methane bubble streams, clustered into more than 1,300 methane emission sites, had been identified along the US Cascadia margin (Merle et al., 2021). Hydrophones listened to bubbles being released at the seafloor, and the chemical composition of these bubbles was being investigated (Baumberger et al., 2018; Dziak et al., 2018). Biological studies of the associated ecosystems revealed that microbial communities show high variability in their spatial distribution and community structure, and a latitudinal trend was observed in species diversity and richness (Seabrook et al., 2018). Nevertheless, structural influence as well as chemical and biological diversity of these seep sites and their importance to coastal margin ecology remain poorly known. High-resolution mapping and ROV-based surveys, sampling, and characterization of methane seep sites are essential for evaluating the tectonic influence on seepage, the chemical variations in the emissions, and the resulting biodiversity of these seep habitats.

During the 2021 expedition, 11 ROV sampling dives were completed over 13 days (Figure 1). The ship mapped 6,956 km^2 of the seafloor with its EM 302 multibeam sonar system, and simultaneously collected water column data and sub-bottom profiles while transiting between dive sites. Typically, ROV dives were conducted during daytime (8 a.m. to 8 p.m. Pacific time; e.g., Figure 2). Upon arrival at a new dive site, the E/V *Nautilus* multibeam sonar was used to locate active bubble streams that offered the most promising dive targets. ROV dives covered a depth range from 149 m to 1,767 m along the Oregon and Washington

FIGURE 2. ROV *Hercules* collects a push core in bacterial mats adjacent to bubbles rising from the seafloor in a crevasse. Image taken by ROV *Argus* during dive H1864.

FIGURE 3. ROV *Hercules* collects samples next to a warm seep during dive H1861.

margin. In addition to the standard operational tools, ROV *Hercules* was equipped with scientific instruments that included up to three gastight sampling bottles, a gastight hydrate sampler, six Niskin bottles, five push core liners, a Norbit multibeam sonar, a miniature autonomous plume recorder (MAPR), and a high-resolution still camera.

A major discovery of this expedition was a warm seep at the base of the continental slope 15 km east of the Cascadia deformation front offshore southern Oregon (dives H1861/H1862; Figure 3). This dive location was selected based on seismic reflection data recently collected by R/V *Marcus Langseth* that indicated the presence of upwelling warm fluid. A warm seep is a rare discovery, and characterizing and sampling it will require further expeditions to this region.

ROV *Hercules* dive H1866 was to a previously located hydrate deposit in Astoria Canyon (identified by a physical marker left at the seafloor on the previous cruise). ROV imagery showed that the deposit was no longer exposed at the seafloor, but that the area was still actively seeping. However, additional dives (H1866/H1867) at the canyon floor revealed an exposed methane hydrate deposit with a volume of about 2 m^3 that had not yet been visited, as well as several deposits closer to the canyon wall.

Numerous biological samples were collected by *Hercules* while investigating the benthic habitat and community diversity of previously unexplored methane seeps and hydrate sites. For example, while exploring a carbonate ridge offshore of Newport, Oregon, during dive H1858, we observed a variety of benthic fauna. In sedimented areas, fauna included ophiuroids, crinoids, and sea stars, while the dominant fauna on rocky substrates included glass sponges; mushroom, bubblegum, and bamboo corals; anemones; gastropods; and various sea stars. Multiple seep habitats were encountered, including some with active bubbling and others characterized primarily by white microbial mats, limited sediment cover, and medium-sized patches of vesicomyid clams, shell hash, and mushroom corals on adjacent rocks. Bottom-dwelling fish included thornyhead rockfish, flatfish, hagfish, eelpouts, and large schools of sablefish.

On the expedition, the E/V *Nautilus* team hosted 14 ship-to-shore interactions, connecting with students from the Oregon coast to Cyprus, and also provided expedition video highlights and full ROV dive recordings on YouTube.

The new findings illustrate that we are still only at the beginning of exploring and characterizing the Cascadia margin methane seeps. The data collected by E/V *Nautilus* in 2021 provide important new baseline information that can be used to investigate possible methane-related impacts associated with climate or the blue economy; to observe changes in marine chemistry and benthic and water column biology; and to learn more about the current tectonic state of the Cascadia margin.

Ocean Networks Canada: Supporting Innovative Technology for Science, Society, and Industry

By Nicolai Bailly, Martin Heesemann, Ian Kulin, Mandy Leith, Fabio De Leo, Steve Mihaly, Kate Moran, and Benoît Pirenne

Ocean Networks Canada (ONC) operates and manages innovative, cabled observatories on behalf of the University of Victoria, supplying continuous power and Internet connectivity to hundreds of scientific instruments located in coastal, deep-ocean, and Arctic environments (Figure 1). ONC's cable network hosts thousands of sensors distributed in, on, and above the seabed, along with mobile and land-based assets. These strategically located instruments address key scientific and societal issues—such as earthquake and tsunami hazards, ocean acidification, and marine biodiversity—within a wide range of ocean environments.

Marking a memorable sixth anniversary of working in partnership with the Ocean Exploration Trust, the E/V *Nautilus* team supported the maintenance of ONC's Northeast Pacific cabled ocean observing network. Despite the global pandemic—which limited the number of onboard crew and required strict adherence to COVID-19 safety protocols—ONC successfully maintained, upgraded, and augmented over four dozen instruments in 2021.

During this 23-day expedition in August 2021, E/V *Nautilus* visited 14 sites to deploy, recover, and maintain sensors and instruments, including seismometers; tiltmeters; bottom pressure recorders; underwater cameras; sonars and hydrophone arrays; phytoplankton, water, and sediment samplers; and autonomous and cabled moorings. In addition, the benthic crawler Wally was redeployed to monitor gas hydrates at Barkley Canyon.

Science and technical objectives were met using the ship's ROVs *Hercules* and *Argus* to perform numerous vertical and horizontal video surveys to study benthic and pelagic ecosystems, map the seafloor, and collect biological and geological samples. The team also conducted several vertical dissolved oxygen surveys to confirm a low-oxygen event that was occurring simultaneously off our shores.

The expedition supported the innovative Northern Cascadia Subduction Zone Observatory project, which aims to provide new insights into the hazards posed by a megathrust earthquake rupturing the Cascadia subduction zone (Farrugia et al., 2019). Acoustic transponders were deployed at several seafloor stations along the subduction zone (Figure 1). At the same time, an autonomous surface vehicle called a wave glider surveyed their exact

FIGURE 1. A map of Ocean Networks Canada's (ONC's) Southern British Columbia infrastructure. The white dots represent the locations of the acoustic transponders surveyed by a wave glider as part of the Northern Cascadia Subduction Zone Observatory.

FIGURE 2. ONC's Director of Observatory Physical Operations Ian Kulin prepares to deploy a Sonardyne FETCH transponder to measure tectonic plate movement to centimeter accuracy as part of the Northern Cascadia Subduction Zone Observatory Project.

positions. This vehicle uses Global Navigation Satellite System-Acoustic (GNSS-A) measurements to determine the absolute location of the underwater stations with centimeter accuracy. By repeating this survey annually, a timeline of successive positions can be built to determine tectonic plate displacement rate and direction at different locations along the subduction zone (Spiess et al., 1998). A deformation-front laboratory was also installed that uses autonomous instruments to monitor fault slip occurring in the uppermost part of Earth's crust (Figure 2).

One of the hydrophone arrays deployed during the expedition was David Barclay's (Dalhousie University) deep acoustic lander, which had just returned from the deepest known part of Earth's ocean, Challenger Deep. It provided an opportunity to further understand the underwater sounds of hydrothermal venting at the Endeavour Hydrothermal Vent Field. The lander consists of four hydrophones that collect acoustic data for discerning source location. It was placed on the seafloor among four large hydrothermal edifices to determine whether it is possible to differentiate the acoustic characteristics of the numerous venting sources. These detailed acoustic data will supplement three years of data gathered by ONC's single cabled hydrophone at the Grotto edifice at Endeavour.

Instrument calibration support work included obtaining specialized vent samples at two sites in the Main Endeavour Field. These samples will inform the future placement of observational equipment at the southern part of this marine protected area, which exhibits signs of reduced hydrothermal flux. Temperature and resistivity measurements and vent fluids were sampled from this area to compare with fluids further north. This is a collaborative effort between the University of Victoria, Dartmouth College, the University of Minnesota, and ONC.

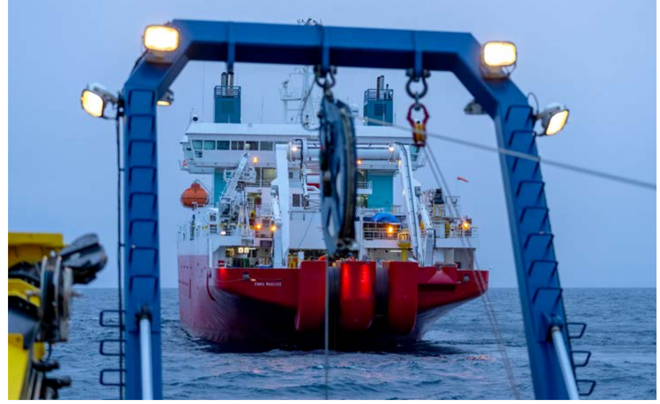


FIGURE 3. Cable Ship *Cable Innovator* is viewed here from the back deck of E/V *Nautilus* during a carefully choreographed dual-ship operation to lay 5 km of fiber-optic cable at Endeavour Ridge.

Biological specimens of sea anemones were collected at vent-periphery sites to better understand the role of microbial symbionts and their reliance on chemosynthetic energy using molecular markers, a collaboration with IFREMER scientists in France.

As part of a multi-institution collaboration led by the University of Oregon, eight passive larval tube trap experiments were successfully retrieved after one-year deployments at Barkley Canyon Axis, Upper Slope, Main Endeavour Field, and Cascadia Basin. Samples of meroplankton (organisms that have both planktonic and benthic stages in their life cycles) are now under analysis to better understand patterns of connectivity, dispersal, and biodiversity of deep-sea animals. Sediment and water samples were collected in Barkley Canyon and Cascadia Basin in support of ongoing studies to describe deep-sea microplastic inventories, sedimentary eDNA, and organic matter content.

In response to a developing low-oxygen event off the coast of Vancouver Island, opportunistic surveys of dissolved oxygen helped to confirm measurements that had been ongoing in the area, most notably at the Folger Deep site of ONC's NEPTUNE observatory.

Five kilometers of fiber-optic cable were laid at Endeavour in a complex dual-ship operation with cable ship *Cable Innovator*, owned and operated by Global Marine Systems Limited (Figure 3). Using specially designed mudmats, ROV *Hercules* monitored cable touchdown along the entire route, with the two vessels maintaining close quarters on the surface. During the final deployment of the second mudmat, communications were lost when both ROVs became detached from the cable connecting them to the ship. The mudmat was discharged to the seafloor using an acoustic release. A planned second cable lay at Cascadia Basin was canceled and the expedition was cut short by three days.

Fortunately, both *Hercules* and *Argus* were successfully recovered a week later in a collaborative rescue mission supported by the University of Washington's R/V *Thompson* and Woods Hole Oceanographic Institution's ROV *Jason*.

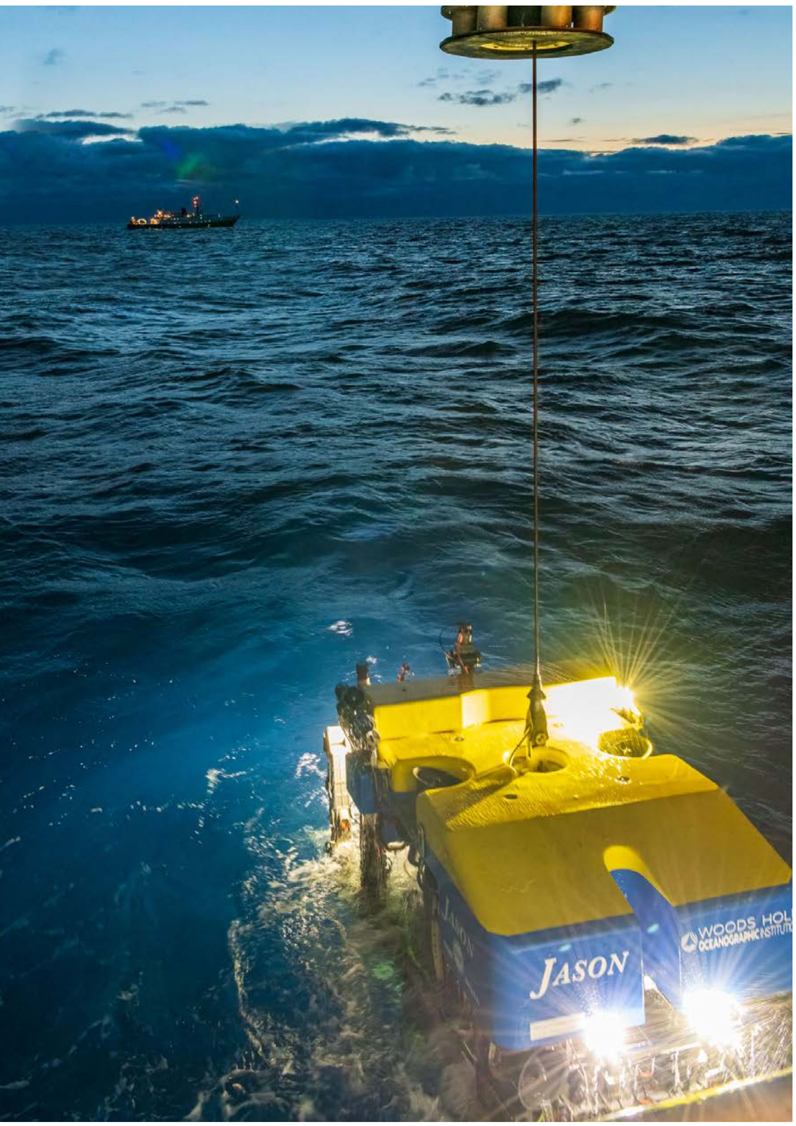
A Herculean Effort: Complex Collaboration to Rescue ROVs

By Allison Fundis and Samantha Wishnak

In the deep-sea exploration and research community, we often talk about what it takes to pull off a successful expedition. No matter the complexity of the mission, it always boils down to teamwork and collaboration. In the middle of the 2021 *Nautilus* expedition season, the Ocean Exploration Trust benefited from precisely this sort of community connection. On August 26, 2021, our remotely operated vehicles unexpectedly became detached from E/V *Nautilus* in the middle of a dive in waters over 2,100 m deep at Endeavour Ridge, approximately 200 km offshore British Columbia, Canada. Thanks to a rallying of support from our partners, colleagues, and collaborators, just one week after the detachment, both ROVs were recovered from the seafloor. In two dives over the course of 26 hours, a team from the Woods Hole Oceanographic Institution (WHOI) Deep Submergence Lab deployed ROV *Jason* from the University of Washington's R/V *Thompson* and were able to work with the team aboard *Nautilus* to safely rescue both vehicles.

At the time of the detachment, OET was 21 days into a 28-day expedition supporting the University of Victoria's Ocean Networks Canada offshore observatory (see pages 30–31). Unable to continue the expedition with our partners, we transited to port, offloaded ONC personnel and equipment, and immediately returned to sea to start recovery efforts. In the six days of planning leading up to this ROV rescue operation, we envisioned that the best-case scenario for vehicle orientation would be that negatively buoyant ROV *Argus* would be on the seafloor and still connected to positively buoyant ROV *Hercules* floating above at the end of the umbilical tether.

On the first reconnaissance dive on September 1, *Jason* was able to quickly locate the vehicles utilizing the coordinates of the last known location of *Argus* and *Hercules* and by pinging *Hercules's* Sonardyne ultra-short baseline navigational beacon utilized by both WHOI and OET. We found the vehicles in precisely the configuration envisioned, which allowed for the ROV *Jason* team aboard



R/V *Thompson* recovers ROV *Jason* after assisting in the rescue of ROVs *Hercules* and *Argus* from the seafloor. E/V *Nautilus* can be seen in the distance *Photo credit: James Tilley, University of Washington*

The team in the control room aboard E/V *Nautilus* monitors live feeds from ROV *Jason* during the initial reconnaissance dive to assess ROVs *Hercules* and *Argus* on the seafloor.

In the first light of September 2, E/V *Nautilus*'s small boat waits in the foreground for ROV *Hercules* to surface in order to tow it to R/V *Thompson*, seen in the background. *Photo credit: Greg Diffendale*

R/V *Thompson* to expertly and efficiently prepare the vehicles for recovery to *Nautilus*. After both vehicles were rigged for recovery by attaching beacons, adjusting flotation, and preparing lift straps, *Jason* returned to the surface to prepare for a second dive timed to release and recover *Hercules* at the surface at daybreak.

On the second dive on September 2, *Jason* descended through the water column, equipped with a hydraulic band saw capable of severing the tether connecting *Hercules* and Argus. Once the operation was complete, *Hercules* free-floated to the surface, ascending at a rate over 30 meters per minute, more than double the normal ascent speed. At sunrise, *Hercules* reached the surface and was hooked into a recovery line using *Nautilus*'s small boat. Approximately two and a half hours after being released from the seafloor and 167 hours since being disconnected from the ship, *Hercules* was craned back aboard *Nautilus*.

The team aboard *Nautilus* then used the ship's traction winch to deploy over 2,000 m of cable to the seabed. This cable, typically attached to *Argus* during normal operations, was rigged with tracking beacons and a lift line and shackle for *Argus*. *Jason* pilots connected the shackle to lift straps threaded through *Argus*'s frame, and *Nautilus* reeled in the ROV with the winch and transferred it to the crane via the lift line. With both ROVs safely onboard, the team aboard *Nautilus* began the long process of thoroughly checking and documenting the condition of both vehicles and their many components, a process that continued through several months.

After fewer than 30 hours on site and a proper farewell salute of the vessels' horns, the team aboard R/V *Thompson* began their transit to demobilize their more than a month-long Ocean Observatories Initiative expedition that had been extended to aid in the ROV recovery effort. *Nautilus* departed shortly after to demobilize this rescue mission and continue with our expedition season.

We are forever grateful to the many individuals and groups who aided in the planning, permissions, and the expedition itself, and to the many partners and collaborators who contributed their assistance, equipment, and expertise. We are especially thankful to the National Science Foundation, University-National Oceanographic Laboratory Systems, University of Washington, WHOI National Deep Submergence Facility, WHOI ROV *Jason* team, Ocean Observatories Initiative, Office of Naval Research, the crews and expedition teams of R/V *Thomas G. Thompson* and E/V *Nautilus*, Maritime Management, Leviathan, Ocean Networks Canada, Fisheries and Oceans Canada, Oregon State University, and OET staff and contractors.

In addition to the oceanographic and research community, students, educators, and Nautilus Live fans from around the world remotely joined in on this recovery mission with an outpouring of interest and support. Our team deeply appreciated this encouragement and is inspired by the care and connection millions of viewers feel for the deep ocean and for ROVs *Hercules* and *Argus* as they open a window to this extreme environment.

Midwater Exploration with *Mesobot*, Radiometry, and Environmental DNA

By Dana R. Yoerger, Annette F. Govindarajan, Allan Adams, Molly Curran, Erin Frates, Eric B. Hayden, Lui Kawasumi, Fredrick Marin, M. Jordan Stanway, and Sarah Stover

Teeming with life and extending from about 200 m to approximately 1,000 m depth, the midwater ocean or "twilight zone" makes up one of the largest and least explored biomes on our planet. Although light levels are insufficient to support primary production, this vast region hosts abundant life and plays a key role in the global carbon cycle, thereby helping to regulate Earth's climate and the biogeochemistry of its ocean.

NOAA Ocean Exploration and the NOAA Ocean Exploration Cooperative Institute have expanded focus to include the midwater ocean, which creates both opportunities and challenges in defining specific objectives for exploration and developing the needed technology. Like our community's ongoing efforts to explore the seafloor, midwater exploration must provide us with an overview of the underlying physical and biogeochemical environments and a comprehensive summary of which animals live there, and reveal the temporal and spatial dynamics of those populations and how they relate to the adjoining epipelagic and deeper layers.

We seek to supplement existing midwater techniques like conventional profiling and shipboard acoustic surveys with imaging surveys, in situ measurements of the ambient light field, and biodiversity assessments using environmental DNA (eDNA). In addition to supporting NOAA Ocean Exploration's push to explore the midwater ocean, our efforts are synergistic with NOAA's strategies for uncrewed systems and 'omics. Likewise, we have benefited from participating in existing NOAA midwater efforts such as the midwater ROV dives conducted from NOAA Ship *Okeanos Explorer*.

In 2021, we demonstrated several important new midwater exploration methods on E/V *Nautilus* cruise NA131.

Mesobot, a hybrid marine robot designed specifically for midwater exploration, was established as a collaborative, National Science Foundation-sponsored effort between Woods Hole Oceanographic Institution, Monterey Bay Aquarium Research Institute, Stanford University, and the University of Texas Rio Grande Valley (Figure 1). As a hybrid vehicle, it can operate as an ROV using a lightweight fiber-optic tether or as an untethered, autonomous vehicle with low bandwidth acoustic communications. *Mesobot* can track slow-moving midwater organisms and can also make a variety of measurements and carry additional sensors and samplers. Designed to reduce animal attraction and avoidance, *Mesobot* displaces ~250 kg, utilizes low-powered, slow-speed propulsors, and can survey with both white and red lights.

Just as detailed bathymetry provides a roadmap for exploring the seafloor, we need to understand the ambient light field to systematically explore the midwater ocean. Many midwater animals exercise diel vertical migration, rising to rich near-surface waters in the evenings to feed and retreating to deeper waters during daylight hours to avoid predation. Understanding the dynamics of the light field can help us understand where animals are most likely to be found, especially when light observations are linked to other observations such as shipboard acoustic and visual surveys and eDNA analyses. Light field measurement presents a significant technical challenge, as the needed sensor must be highly sensitive, have a wide dynamic range, and distinguish between background irradiance

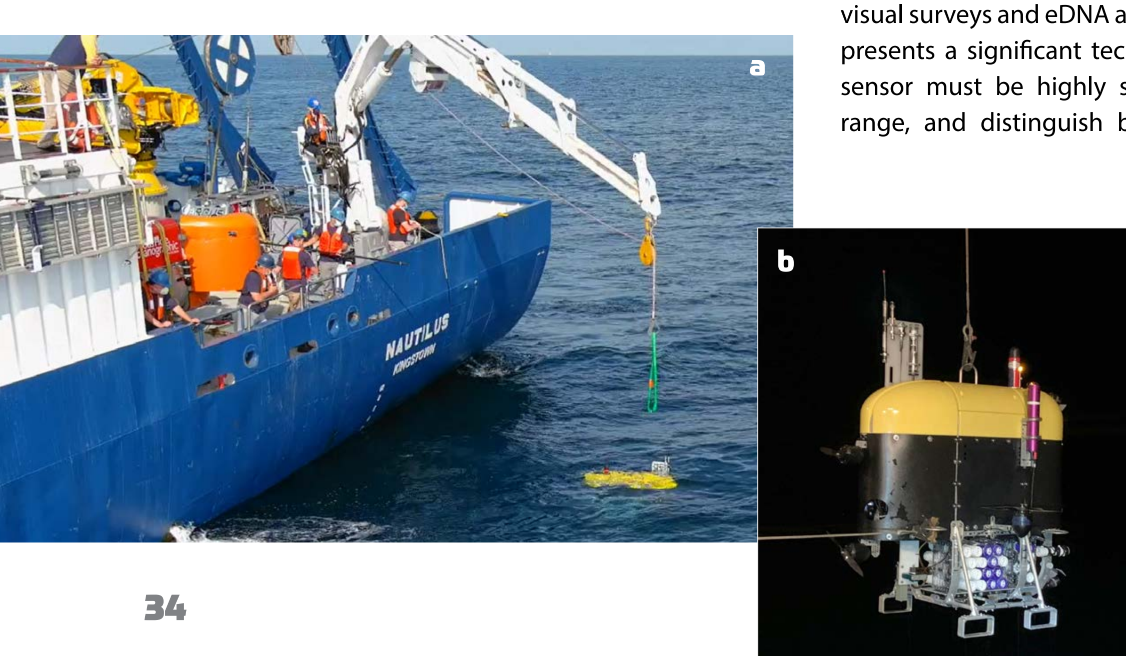


FIGURE 1. (a) Drone image of a *Mesobot* launch from E/V *Nautilus*. (b) A photo of *Mesobot* during launch shows the eDNA sampler (white and blue structure in the lower bay) and one of the radiometers (magenta cylinder top right). *Photo credit: Lui Kawasumi*

FIGURE 2. (a) WHOI mechanic Brian Durante conducts pressure testing of the eDNA sampler in Woods Hole. *Photo credit: Lui Kawasumi.* (b) WHOI research assistant Erin Frates and Oceanic Labs engineer Lui Kawasumi prepare the eDNA sampler. *Photo credit: Dana Yoerger*

and bioluminescence. Author Adams has developed such a sensor. We have integrated it into *Mesobot's* data logging and control systems, and we have demonstrated its operation on several recent cruises, including on NA131. In addition to measuring the light field, *Mesobot* actively used real-time radiometer data to follow light levels much as migrating animals do.

Environmental DNA analysis offers a new approach to exploring biodiversity in which the presence of animals can be detected without having to sample the animals themselves. It has great potential to reveal the identity of midwater species, many of which are otherwise difficult to sample, and to elucidate phenomena such as diel vertical migration. In eDNA analyses, seawater is sampled and filtered to collect traces of DNA shed by animals in the sampling location, and later in the laboratory DNA is extracted from the filters and diagnostic genetic "barcode" markers are sequenced. We recently developed an autonomous eDNA sampler with in situ filtration for *Mesobot*, and we have collected several samples with it (Figure 2). *Mesobot's* tracking and sensor capabilities provide a unique context for eDNA collection, and the combination of eDNA sampling with *Mesobot* provides new and exciting opportunities for biodiversity exploration.

We participated in a week-long Technology Demonstration cruise on E/V *Nautilus* in September 2021 in the Santa Monica Basin off Southern California. *Mesobot* dove each day, focusing on the sunset transition to enable our eDNA experiments. We tracked *Mesobot*'s position using *Nautilus*' ultra-short baseline system, which was also used for acoustic communications to monitor vehicle status and to send commands. Simultaneously with the *Mesobot* dives, we obtained images (~20 frames per second) with the Digital Autonomous Video Plankton Recorder set at its widest field of view (~3 cm × 4 cm) while carrying a pumped conductivity-temperature-depth instrument (CTD) and a fluorometer. We also utilized an EK80 biosonar operating at 38 kHz and 200 kHz to image layers in real time. *Mesobot* made five eDNA surveys, collecting 101 pumped filter samples with volumes between 28 L and 250 L. Three dives focused on vertical migration during the evening transition, and two dives collected samples after sunset at preprogrammed depths between 425 m and 50 m.

For the evening transition dives, we collected a time series of eDNA samples centered around dusk, when vertical migrators are moving into shallower waters. We also demonstrated isolume (lines of equal light intensity) following at depths of approximately 100 m under moonlight (Figure 3), followed the sunrise transition between depths of 100 m and 270 m, and tracked an isolume at about 400 m depth around local noon. Using *Mesobot* in its untethered mode and other complementary sensors, we demonstrated several key elements of an emerging model for midwater exploration, including sampling eDNA, measuring the downwelling light field, conducting shipboard acoustic and in situ imaging surveys, and actively following isolumes. We expect these data to provide important insights into which species are present, their relationship with the physical environment, the species that migrate, the timing of their migration, and animal behavior in situ, as well as to demonstrate a new approach for midwater exploration.

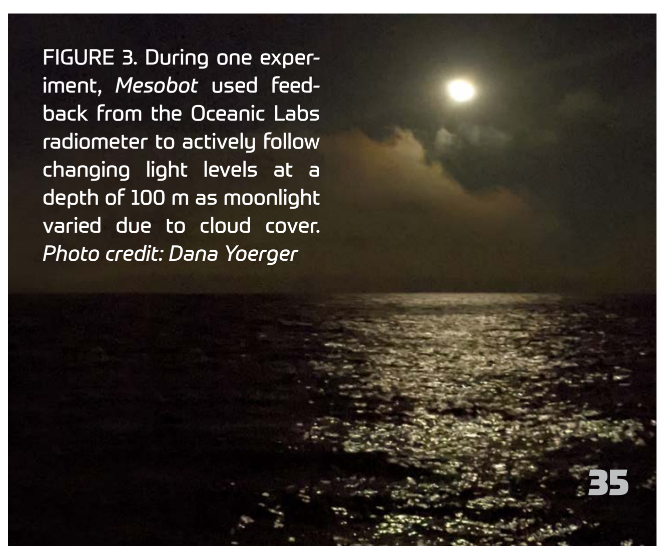


FIGURE 3. During one experiment, *Mesobot* used feedback from the Oceanic Labs radiometer to actively follow changing light levels at a depth of 100 m as moonlight varied due to cloud cover. *Photo credit: Dana Yoerger*

Lu‘uaeaahikiikapapakū: Ancient Volcanoes in Papahānaumokuākea Marine National Monument

By Andrea Balbas, Beth N. Orcutt, Christopher Kelley, Steven Auscavitch, Emil Petruncio, John R. Smith, Nicole Raineault, and Kainalu Steward

E/V *Nautilus* expedition Lu‘uaeaahikiikapapakū (NA134) ROVs *Hercules* and *Argus* along with the ship's EM302 multibeam sonar to explore the Voyager Seamounts located in the southern "expansion" area of Papahānaumokuākea Marine National Monument (PMNM). The lineation of these seamounts suggests they could be a southerly extension of the poorly delineated Wentworth seamount chain located north of the Hawaiian Ridge. Given the lack of geochemical constraints and age determinations of these seamounts, we tentatively hypothesize that they are an extension of the Wentworth chain comprising an age-progressive seamount track (Garcia et al., 1987; Pringle and Dalrymple, 1993). A major focus of the expedition was to sample rocks from these seamounts to test this geologic origin hypothesis.

Thirteen ROV dives were completed on nine of the Voyager Seamounts, none of which had been previously explored with modern techniques (Figure 1). During the ROV surveys, 91 rock samples were collected for $^{40}Ar/^{39}Ar$ age determinations and for chemical analyses to determine the similarity of their basalts to those of the Wentworth seamounts. Eighteen highly altered rocks with parallel water samples plus two sediment cores were collected to determine microbial ecosystem services and mineral content for the purpose of examining microbe-mineral interactions in ferromanganese crusts (Figure 2).

In addition to geological sampling, ROV surveys documented the seamounts' biological communities, particularly looking for high density coral and sponge communities similar to those previously observed in the Musicians Seamounts and on a number of banks within the

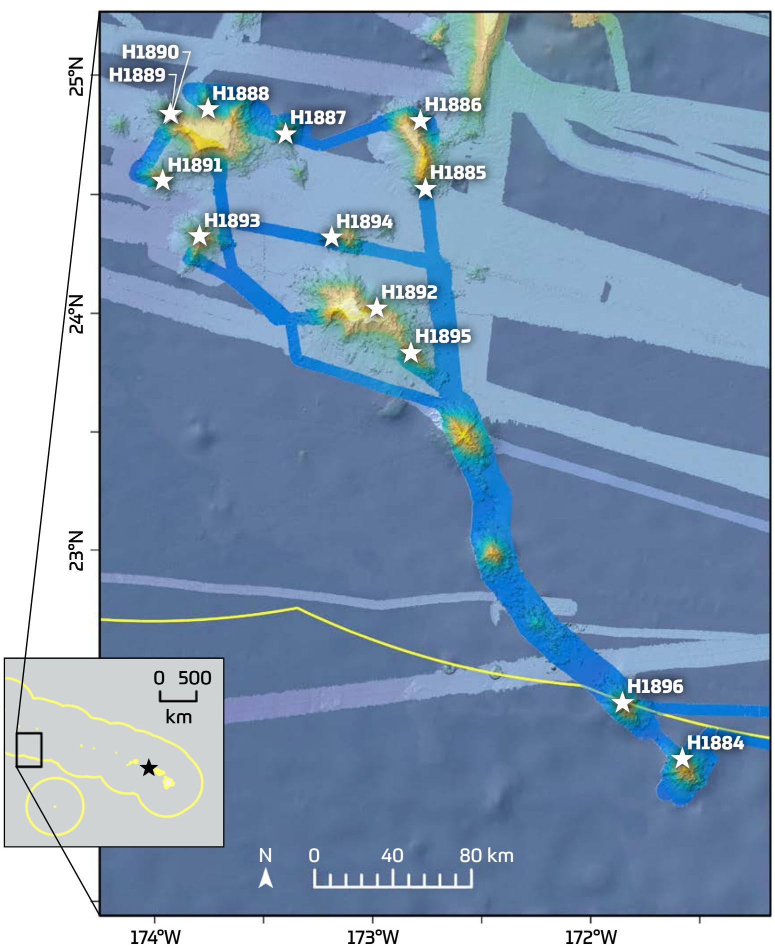


FIGURE 1. Map showing the dive locations (white stars) during E/V *Nautilus* expedition Lu‘uaeaahikiikapapakū in the Voyager Seamounts. The inset map shows the location of the expedition in relation to the main Hawaiian Islands, with Honolulu marked by a black star. Dark blue areas are unmapped seafloor, light blue areas were previously mapped, and bright blue indicates seafloor mapped on this expedition (NA134). The yellow line denotes the limits of the US Exclusive Economic Zone. *Image credit: Erin Heffron*

FIGURE 2. The arm of ROV *Hercules* collects an altered rock sample for analysis of microbial ecosystem services and mineral content in seamount rocks.

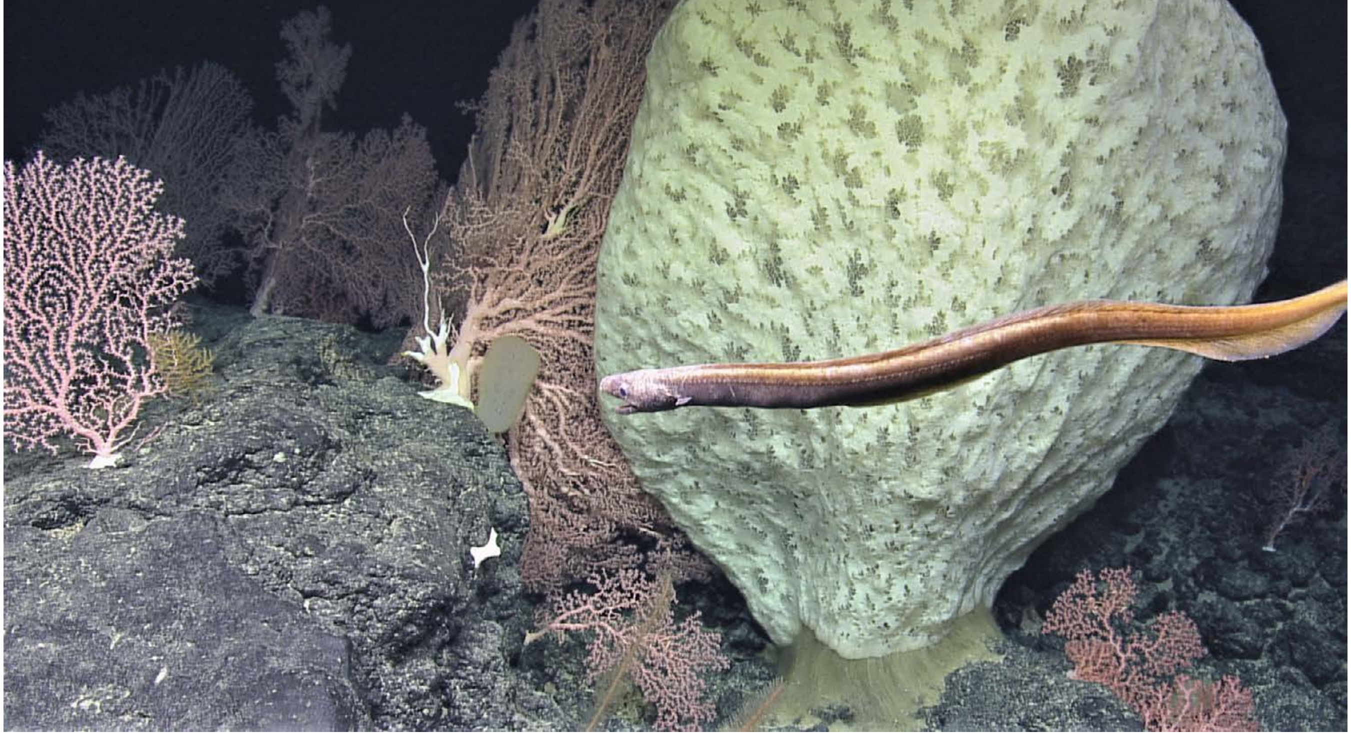


FIGURE 3. Video capture of the high density Tamana Seamount animal community, including several species of corals and sponges along with a cutthroat eel (family Synaphobranchidae).

PMNM. Eventual annotation of the video will determine, among other things, the diversity and density of animals observed during each of the dives. Even before these data are available, it is clear that at least two of the seamounts, Don Quixote and Tamana, host very high densities of corals and sponges while there are moderately high density communities on Ha'aheo and Ho'oikaika (Figure 3). Very sparse communities were observed on several other seamounts, including Euphemia and Sovereign. Whether a seamount has a volcanic summit or is flat-topped (i.e., a guyot) does not seem to be a particularly important factor in determining the density of communities: Don Quixote and Ha'aheo are guyots while Ho'oikaika is not. Although Tamana is a guyot, the dive site was a large volcanic ridge extending southeast from its base that may have been created from a different eruptive event than the main guyot. It is important to note that dive site selection was biased toward rift zone ridges at 1,000–3,000 m depth on virtually all seamounts, because these features were known to have suitable rocks for age dating as well as suitable environmental conditions (i.e., strong current flow) for high density community development. During dives, there was minimal evidence of marine debris, and one fossilized beaked whale bone was observed on Don Quixote Seamount.

Ninety-four macrobiology specimens were collected, some of which may prove to be potential new species or new records of species for the PMNM. These included 15 sponges, all but three of which (*Asbestopluma* sp., *Abyssocladia,* and an unidentified demosponge) were hexactinellids. The cnidarians included 11 hexacorals (five Actiniaria, four Antipatharia, two Scleractinia) and 16 octocorals. Other invertebrates included stalked and unstalked crinoids, polyplacophoran mollusks, and a chirostylid squat lobster.

Forty-seven water samples were collected to support an eDNA study of deep-sea coral habitats in the monument that began in 2018 during *Nautilus* expedition NA101. Thirty-six of these samples were collected where the animal community density was higher, with 11 samples as background from lower density areas.

The total area mapped by multibeam sonar was 21,328 km^2 (18,817 km^2 in the US Exclusive Economic Zone), including filling in of some gaps in existing coverage. In addition, previously undocumented Voyager Seamounts that were completely mapped included Paul, Starling, Akamai, Ho'oikaika, an unnamed seamount east of Don Quixote, and the group's most southerly seamount, which we temporarily designated "Seamount A." All of the newly mapped seamounts were conical in shape, indicating that they had never reached above the sea surface. Complete or near complete coverage now exists for all 14 Voyager Seamounts.

In accordance with guidance from the Native Hawaiian Cultural Working Group of the Office of Hawaiian Affairs, ceremonial protocol was observed at the beginning and end of each science operation in the PMNM, as well as during all ROV dives, in recognition that the working area is considered sacred in Native Hawaiian culture. Shipboard speakers of 'Ōlelo Hawai'i (Hawaiian language) helped visiting scientists and crew to learn these protocols and led engagement with Native Hawaiian audiences during the expedition. In total, 77 live ship-to-shore interactions were conducted, including 11 in 'Ōlelo Hawai'i.

Exploration of an Unnamed Seamount Chain

By Adam Soule, Steve Auscavitch, Allison Fundis, Robert D. Ballard, Coralie Rodriguez, Erin Heffron, and Kelly Moran

E/V *Nautilus* expedition NA135 conducted the first human exploration of an unnamed seamount chain ~240 km west of the Hawaiian island of Kauai in the Central Pacific. The chain is composed of seven seamounts that rise roughly 2,000 m from the abyssal seafloor to summit depths of 1,800 m to 1650 m. The seamounts are each 15–25 km in diameter and display typical structures, including elevated ridges or rift zones arrayed radially around the summit. The seamount chain sits between the Mid-Pacific Mountains to the southwest and the Hawaiian chain to the northeast and is bracketed in the northwest and southeast by Necker Ridge and the Molokaʻi Fracture Zone, respectively (Figure 1).

The primary exploration objectives were to map the seafloor to fill bathymetric gaps, identify the distribution and abundance of deep-sea benthic fauna, and evaluate the extent and conditions of iron-manganese (Fe-Mn) crust formation on seafloor rocks. We conducted ROV transects with *Hercules* from the seamount flanks, near their bases, to their summits, crossing potential depth-dependent biological gradients. A total of five ROV transects were run on five seamounts (provisionally identified as B, C, D, F, G), each along a distinct radial azimuth in order to evaluate the potential role of prevailing current directions on biological density and diversity and Fe-Mn crust development (Figure 2).

Seamount chains provide important markers for paleo-tectonic reconstructions, illustrating when and where magmatic activity occurred and how plate motion has varied through time. The origin of this unexplored seamount chain remains in question. Early geophysical studies of the seamounts' magnetic orientation suggest a Cretaceous age (>250 million years) and a location of origin more than 2,000 nautical miles to the southeast (Schimke and Bufe, 1968), consistent with the Mid-Pacific Mountains and other magmatic features of the region. Alternatively, the seamounts may have formed more recently (~5 million years ago) from the Hawaiian mantle plume, as their position is also consistent with the Hawaiian Arch that forms a volcanic "halo" around the Hawaiian chain (Normark and

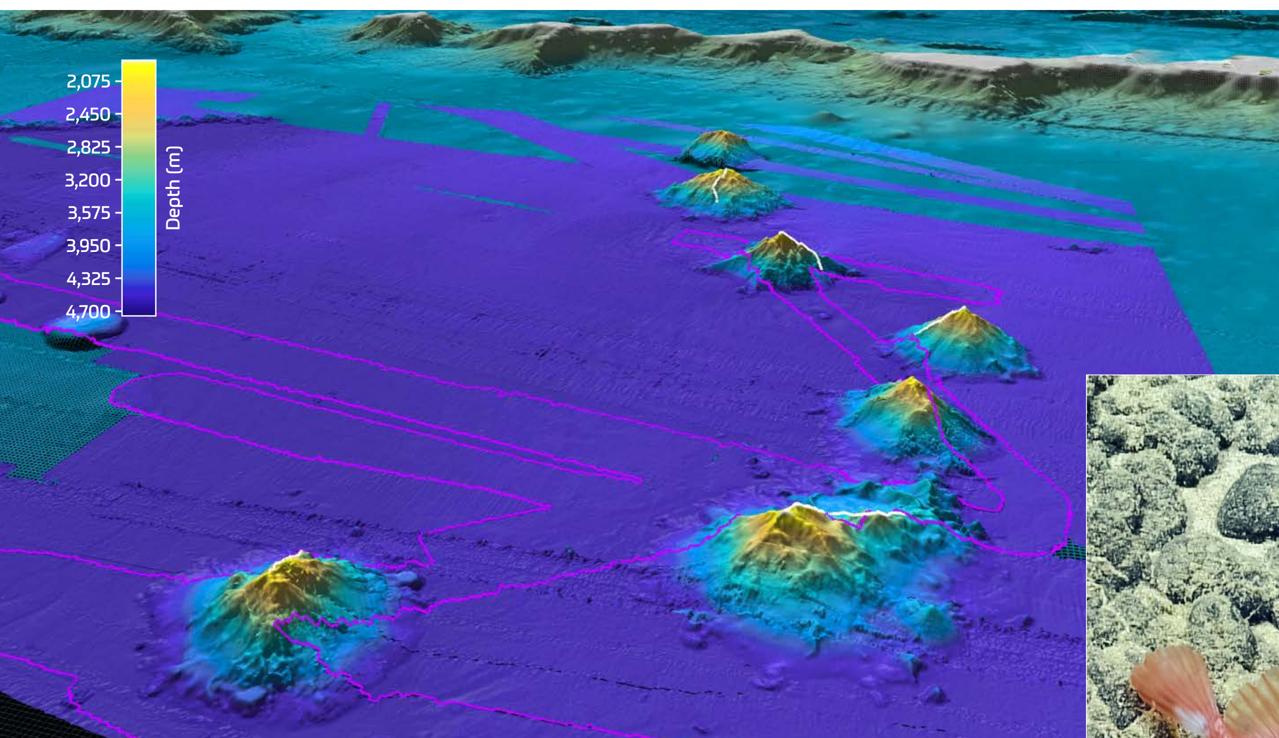


FIGURE 1. Perspective view to the north of the unnamed seamount chain. The summits of these seamounts rise to ~2,000 m depth from the abyssal seafloor at ~5,000 m depth. Newly mapped seafloor that filled bathymetric gaps is highlighted in magenta. White lines show ROV *Hercules* dive tracks.

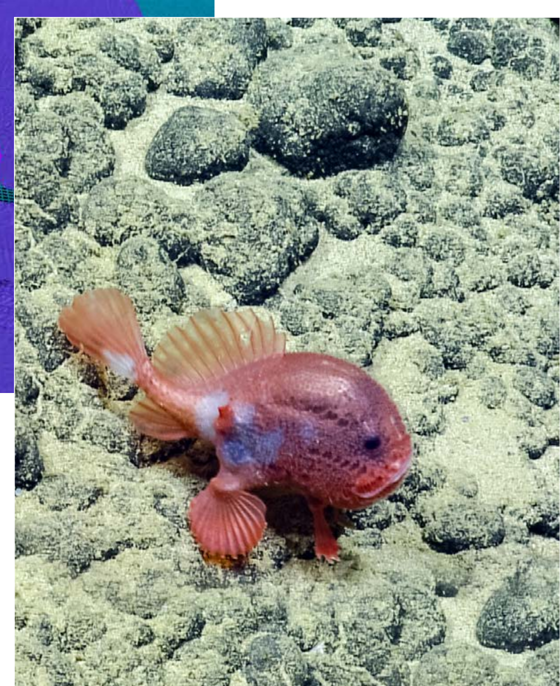


FIGURE 2. The bathyal fish *Chaunacops roseus* rests on lightly sedimented Fe-Mn oxyhydroxide coated basalt on the flanks of an unexplored seamount.

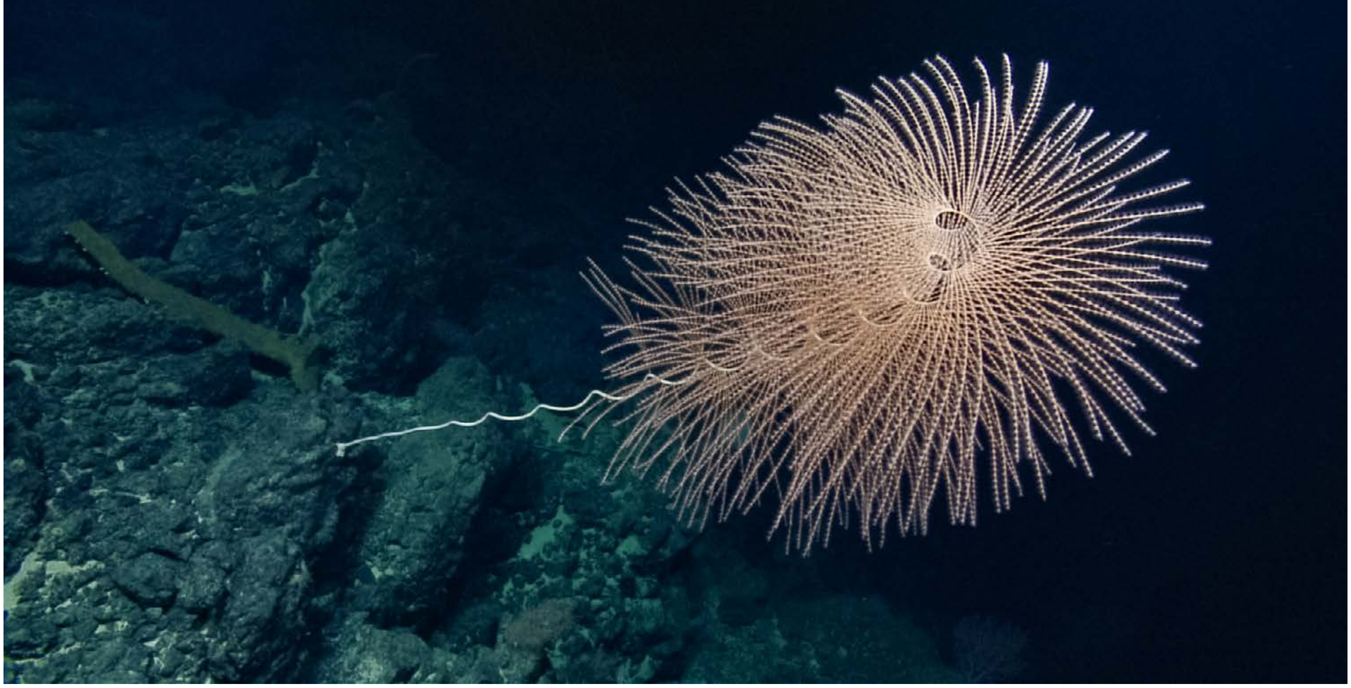


FIGURE 3. *Iridigorgia* soft corals were common on the seamount flanks, especially on ridges where their upright habit allows them to take advantage of upwelling currents.

Shor, 1968). Geochemical analyses of recovered samples will help constrain the magmatic source and provide critical evidence of the seamounts' age, which will yield important context for the distribution and grade of rare metals contained in their Fe-Mn crusts, as well as the thickness and thus total metal content of their deposits.

Our initial exploration of this region showed that all hard surfaces displayed a thick Fe-Mn crust. Despite this observation, it was possible to identify the volcanic and geologic morphology of the seafloor. We found a wide range of lava morphologies on the seamounts, including smooth sheet flows on steep slopes, pillow lavas on ridges, lobate lavas on low-relief benches on the flanks, and massive, columnar-jointed flows most commonly near the summits. Between the seamount ridges/rift zones, we found valleys filled with volcanic breccia as well as regions of heavy sedimentation, most of which were blanketed by extensive fields of manganese micro-nodules. The micro-nodules ranged in size from 10 mm to 60 mm in diameter and were surrounded by small, angular basalt fragments and sediment. In addition to micro-nodules, sedimented regions were found to be coated by Fe-Mn pavement that likely represents the coalescence of Fe-Mn micro-nodules. Many of the nodule fields showed evidence of active downslope movement of material, including the collection of nodules in the downslope shadows of large boulders, sorting of nodules by size, and the partial burial of nodule fields by sediment.

A total of 41 rock samples were collected on ROV dives at roughly equally spaced depths between the seamounts' bases and their summits for subsequent geochemical analyses of the basalt and Fe-Mn crusts. At most rock sample locations, a companion seawater sample was collected for comparison to crust trace metal concentrations. In addition, a few samples of manganese micro-nodules were collected using the ROV scoop. The thickness of Fe-Mn crust, examined on a small subset of samples, was 35–40 mm, much thinner than the crusts on intact volcanic surfaces.

Seamounts within the chain, along with others in the Central Pacific, provide hard substrate for sessile fauna; span significant depth-dependent chemical, light, and pressure gradients; and induce complexity in seawater currents, which makes them an important marine habitat. Because of these characteristics, seamounts are viewed as potential oases of benthic life in the deep ocean. The isolation of individual seamounts and chains of seamounts in the Central Pacific provide a natural laboratory for examining the range and potential endemism of benthic fauna. This seamount chain is proximal to ridges (e.g., Necker Ridge) that are hypothesized to act as genetic conduits, but their isolation and greater depth may make them less viable for genetic flow. Benthic organisms observed were dominated by sponges and corals (Figure 3), and differences in community composition were noted between abyssal and bathyal depths. At abyssal depths, sediment mounds created by burrowing organisms were observed, and spoon worms were identified at some of the mounds. At seamount summits, bamboo corals dominated high densities of deep-water corals that were found in patches.

The livestream of the expedition was viewed over 280,000 times, and during the cruise we connected with approximately 3,000 students across 17 US states, Canada, Czech Republic, and South Korea via 46 ship-to-shore connections.

Autonomous Mapping Technology Returns to the Great Lakes

By Stephanie Gandulla, Dwight Coleman, Erin Heffron, Val Schmidt, Lindsay Gee, John Bright, Kathryn Lohr, Clint Marcus, Samantha Wishnak, and Sarah Waters

Building on a successful 2019 survey of 153 km^2 of Lake Huron bottomlands, the Ocean Exploration Trust and partners returned to Thunder Bay National Marine Sanctuary (TBNMS) in June 2021 for a 16-day mapping and five-day ROV exploration expedition. Concurrent with the 2021 E/V *Nautilus* expedition season, this two-phase, mobile mission brought together a variety of science and outreach partners to support the sanctuary mission to search for and document historically significant archaeological sites.

Located in northern Lake Huron, TBNMS is the first freshwater national marine sanctuary in the United States and is part of a network of sites encompassing more than one and a half million square kilometers of marine and Great Lakes waters (Figure 1). The work done in these 15 national marine sanctuaries and two marine national monuments is backed by the National Marine Sanctuaries Act of 1972, one of the nation's strongest pieces of ocean and Great Lakes conservation legislation. Designated in 2000, TBNMS protects one of the nation's best-preserved collections of shipwrecks. There are 100 known shipwrecks within its 11,137 km^2, and historical research indicates as many as 100 more are yet to be found. The diverse collection represents over a century of commerce in the heart of North America and includes wooden schooners that date to the early nineteenth century and modern, massive steel freighters. Together, the early shipwrecks tell a story of a time when schooners and steamers ruled the lakes and, through transport and trade, fueled a developing industrial economy. Individually, they recall the lives of thousands of sailors who made their living taking risks in some of the world's most treacherous waters.

TBNMS protects this significant collection of shipwrecks through research, resource protection, outreach, and education. An integral part of its management philosophy is to understand the lake bottom, yet, as of 2019, only a small portion of the sanctuary had been mapped to a level of detail sufficient to identify historical resources. After the autonomous surface vehicle (ASV) *Bathymetric Explorer and Navigator* (*BEN*) successfully joint-mapped 153 km^2 with R/V *Storm* during Expedition M001 in 2019, it returned to the remote waters of northwestern Lake Huron to continue its mission. Representing some of the latest autonomous exploration technology, *BEN* is a custom prototype built by ASV Global Unmanned Marine Systems (now L3Harris) in Portsmouth, UK, for the University of New Hampshire's Center for Coastal and Ocean Mapping/Joint NOAA Hydrographic Center. *BEN* is a 4 m long vessel with diesel jet drive propulsion, a top speed of 5.5 knots, and an endurance of approximately 16 hours. Equipped with state-of-the art seafloor mapping systems, including a Kongsberg EM 2040P MKII multibeam sonar that can map up to depths of 500 m, *BEN* and the expedition team successfully mapped 76 km^2, 57 km^2 of which was previously unknown sanctuary bottomlands. NOAA R/V *3011* acted as a support vessel and collected numerous sound velocity profiles per day (Figure 2).

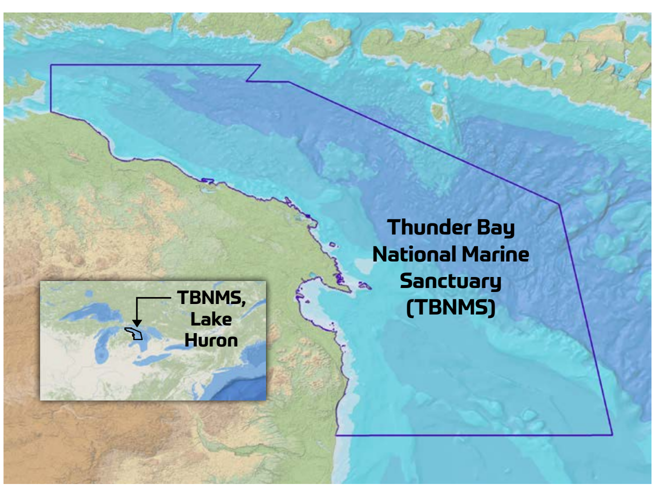
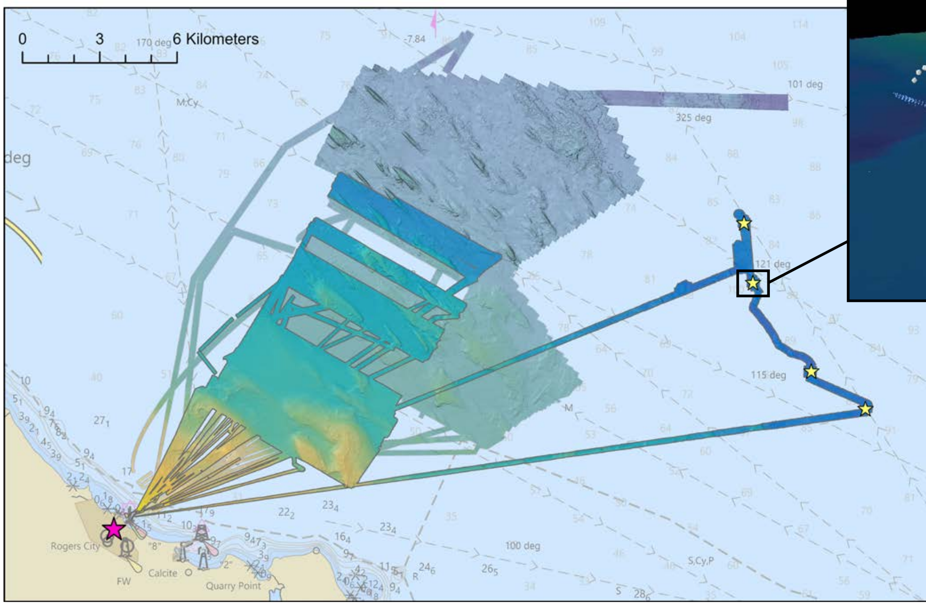


FIGURE 1. Map of the 11,137 km^2 Thunder Bay National Marine Sanctuary (TBNMS) in northern Lake Huron. *Image credit: NOAA, TBNMS*

FIGURE 2. NOAA R/V *3011* tracks autonomous surface vehicle (ASV) *BEN* during mapping operations. Once in range, sound velocity cast data are wirelessly transmitted to *BEN*.



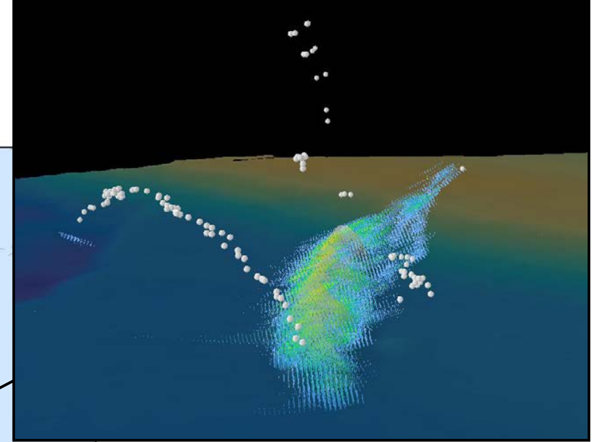


FIGURE 3. (left) Combined TBNMS mapping coverage from 2019 and 2021 at depths ranging from less than 1 m (pale yellow) to 110 m (purple). Rogers City is shown as a magenta star, and shipwrecks explored by the ROV are marked by yellow stars. (above) Multibeam sonar bathymetry and water column data collected by ASV *BEN* over the wreck of the wooden bulk carrier *Ohio*, wrecked in 1894. White dots were water column returns from unexpected mooring lines.

This first phase of the project focused on the shallow waters off the shores of Rogers City, Michigan (Figure 3). These areas feature dangerous, nearshore shoals that are difficult to access with traditional survey platforms on crewed vessels. Dynamic shorelines and shifting sands, characteristic of near-coastal environments, make surveying such areas vital to resource management and the identification of historic resources.

Taking the next step in documenting sanctuary resources, OET and TBNMS partnered with the US Coast Guard (USCG) and the University of North Carolina at Wilmington's (UNCW) Undersea Vehicle Program to conduct ROV-based video documentation of sanctuary shipwreck sites in depths ranging from 60 m to 100 m. This five-day expedition offered archaeologists unparalleled views of these fragile sites. The team mobilized the UNCW-operated ROV *Mohawk* onboard USCG Cutter *Mobile Bay*, an icebreaking vessel stationed in the northern Great Lakes. This platform came equipped with an integrated crane barge to support launch and recovery of the ROV; the UNCW team added navigation electronics, surface and subsea positioning equipment, and an ROV control area and viewing laboratory.

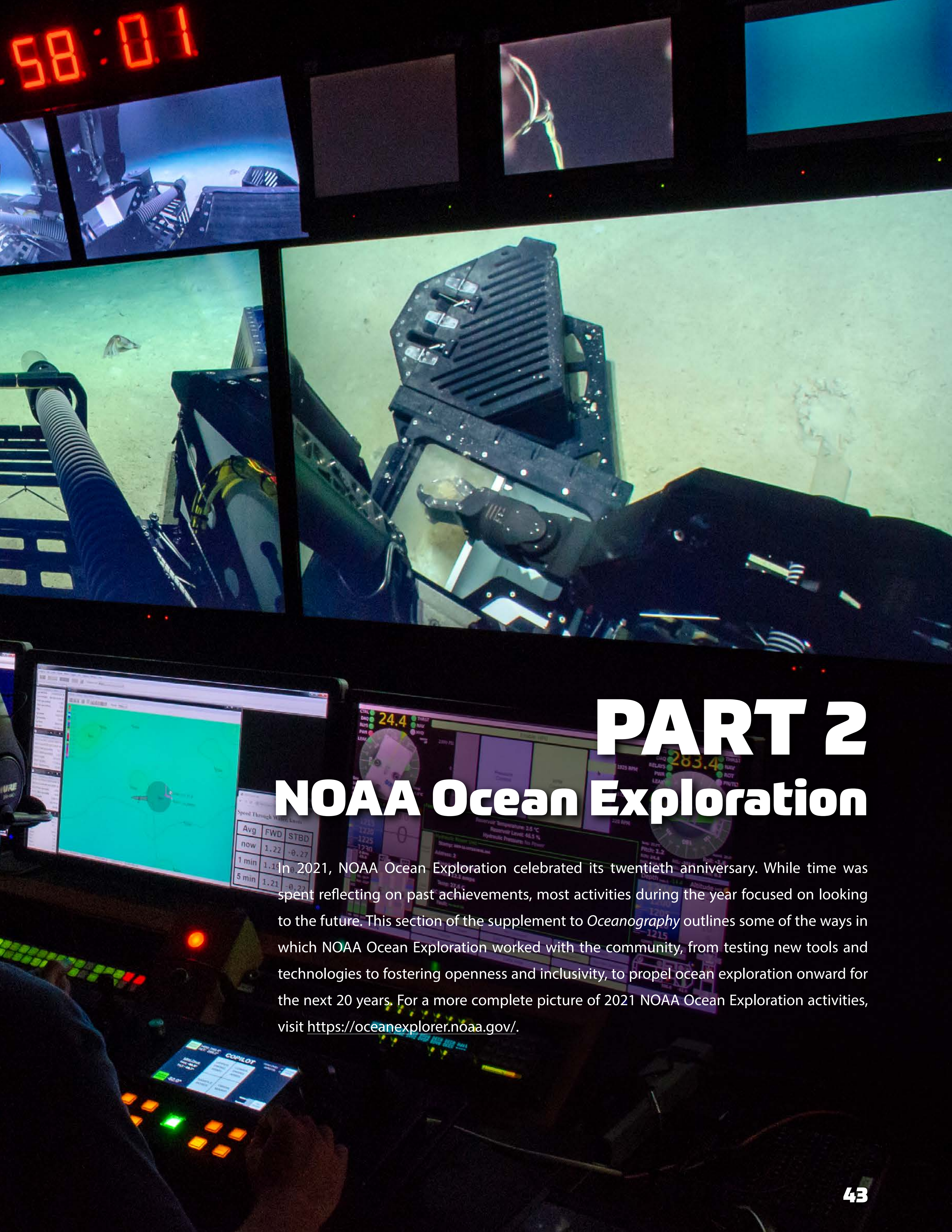
Within TBNMS, numerous historic shipwreck sites remain nearly intact and well preserved by the cold, fresh water of Lake Huron. Two of the sites imaged were discovered during multibeam sonar surveys in 2011 and documented in the film *Project Shiphunt*, and two more sites located by a TBNMS-led team in 2017 were visited. All four sites were in depths greater than 90 m. During the remaining ROV deployments, another four sites were studied. Each ROV mission lasted between four and six hours. TBNMS archaeologists operated cameras onboard the ROV, captured digital screen grabs from the HD video feed, identified features, and guided the exploration to assist the ROV pilot and navigator in achieving the archaeological goals of the dive.

As with every OET and TBNMS expedition, bringing the science to the public was key. Inviting public participation through live, interactive broadcasts comprised a vital tool for communicating the importance of national marine sanctuaries and the Great Lakes, as well as for engaging the next generation of STEM innovators. In addition to promotion via OET and TBNMS social media channels, the expedition included two live broadcasts that allowed viewers to learn about the expedition and TBNMS and ask scientists and engineers questions in real time. Recordings of these broadcasts were also made available to view and share via online platforms. These broadcasts were viewed over 15,000 times, increasing public access to sanctuary science and exploration and inspiring the next generation of explorers.

By working with diverse partners, the sanctuary has increased scientific and technological capacity to search for and monitor maritime heritage resources and thus ensure their long-term protection. These partnerships have been, and will continue to be, critical to the success of TBNMS. In addition to mapping new areas of Great Lakes bottomlands, reaching new audiences with technology and science, and documenting some of the deepest, most fragile archaeological sites in sanctuary waters, this project also demonstrates the capacity for OET expeditions to go beyond the ship and deploy mobile-system expeditions in the Great Lakes and around the globe.

The pilots command the remotely operated vehicles from the control room of NOAA Ship *Okeanos Explorer* during a dive.

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



PART 2
NOAA Ocean Exploration

In 2021, NOAA Ocean Exploration celebrated its twentieth anniversary. While time was spent reflecting on past achievements, most activities during the year focused on looking to the future. This section of the supplement to *Oceanography* outlines some of the ways in which NOAA Ocean Exploration worked with the community, from testing new tools and technologies to fostering openness and inclusivity, to propel ocean exploration onward for the next 20 years. For a more complete picture of 2021 NOAA Ocean Exploration activities, visit https://oceanexplorer.noaa.gov/.

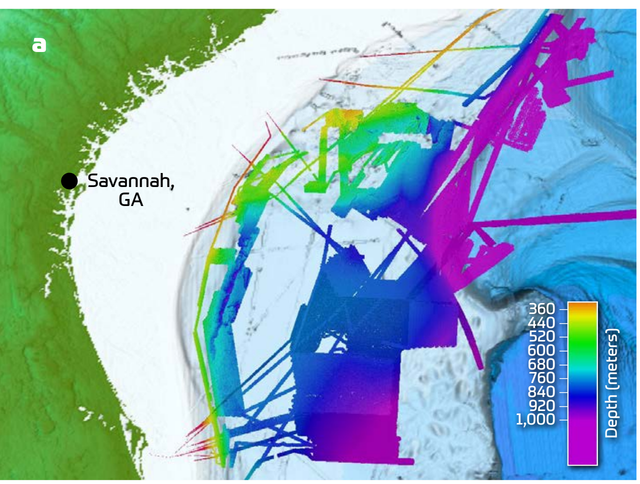
Mapping the Deep Ocean

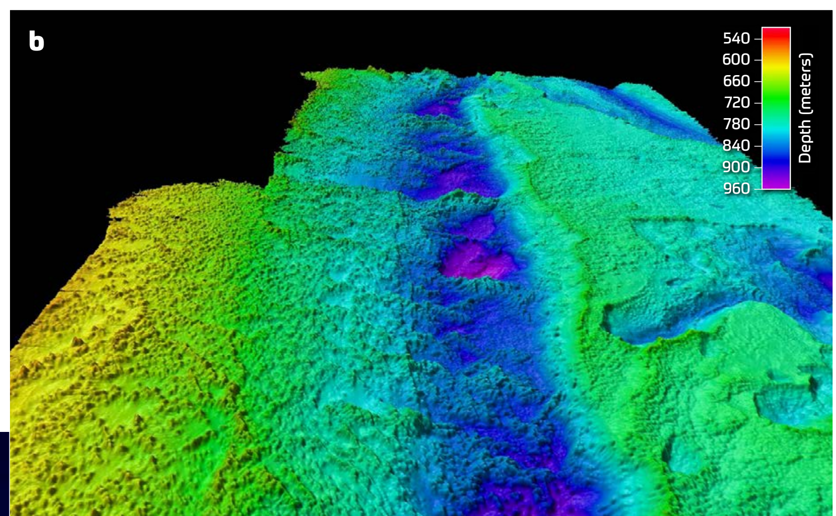
In 2021, NOAA Ocean Exploration made significant strides in expanding the pace and efficiency of ocean mapping operations. The application of new tools and solutions facilitated meaningful contributions toward reaching the goals outlined in the National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone (https://www.noaa.gov/nomec/nomec-strategy).

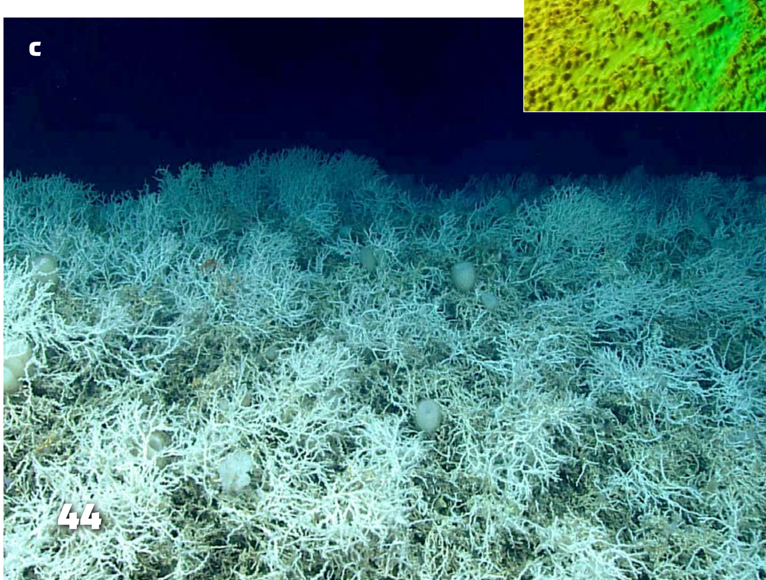
With the upgrade of the multibeam sonar transducer on NOAA Ship *Okeanos Explorer,* done in partnership with the NOAA Office of Marine and Aviation Operations (OMAO) and Kongsberg Maritime, the transition to Kongsberg's new EM 304 multibeam echosounder was completed. Successfully tested in spring 2021 and then applied during expeditions for the remainder of the year, this new sonar system improves the seafloor mapping data quality and coverage, increasing the efficiency of our deep-sea mapping work. It also allowed us to achieve two important mapping milestones.

On November 1, 2021, while conducting operations on the Blake Plateau off the southeast coast of the United States, NOAA Ocean Exploration surpassed a total of 2,000,000 km^2 (772,204 mi^2) of seafloor mapped with multibeam sonar on *Okeanos Explorer* since the ship was commissioned in 2008. Reaching this milestone while mapping on the Blake Plateau marked another major achievement for the office: a near-complete map of the deep waters (greater than 200 m) of the Blake Plateau within the US Exclusive Economic Zone, an area of interest for multiple agencies in implementing the National Strategy.

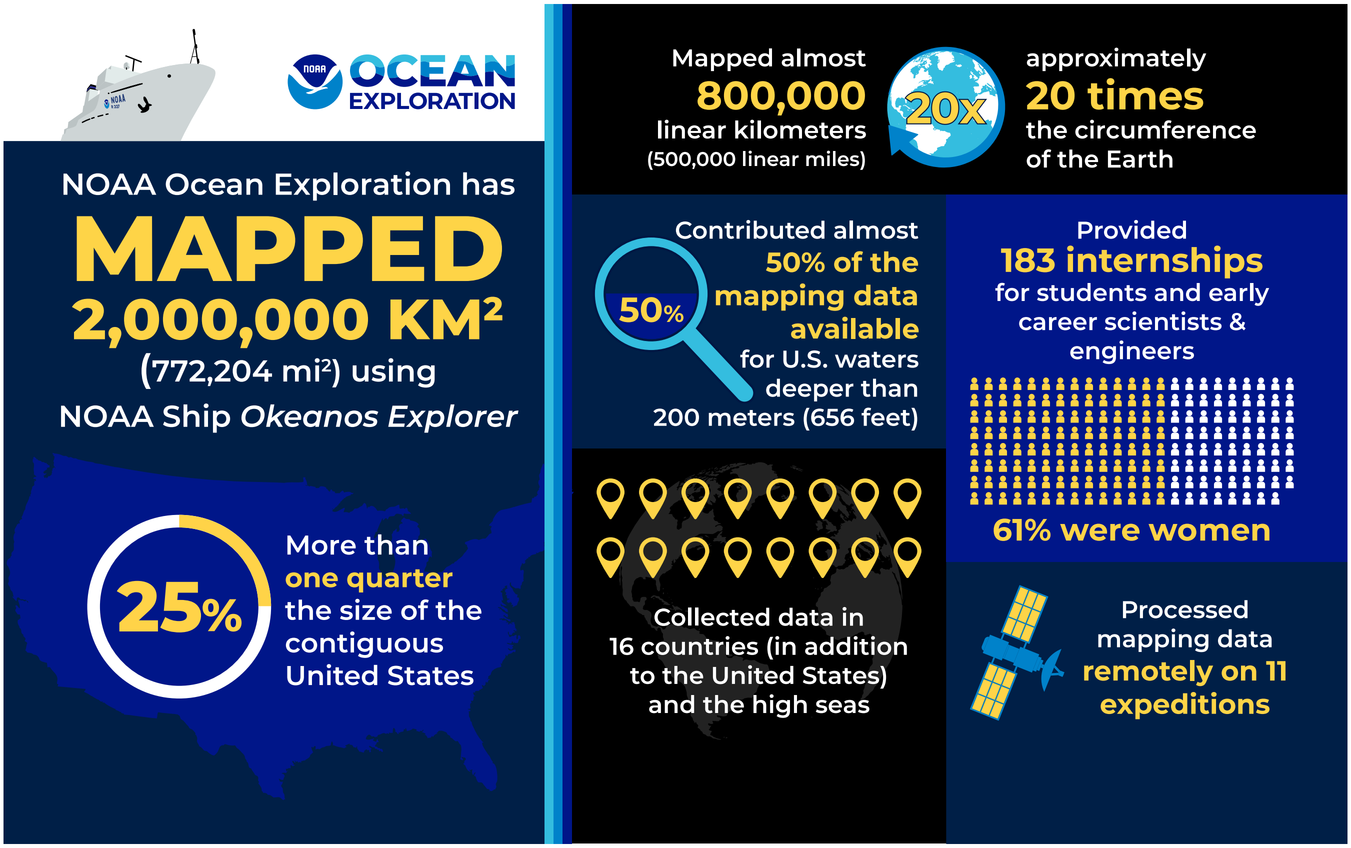
Throughout the year, the team piloted the processing of mapping data in the Cloud, creating an environment where multiple experts can simultaneously work on data from anywhere in the world. In addition to broadening scientific capacity and advancing efforts to develop capabilities for conducting ocean mapping missions using shore-based scientists, these advances resulted in improved ocean education and outreach. Four interns hosted during the year contributed to the Cloud-based mapping effort.

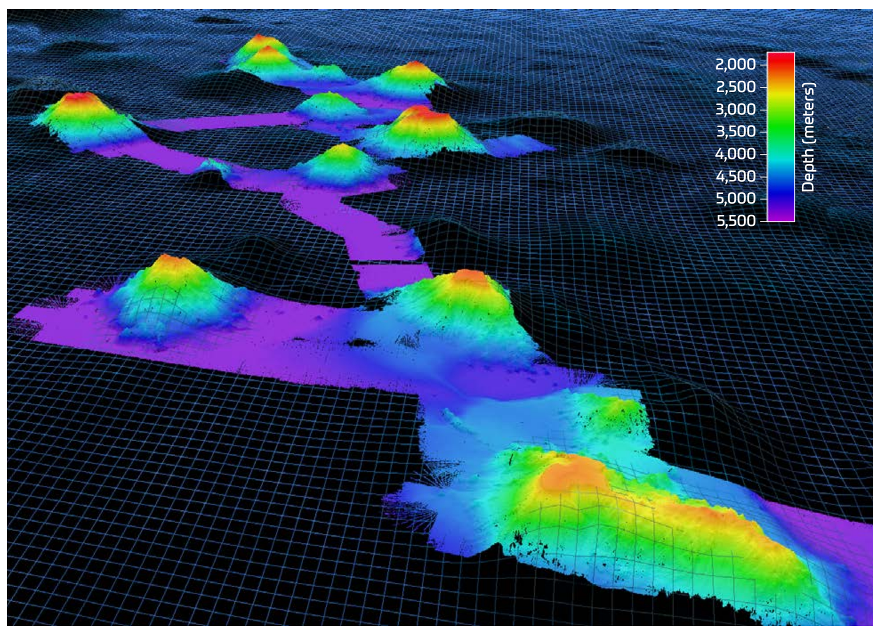






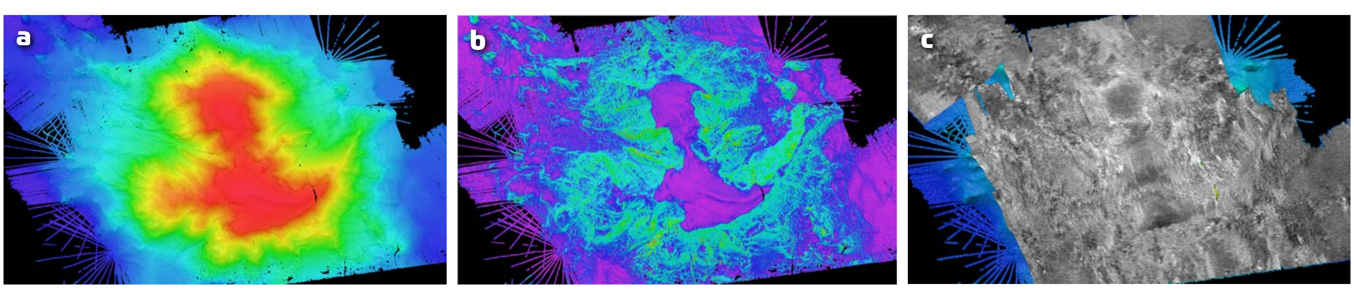
With partner scientists, NOAA Ocean Exploration has been mapping the seafloor of the Blake Plateau off the southeastern United States aboard NOAA Ship *Okeanos Explorer* (a) since 2011. This mapping resulted in the discovery of extensive, dense mounds of the reef-building coral *Lophelia pertusa* (b and c)—some in areas previously believed to be flat and featureless. These mounds have been growing for thousands, perhaps millions, of years and provide shelter and habitat to a variety of marine life. This area is considered to be the most extensive continuous deep-sea coral mound habitat discovered in the world thus far.





Seafloor topography data collected along the New England Seamounts with *Okeanos Explorer*'s new EM 304 MKII multibeam echosounder during the 2021 North Atlantic Stepping Stones: New England and Corner Rise Seamount Chain expedition is overlaid here on the Global Multi-Resolution Topography data synthesis grid. Forty seamounts were mapped over the course of the expedition, 20 of them for the first time.

Data collected during mapping operations play a critical role in planning remotely operated vehicle (ROV) dives. These images show dive planning products developed during the 2021 North Atlantic Stepping Stones: New England and Corner Rise Seamount Chain expedition prior to exploration of Michael Seamount: (a) bathymetry, (b) slope, (c) backscatter. During this expedition, 14 of 20 ROV dives conducted were "map and dives," where higher-resolution mapping data needed to successfully execute the dive were collected just hours before the dive took place, because previously there were no, or poor, data available for each dive site.



Putting "Eyes" on the Deep Ocean: Remotely Operated Vehicle Operations

In 2021, NOAA Ocean Exploration led or supported several expeditions that included remotely operated vehicle (ROV) operations to conduct visual surveys and collect physical samples needed to identify, understand, protect, and manage marine life and habitats, geological features, and potential resources.

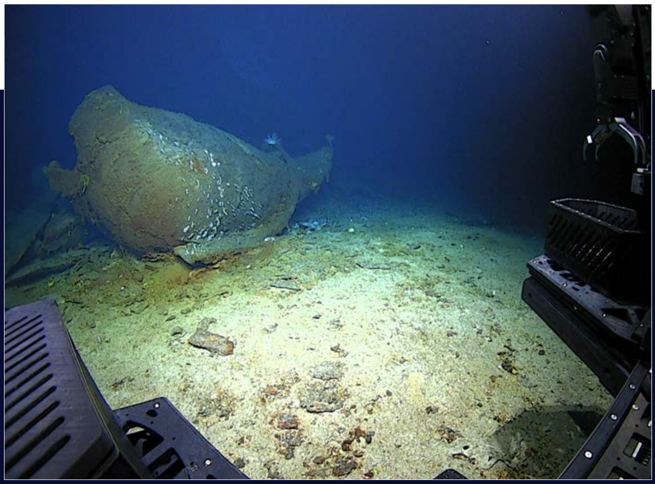
With 30 days at sea, the 2021 North Atlantic Stepping Stones: New England and Corner Rise Seamounts expedition on *Okeanos Explorer* was the longest single mission ever undertaken aboard the ship. ROV operations resulted in the discovery of deep-sea coral and sponge communities on every dive except one that was dedicated to water column exploration. Several potential new species were observed, significant depth and geographic range extensions were recorded for several species, and other visual observations yielded new insights into animal behaviors. Scientists also made the first visual confirmation of ferromanganese nodule fields in the New England Seamount Chain region, a valuable contribution to understanding seamount nodule occurrences in the Atlantic Ocean.

During the Windows to the Deep 2021 expedition aboard *Okeanos Explorer*, ROV operations included collection of 78 water samples for later environmental DNA analysis. Two dives on the Blake Spur escarpment, located on the eastern edge of the Blake Plateau, resulted in the discovery of rich sponge gardens that are home to a diversity of organisms. The wreck of SS *Bloody Marsh*, a World War II-era oil tanker sunk by a German U-boat in 1943 off the coast of South Carolina, was discovered and explored during the expedition. This was just one of the year's several exciting maritime heritage discoveries.

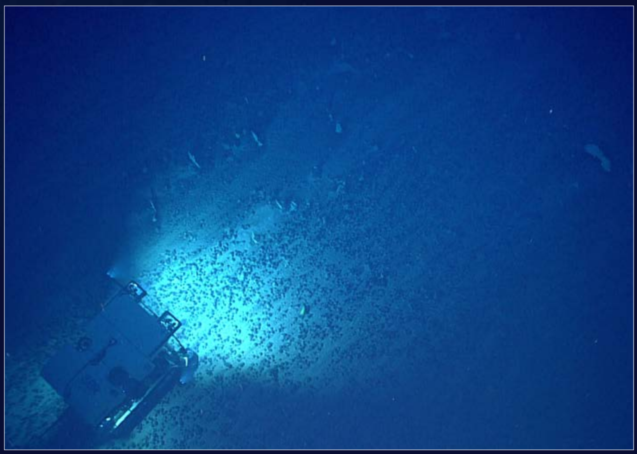
These expeditions plans were based on input from the broader scientific community on exploration priorities. During both expeditions, scientists from around the world contributed their expertise in narrating live dives and annotating dives via SeaTube, a web-based annotation interface implemented in partnership with Ocean Networks Canada.

Eventually, ROV operations such as these will be supplemented with work done by autonomous systems like those described on the next page, increasing the future pace and scope of exploration in order to unlock the mysteries of the deep.

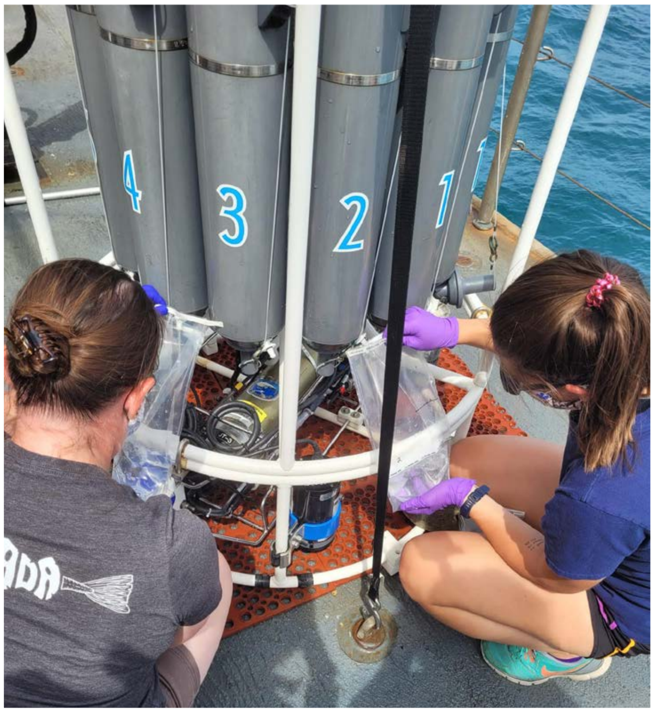
During Windows to the Deep 2021, ROV *Deep Discoverer* captured remarkable footage of an adult bigfin squid (*Magnapinna* sp.). Bigfin squid are the deepest known types of squid, and while sightings have been recorded globally, the total number of sightings is likely less than two dozen, making this observation rare and all the more exciting.



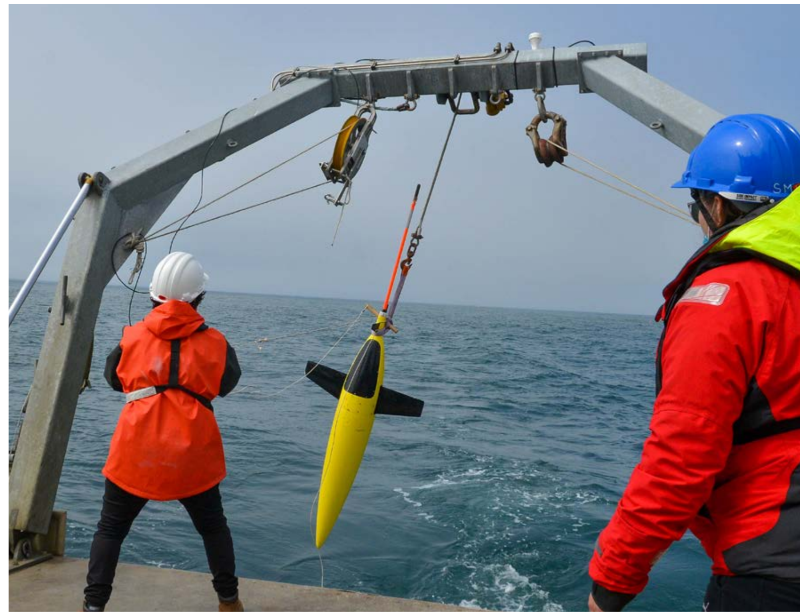
The wreck of SS *Bloody Marsh* was discovered during Windows to the Deep 2021. In addition to its historical significance and connection to World War II, this shipwreck is on NOAA's list of Potentially Polluting Wrecks in US Waters.



Deep Discoverer traverses an extensive field of ferromanganese nodules that formed the bulk of the hard seafloor substrate observed during a 2021 North Atlantic Stepping Stones expedition dive on Gosnold Seamount. The discovery and study of these nodules is a valuable contribution to understanding seamount nodule occurrences in the Atlantic Ocean.



During the 2021 Technology Demonstration, water sample collection processes were refined to detect environmental DNA, also known as eDNA, throughout the water column. These efforts led to the development of detailed standard operating procedures for future eDNA collection on *Okeanos Explorer*.



NOAA Ocean Exploration provided funding to a team from the University of Washington Applied Physics Lab to test the use of an acoustic Doppler current profiler-equipped Seaglider to simultaneously sample the physical and biological properties of waters where mid-trophic organisms reside. With their long endurance and access to remote ocean environments, gliders provide an efficient and cost-effective solution to exploring the deep ocean. *Image courtesy of Coordinated Simultaneous Physical-Biological Sampling Using ADCP-Equipped Ocean Gliders*

Advancing Technology

A key theme throughout 2021 was working with partners to push the boundaries of technology, from advancement and development of shipboard and uncrewed systems to the application of emerging tools such as omics, allowing more effective and efficient mapping, exploration, and understanding of the ocean environment.

During the 2021 Technology Demonstration on *Okeanos Explorer*, NOAA Ocean Exploration partnered with NOAA's Northwest Fisheries Science Center, NASA's Jet Propulsion Laboratory, and two NOAA Ocean Exploration Cooperative Institute (OECI) member institutions: the Woods Hole Oceanographic Institution and the University of Rhode Island. During the expedition, partners worked to determine the potential for expanded environmental DNA (eDNA) sampling operations and to test an autonomous underwater vehicle that may one day expand exploration of hadal depths.

Through our competitive grants program, we provided funding for two projects aimed at better study of the water column using emerging technologies. One expedition included successful testing and deployment of new technologies aboard two autonomous sensor platforms: the National Geographic Society Driftcam and the Teledyne Webb Research Slocum Glider. Developed to explore the sound scattering layers of the Gulf of Mexico, these tools will allow scientists to non-invasively collect information about the composition and behavior of animals in mesopelagic regions of the ocean. NOAA Ocean Exploration also supported an expedition focused on the collection of data needed to develop new acoustics-based methodologies that will pave the way for persistent, distributed observations of mid-trophic organisms using gliders.

Development of several OECI ocean exploration technologies continued throughout 2021. Construction and delivery of a new *DriX* autonomous surface vehicle (ASV) was completed by iXblue and acceptance testing was undertaken by the OECI partner the University of New Hampshire. *DriX* is an 8 m, seven-day endurance ASV that will expand mapping capacity by enabling concurrent multibeam sonar data collection by two vessels. Additionally, technology updates to the University of Southern Mississippi's AUVs *Eagle Ray* and *Mola Mola* occurred in 2021.

Discovering Our Maritime Heritage

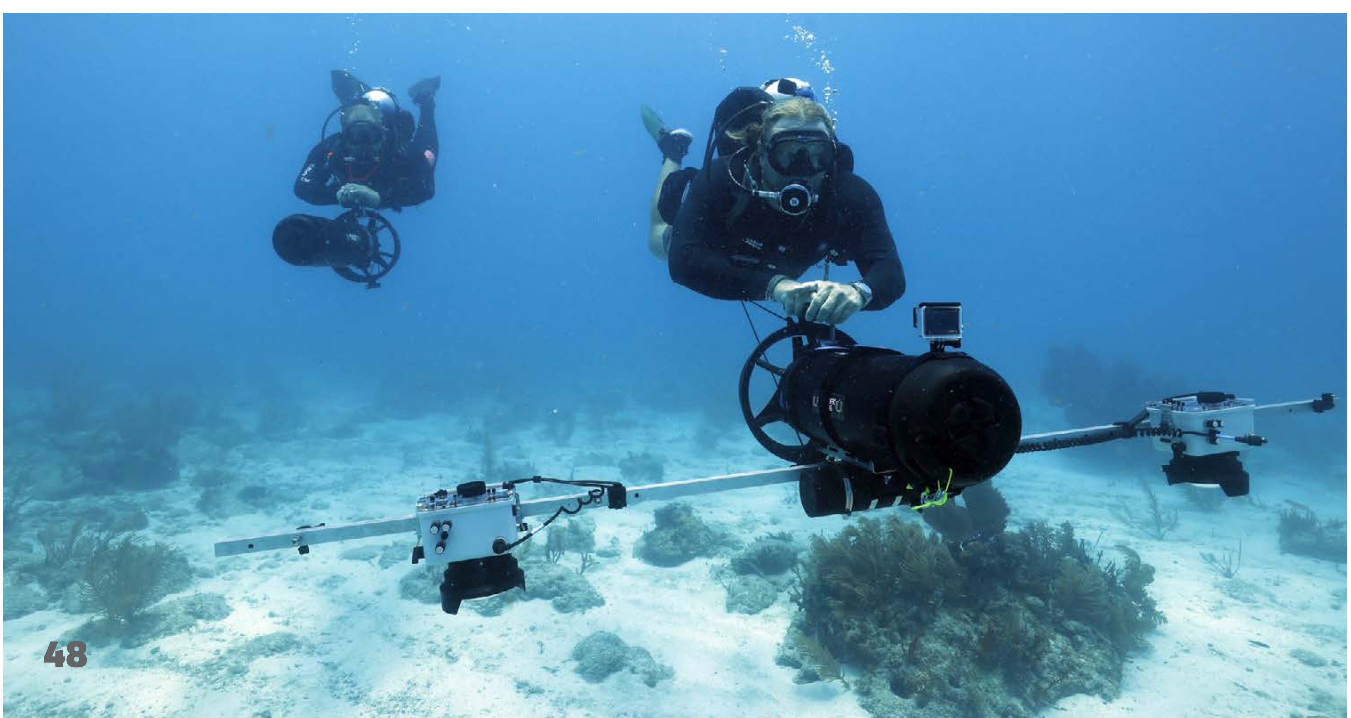
By studying maritime heritage resources such as shipwrecks and prehistoric archaeological sites, we can better understand the past, connect to our cultural heritage, and learn more about environmental and human interactions and impacts. In 2021, NOAA Ocean Exploration worked closely with partners to discover and explore several key submerged cultural resources in US waters.

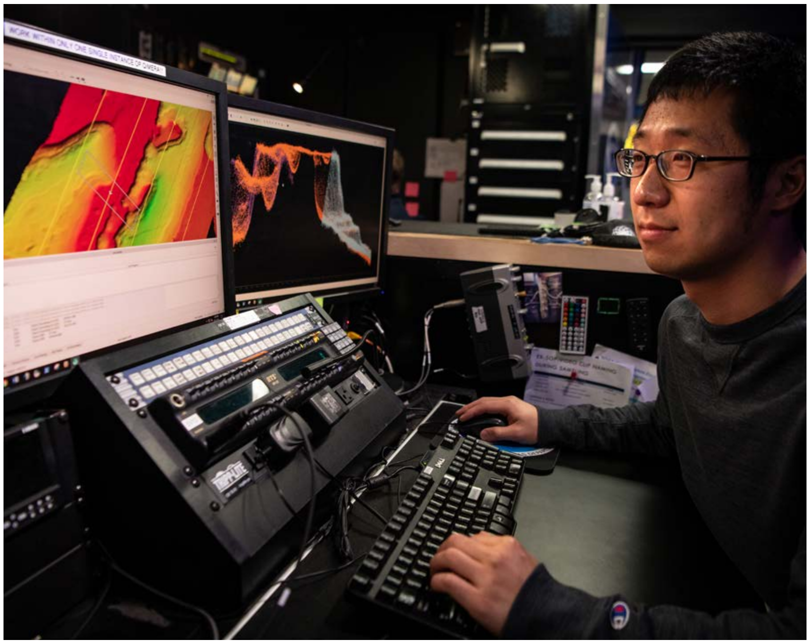
The NOAA Ocean Exploration competitive grants program supported several expeditions to explore maritime heritage resources using innovative and emerging technologies. These projects included expeditions that employed autonomous vehicles to assess shipwreck sites in the Great Lakes and to begin the search for SS *Norlindo*, an American steam freighter sunk by the German submarine *U-507* in the Gulf of Mexico; the latter work also co-funded with the OECI. Funding was also provided to use acoustic remote-sensing technologies to identify targets for exploration in 2022 that may provide evidence that prehistoric people once inhabited the shores of the Paleo-Suwannee River and its surroundings.

After nearly two decades of searching, NOAA Ocean Exploration, the NOAA Office of National Marine Sanctuaries' Maritime Heritage Program, the US Coast Guard, and a number of partners discovered, with "reasonable certainty," the final resting place of US Revenue Cutter *Bear* 145 km (90 miles) due south of Cape Sable, Nova Scotia. Having served for nearly 80 years, including for the US Revenue Cutter Service, for the US Navy, and as a ship of exploration in the Antarctic, *Bear* is considered one of the most historically significant ships in US history for its long and meritorious service.

A diver collects a sample of peat from an extensive deposit discovered during surveys along the Alpena-Amberley Ridge, a landform that was once dry land but is now underwater in the middle of Lake Huron. Results from this project will increase understanding of how people in the past responded to climate change and rising water levels. *Image credit: Discovering the Submerged Prehistory of the Alpena-Amberley Ridge in Central Lake Huron expedition*

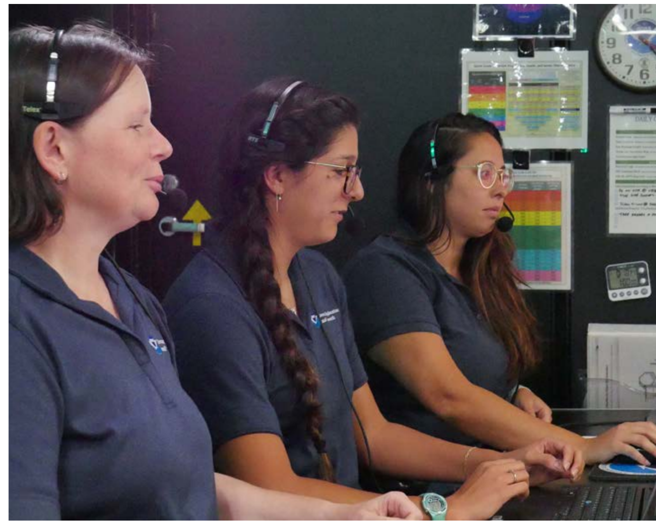
Divers collect data for multi-image photogrammetry and 360° panoramic imaging to document archaeological sites within the "Quicksands" region of Florida Keys National Marine Sanctuary. The work resulted in the discovery of the Spanish steamship *Valbanera*, which sank in a 1919 hurricane. *Image credit: NOAA/UM-RSMAS, Quicksands Archaeological Survey*





Explorer-in-Training Edward Kim processes multibeam bathymetry data aboard *Okeanos Explorer*. *Image credit: Caitlin Bailey, GFOE*

Left to right, biology science lead Rhian Waller from the University of Maine, expedition coordinator Kimberly Galvez from NOAA Ocean Exploration, and NOAA Ocean Exploration mapping lead Shannon Hoy participate in a dive planning call from the control room on *Okeanos Explorer* during the 2021 North Atlantic Stepping Stones expedition. *Image credit: Emily Narrow, GFOE*



Accelerating Ocean Exploration Through a Culture of Diversity, Inclusivity, and Openness

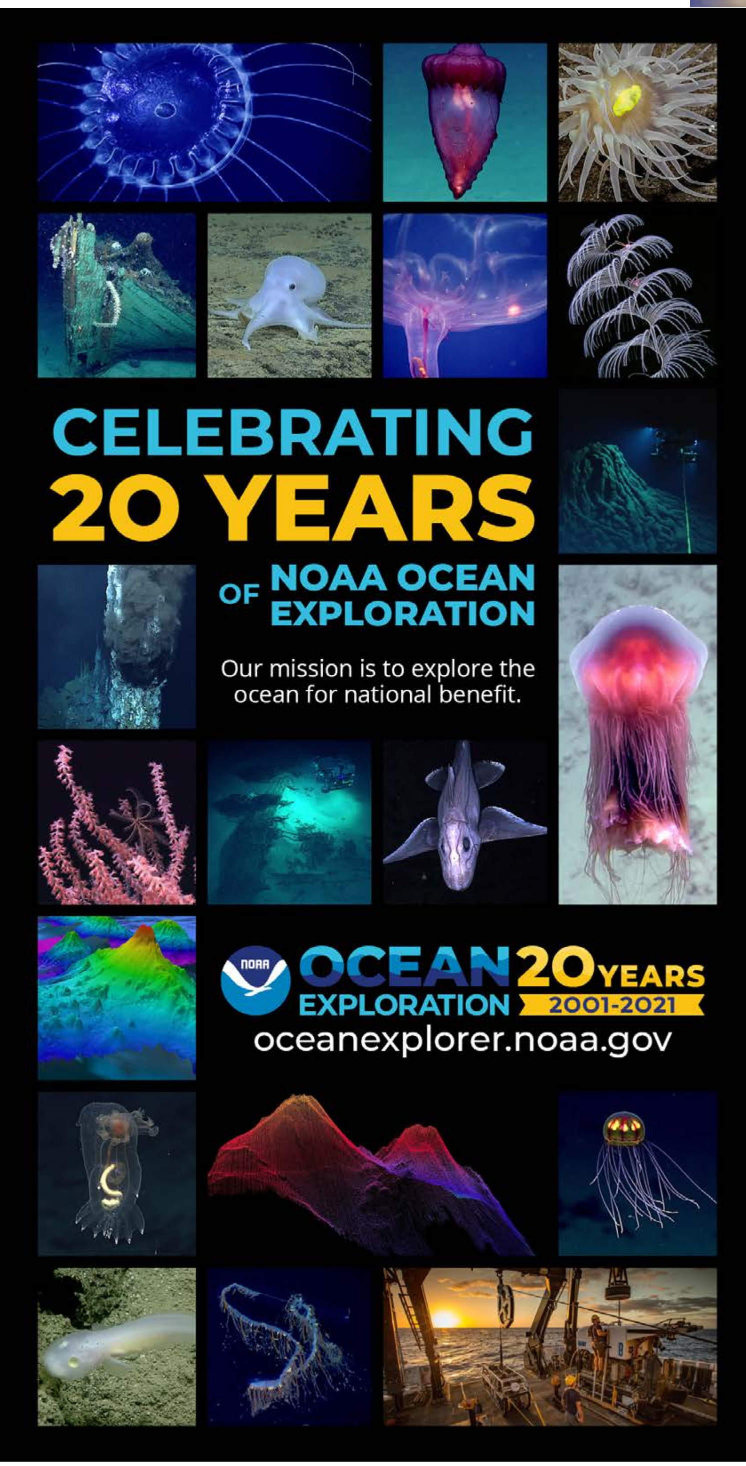
In 2021, NOAA Ocean Exploration worked to further create a diverse and inclusive office culture internally while also expanding and making external opportunities more accessible and open. Leveraging telepresence technology and Cloud-based data processing made participation in ocean exploration more accessible for scientists, students, and members of the public who may have disabilities, health issues, or other commitments that would otherwise preclude them from participating. We continued a successful push to increase the number of women and early career science leads for expeditions on *Okeanos Explorer* and began investigating ways to prioritize the physical and emotional safety of marginalized members of the science community who participate in expeditions at sea.

Diversity, equity, inclusion, and accessibility (DEI&A) was added in 2021 as a critical evaluation criteria in scoring proposals through our competitive grants program, and we are actively working to recruit more diverse panel and mail reviewers to evaluate grant proposals. In partnership with the National Marine Sanctuary Foundation, grants were awarded to fund projects that support DEI&A efforts related to ocean literacy, stewardship, and workforce development in order to engage diverse student groups in ocean exploration learning opportunities.

In 2021, we publicly released the "Exploration Variables Identified by NOAA Ocean Exploration" report (https://oceanexplorer.noaa.gov/data/publications/exploration-variables.html), which identifies the highest-priority exploration variables needed to complete initial exploration of an area. Standard operating procedures for mapping work on *Okeanos Explorer* shared during the year were met with enthusiasm and adapted or adopted by the community. These efforts increase transparency of operations, allow for greater input and collaboration, help to ensure operations are efficient, increase capacity for ocean exploration, and result in verifiable and dependable data.

Internally, an office DEI&A working group is actively developing a DEI&A strategic plan, and internship recruitment focuses on underrepresented and marginalized groups. Onboarding and orientation materials for staff are being developed with an eye toward inclusion. Regular remote office events also helped to build community even during a time when our physical offices remain closed due to the COVID-19 pandemic.

Explorer-in-Training Rebekah Hernandez (left) and mapping watch lead Amanda Bittinger (right) process bathymetric data in the control room of *Okeanos Explorer* during the 2021 US Blake Plateau Mapping expedition. Throughout 2021, NOAA Ocean Exploration hosted eight mapping Explorers-in-Training. *Image credit: Caitlin Bailey, GFOE*



In 2021, NOAA Ocean Exploration celebrated its twentieth year and the role that collaboration with and support from the scientific community and the public have played in efforts to explore and understand the deep ocean. Throughout the year, highlights of this 20-year history were shared on the office website and in social media accounts.

Expanding Outreach and Education

The celebration of 20 years of ocean exploration was marked with a full “brand refresh” that featured a new office emblem and a transition from our official name of NOAA Office of Ocean Exploration and Research to the shorter, more memorable “NOAA Ocean Exploration” for public products. These efforts are designed to enhance the office’s recognition and better engage audiences in deep-ocean exploration.

NOAA Ocean Exploration continued to refine new approaches to reach educators. In June 2021, we partnered with the Ocean Exploration Trust and the Schmidt Ocean Institute to launch the Deep Ocean Education Project website, which brings standards-aligned student activities, images and videos, stories from the field, and information on current expeditions to one central place (https://deepoceaneducation.org). Additional ocean science videos and instructional resources paired with web-based professional development programs, developed in partnership with the University of Rhode Island’s Inner Space Center through OECI, were released throughout the year.

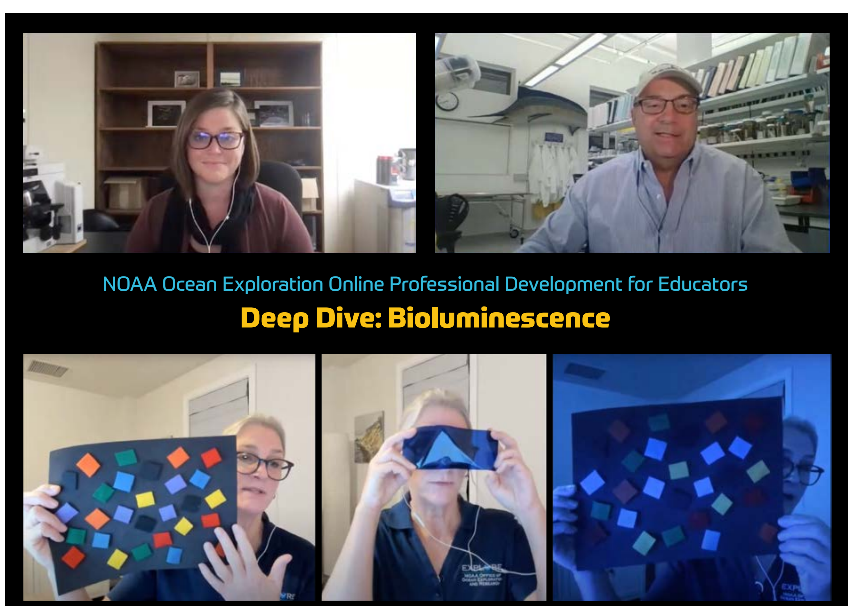
In 2021, the web continued to be a focal point for reaching members of the public. The online centerpiece of NOAA Ocean Exploration, https://oceanexplorer.noaa.gov/, received over 4.3 million views, and livestreams of dives from *Okeanos Explorer* were viewed more than 263,000 times. And, between accounts on Facebook, Twitter, Instagram, and YouTube, NOAA Ocean Exploration’s social media following grew to more than half a million. These social media accounts were used to deliver two large public live interactions with *Okeanos Explorer* expeditions, events that received over 170,000 views.

During 2021, NOAA Ocean Exploration participated in a live interaction webcast from the Smithsonian's National Museum of Natural History, hosted by the President's Science Advisor, Eric Lander, and NOAA's Symone Barkley (a), and featuring remarks by NOAA Administrator Richard Spinrad (b). https://www.noaa.gov/education/multimedia/video/video-windows-to-deep-live-conversations-on-blake-plateau

As part of efforts to educate and inspire the next generation of ocean explorers, we offered robust internships, including specifically recruiting underrepresented groups and expanding our long-standing Explorer-in-Training program beyond seafloor mapping to include experiences in exploration planning and science communication. Thirteen interns had experiences supporting ocean exploration efforts within the Explorer-in-Training program, the William M. Lapenta NOAA Student Internship Program, the Ernest F. Hollings Undergraduate Scholarship, and the NOAA Educational Partnership Program with Minority Serving Institutions Undergraduate Scholarship Program. Also, the OECI supports marine science and technology internships for university and community college students, including a program with Tuskegee University, a member of Historically Black Colleges and Universities.

OECI Intern Darielle Williams (center) from Tuskegee University learned firsthand about ocean exploration technologies during the preliminary search for the shipwreck *Norlindo* in the Gulf of Mexico. The *Norlindo* project was supported jointly through OECI and a NOAA Ocean Exploration competitive grant. *Image credit: Rachel Mugge, University of Southern Mississippi*

Through an online professional development topical series that was originally intended to share ocean exploration content with educators and support them as many transitioned to virtual instruction in response to the COVID-19 pandemic, NOAA Ocean Exploration, partnering with the University of Rhode Island's Inner Space Center, has now reached over 1,800 participants. In 2021, this program was expanded to encompass events and resources on hydrothermal vents, seafloor mapping, and bioluminescence and will now be a regular part of the office's education programming.



Note: All images in the Falkor *section of this publication are copyright Schmidt Ocean Institute unless otherwise indicated.*

PART 3

Schmidt Ocean Institute – R/V *Falkor*

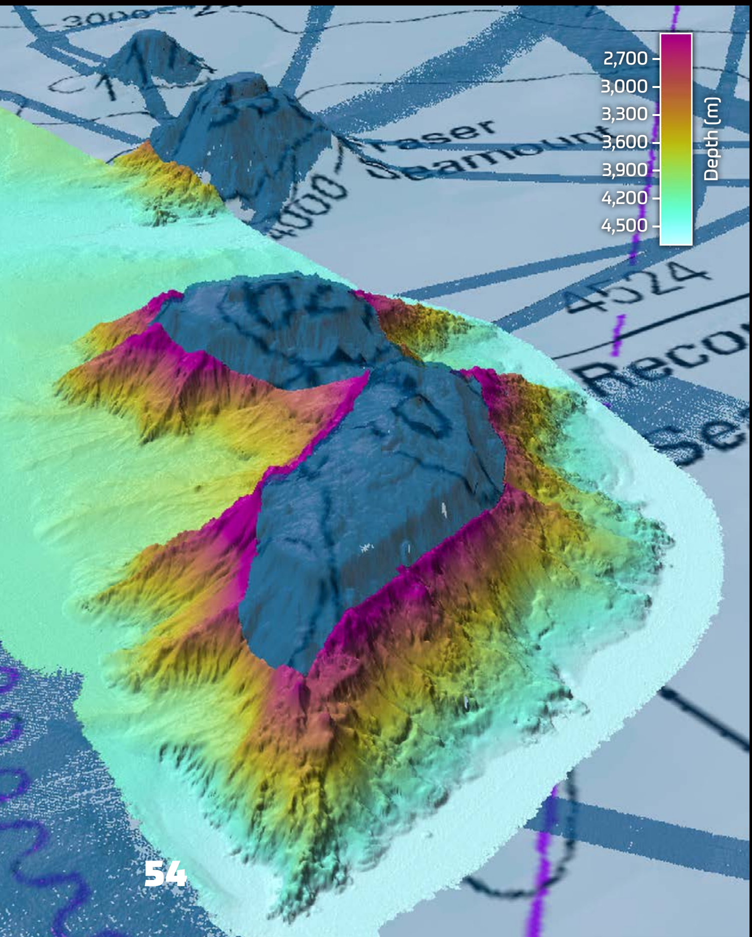
During the Discovering Deep-Sea Coral expedition, scientists made two rare sightings of the glass octopus, a nearly transparent species whose only visible features are its optic nerve, eyeballs, and digestive tract. Prior to this expedition, scientists could only learn about the animal by studying specimens found in the gut contents of predators.

Expanding Horizons

The Schmidt Ocean Institute 2021 Field Season

By Brandon Chan and Hannah Nolan

Schmidt Ocean Institute (SOI) continued to foster ocean innovation and research throughout 2021. Aboard R/V *Falkor*, seven expeditions led by experts worldwide aimed to characterize unexplored regions of the Pacific. The expeditions led to the discovery of new species, range expansions for several mesophotic and deep-sea organisms, and the collection of samples that will assist in better understanding our deep ocean. R/V *Falkor* aided in mapping 119,000 km^2 of seafloor, and scientists identified new geographic features in Australia, the Phoenix Islands, Southern California, and the Gulf of California. As SOI ends its tenure with R/V *Falkor*, the team looks forward to implementing a new strategic framework onboard SOI's recently acquired research vessel *Falkor (too)*.



PINGING IN THE NEW YEAR: MAPPING THE TASMAN AND CORAL SEAS

Led by Robin Beaman (James Cook University) and
Helen Bostock (The University of Queensland)

SOI, in partnership with the Nippon Foundation and General Bathymetric Chart of the Oceans (GEBCO), pinged in the new year with extensive mapping of remote areas in the Tasman and Coral Seas off the coast of Queensland, Australia. The new maps contribute to the AusSeabed marine database and the Seabed 2030 Project, a global effort to map the seafloor by 2030. Over 40,000 km^2 of the ocean floor were mapped, providing new details of several of the Tasmantid Seamounts and revealing features such as underwater landslides, small volcanic cones, and deep-water channels. Additionally, the expedition surveyed seabird populations as indicators of ocean health and productivity.

Image of seamounts derived from the multibeam bathymetric data gathered on R/V *Falkor* during the Pinging in the New Year expedition.

Marine Technician Karrel Kaspar leads the magnetometer deployment from *Falkor*'s aft deck.

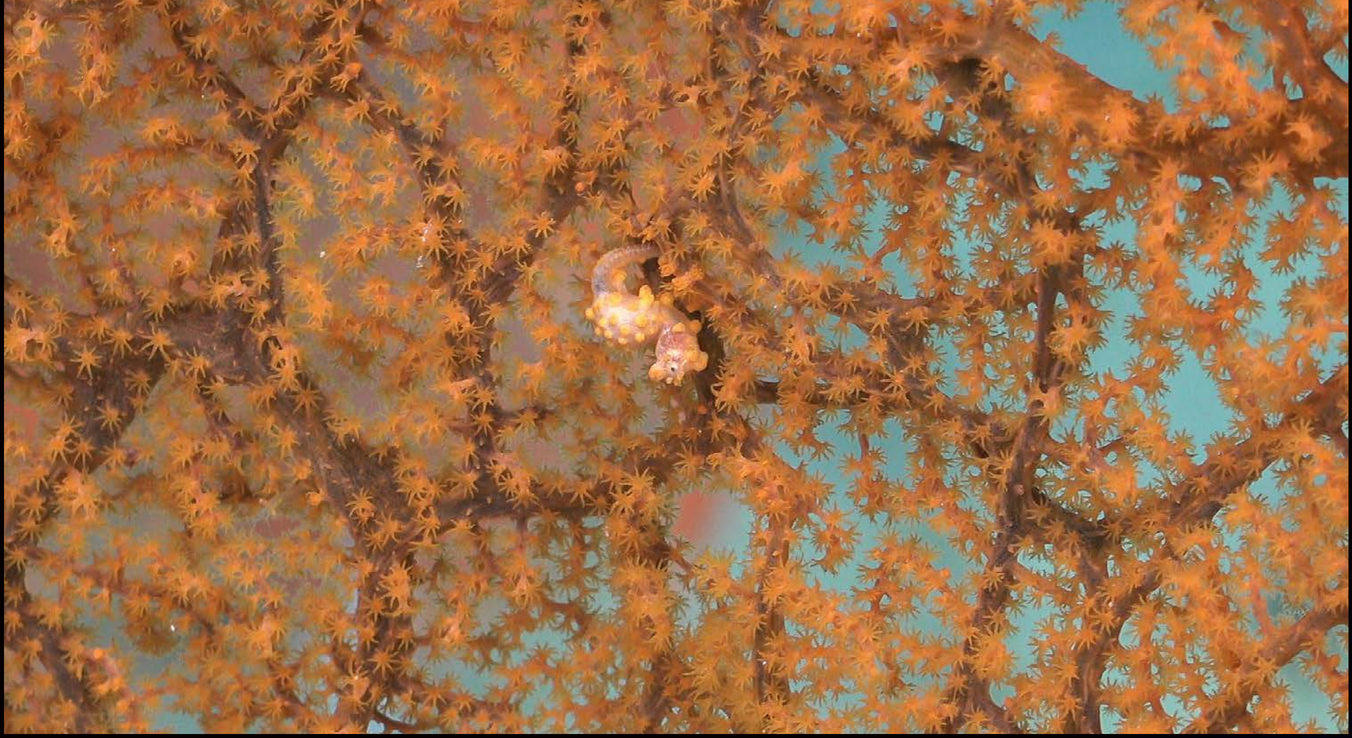
During the Seafloor to Seabirds expedition, one aspect of the work aboard R/V *Falkor* involved the team setting up and testing methodologies for sampling microplastics in seawater.

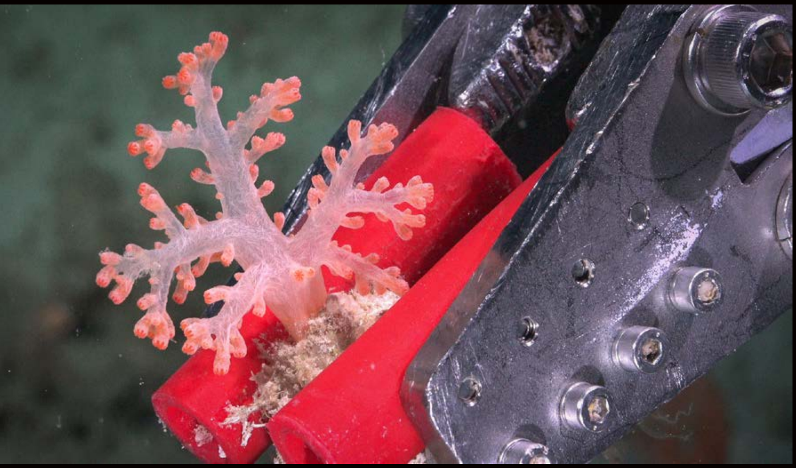
SEAFLOOR TO SEABIRDS IN THE CORAL SEA

Led by Derya Guerer and Helen Bostock (The University of Queensland) and Robin Beaman (James Cook University)

The Seafloor to Seabirds expedition continued work undertaken on the Pinging in the New Year expedition. Its predominantly student-led research facilitated at-sea training for Australian PhD, postdoctoral, and honors students. The science team mapped features in Coral Sea Marine Park to study the geologic evolution of ocean basins along the eastern Australian margin. The data will help to better characterize the separation of the submerged continent of Zealandia from the Australian landmass. In addition, the science team tested and refined novel techniques for studying microplastics using 100 water samples collected at varying depths. All but one sample contained visible microplastics, a sobering finding that indicates the need for future study. Seabird surveys augmented those done on the previous expedition. The science team documented more than 3,300 seabirds from 17 different species. The data collected from samples of microplastics, seabird observations, and CTD casts give an overall picture of ocean health in Coral Sea Marine Park, information that will aid in future management decisions regarding Australia's largest marine protected area.

Seabirds, including red-footed boobies (*Sula sula*), preening on *Falkor*'s foremast. The expedition gave students an opportunity to identify, observe, and study seabirds interacting in their habitat at sea.





A gorgonian coral hosts a pygmy seahorse along the southern edge of Ashmore Reef Marine Park.

ROV *SuBastian* pilots transfer a soft coral into one of the ROV's bioboxes while transiting along the seafloor of Ashmore Reef.

AUSTRALIAN MESOPHOTIC CORAL EXAMINATION

Led by Karen Miller (Australian Institute of Marine Science) and
Nerida Wilson (Western Australian Museum)

A women-led science team investigated the mesophotic coral ecosystems (MCEs) of Ashmore Reef Marine Park, a high-biodiversity site in North West Australian waters. Located between 30 m and 150 m depth, MCEs are difficult to study without ROVs like *SuBastian*, emphasizing the value of providing ROV access to countries without dedicated scientific ROVs. The science team mapped the entirety of the marine park's MCE and collected more than 270 samples for the Western Australian Museum, including coral for genetic and physiological analyses and water for environmental DNA analyses. Scientists found evidence of coral recruitment, indicating that conservation efforts seem to be working to preserve the Ashmore Reef MCE. Researchers also collected new records in Western Australian waters, such as the great spotted cowrie (*Perissersoa guttata*). The most surprising and exciting discovery concerned four different species of sea snakes, which were spotted in considerable numbers in the mesophotic zone. Sea snakes were once abundant at Ashmore Reef but have been steadily disappearing from the marine protected area since the 1990s. One of the observed species, the shortnose sea snake, was thought to be locally extinct at Ashmore Reef.

DISCOVERING DEEP-SEA CORAL OF THE PHOENIX ISLANDS 2

Led by Randi Rotjan (Boston University), Tim Shank (Woods Hole Oceanographic Institution), and Jonathan Kagan (Harvard Medical School)

In 2017, an interdisciplinary team of scientists explored the southern region of the Phoenix Islands aboard R/V *Falkor*. The team returned and ventured north this year to expand their research on environmental factors that influence deep-sea coral diversity and microbes that are important to the mammalian immune system. Primary goals of the expedition were to better understand deep-sea corallivory (the predation of live coral) and to study coral immune responses to microbes using a series of novel experiments. The expedition surveyed and mapped five unexplored seamounts in Areas Beyond National Jurisdiction (ABNJ), the US Pacific Remote Islands Marine National Monument, and the US Exclusive Economic Zone surrounding this area. The team captured rare ROV footage of a glass octopus and the deepest ROV recording of a whale shark. The mapping of and visual data from more than 44,000 km^2 will help monument managers better develop strategies for the future.

ROV *SuBastian* images a squat lobster sitting on a golden coral at ~2,000 m depth on a previously unexplored seamount.

This beautiful image of a metalagorgia coral with a brittle star entwined, and a possible egg case, was collected by ROV *SuBastian* at 1,450 m depth on an unnamed seamount in the Winslow reef complex on the Tokelau Ridge.

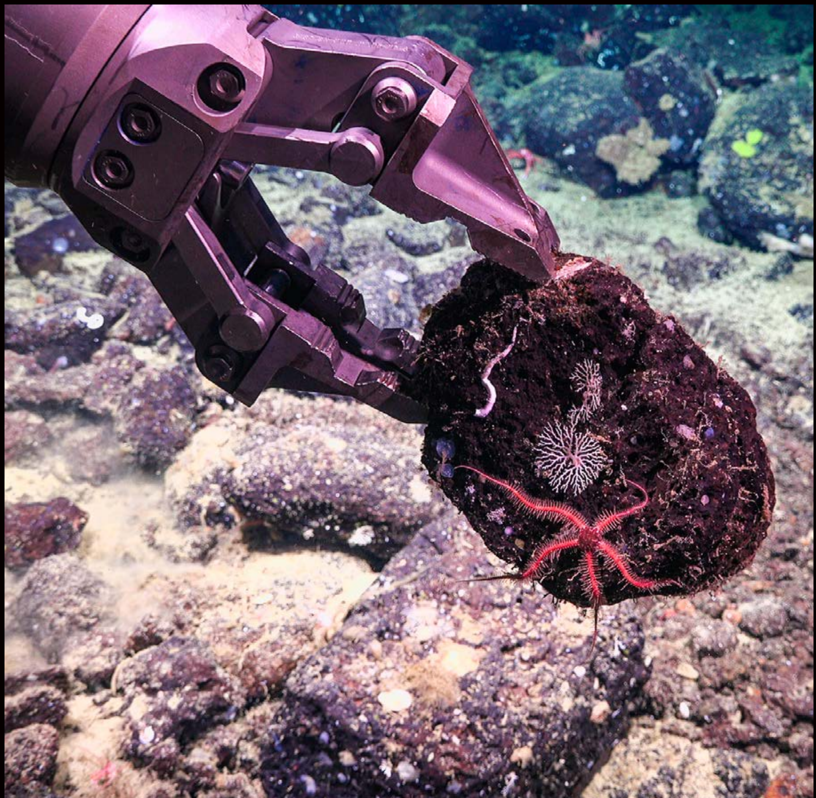
CHARACTERIZING COMMUNITIES IN THE SOUTHERN CALIFORNIA BORDERLAND

Led by Lisa Levin, Greg Rouse, and Paul Jensen (Scripps Institution of Oceanography), and Kira Mizell (US Geological Survey)

R/V *Falkor* hosted an interdisciplinary team of scientists to provide a baseline of biological, chemical, and geological data along the Southern California Borderland (SCB), specifically looking for potential ecosystem associations with ferromanganese crust and phosphorite deposits. These seafloor minerals are being considered as potential mining resources in other regions. During the expedition, over 350 samples of rocks and their minerals, sediments, and animals were collected for characterization. Scientists are also examining the microbes from the samples collected in the SCB to assess the biopharmaceutical capabilities of these poorly understood communities. Additionally, the team looked at the ecological impacts of a DDT dumping site nearby. For approximately 30 years beginning in the late 1940s, barrels containing over 760 tons of DDT and toxic waste were dumped off the coast of Los Angeles. Samples were collected to investigate the impacts of DDT and its chemical derivatives on the surrounding environment. Scientists observed unusual sediment formation and microbial mats around some of the barrels as well as a high number of sponges and worms that were tolerant to the hypoxic environment. Ultimately, more research is required to comprehensively understand how this deep-sea environment is responding to contamination from DDT and its derivatives.

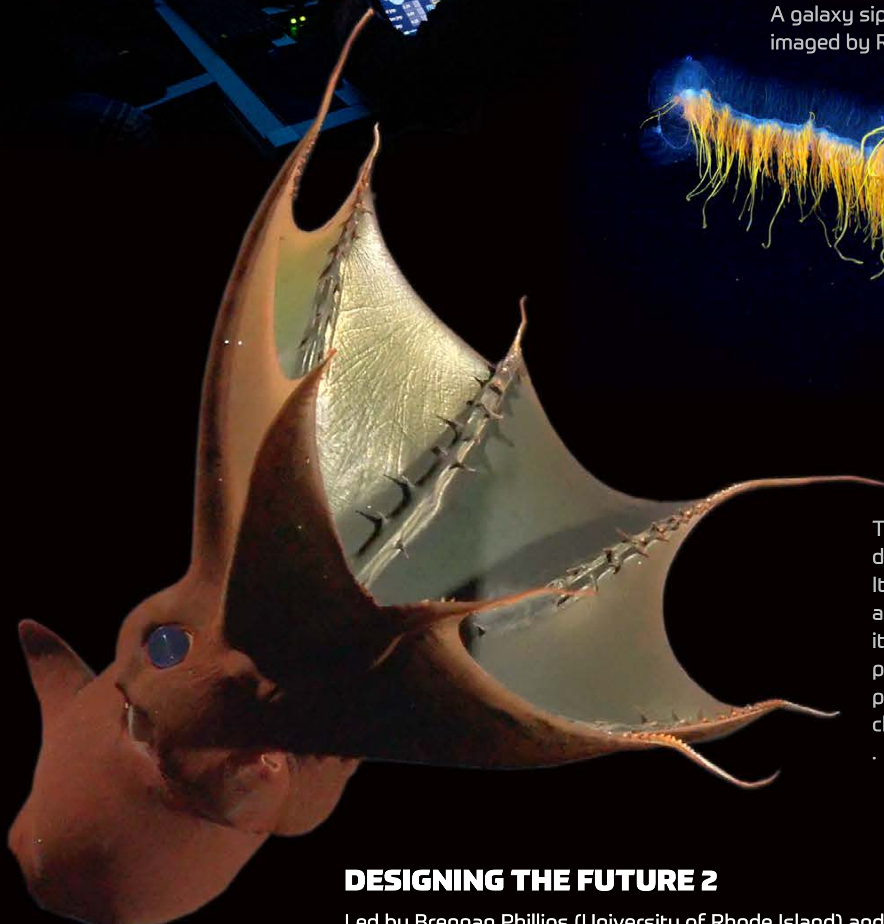
Paul Jensen uses a scalpel and a swab to pull microbes off of a rock substrate recovered from the seafloor.

ROV *SuBastian*'s manipulator arm picks up a brittle star and coral, along with their deep-sea rock habitat. Collecting the rock along with the accompanying organisms allows scientists to study whether certain organisms prefer certain substrates.



Kakani Katija, right, watches from the control room aboard R/V *Falkor* as the DeepPIV instrument scans a *Solmissus*, a type of jellyfish.

A galaxy siphonophore was imaged by ROV *SuBastian*.



This vampire squid was documented at 630 m depth in the East Cortes Basin off Baja California. Its defining characteristic is the two filamentous arms (visible here) that capture marine snow as it sinks to the seafloor. Rather than confusing its predators by releasing dark ink as do squids, octopuses, and cuttlefish, the vampire squid releases a clear bioluminescent fluid when feeling threatened.
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DESIGNING THE FUTURE 2

Led by Brennan Phillips (University of Rhode Island) and Kakani Katija (Monterey Bay Aquarium Research Institute)

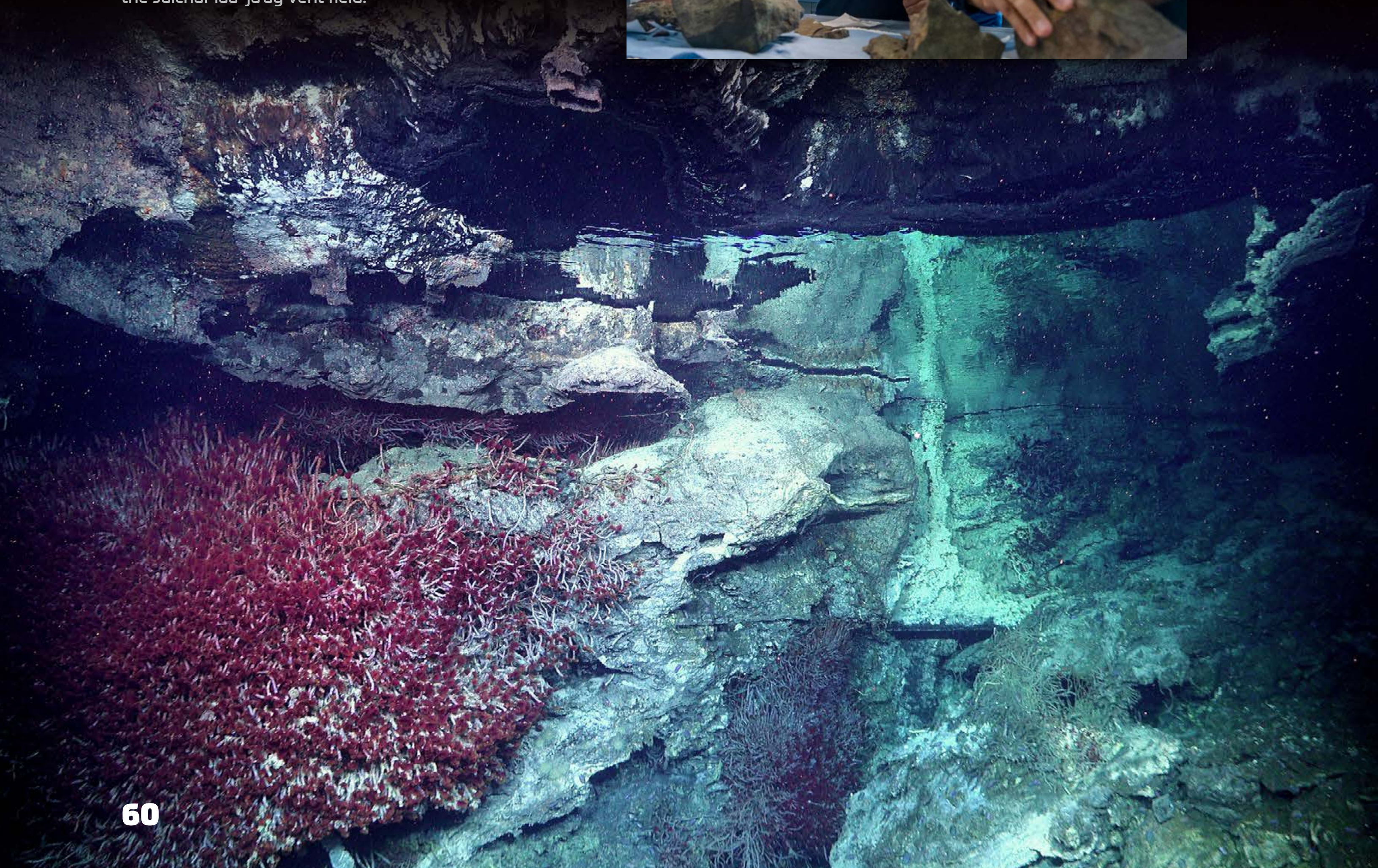
The delicate nature of many open ocean species presents a challenge to scientists seeking to study them because they are difficult to capture with traditional sampling techniques. Following a technology trial in 2019, a team of engineers returned to R/V *Falkor* to further test three in situ sampling devices designed for characterizing midwater species. The tools were integrated onto ROV *SuBastian* and included the Rotary Actuated Dodecahedron (RAD2), an origami robot that encapsulates an organism, takes an image up close, and preserves tissue samples; the Deep Particle Image Velocimetry (DeepPIV) instrument that captures fine-scale movements of water and creates three-dimensional (3D) scans of gelatinous organisms; and the Eye Remote Imaging System (EyeRIS), a 3D imaging system that uses light-field imaging to capture volumetric data of organisms, resulting in 3D models of animals at a millimeter scale. The three instruments were successfully tested in tandem, and a comprehensive workflow was created for rapidly collecting data on midwater species. Scientists hope that the refinement of these new technologies will permit wider accessibility to the scientific community and rapid descriptions of midwater organisms.

INTERDISCIPLINARY INVESTIGATION OF THE PESCADERO BASIN

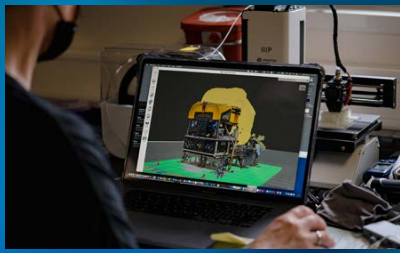
Led by David Caress (Monterey Bay Aquarium Research Institute), Ronald Spelz-Madero (Universidad Autónoma de Baja California), Raquel Negrete-Aranda (Centro de Investigación Científica y de Educación Superior de Ensenada), Victoria Orphan (Caltech), and Shana Goffredi (Occidental College)

An international team of interdisciplinary experts explored the southern portion of the Gulf of California, continuing their decade-long research in the region. The expedition was split into three legs. The first leg was focused on mapping the poorly known Farallon and Carmen basins, the second examined heat flow and hydrothermal vent connectivity in the Pescadero basin, and the third featured work on the biology and microbiology of hydrothermal vents. Notable discoveries were two new hydrothermal vent features, named Maija awi and 'Melsuu, as well as six possible new species. The names of the vents derive from the language of the Indigenous Yuman people of Baja California. The data collected throughout this expedition will aid researchers in understanding the potential connections between hydrothermal vent fields and will be used to better characterize chemosynthetic organisms and their affiliated microbes.

Researchers inspect volcanic rock samples, deciding the best way to proceed with further examination, including cutting them.



Hydrothermal vents, chimneys, and mirror pools and accompanying large populations of tubeworms were imaged while exploring the JaichaMaa' ja'ag vent field.



FROM LEFT TO RIGHT. Artists-at-Sea at work. Constance Sartor assembles her collages in *Falkor*'s library, Shona Kitchen works on a three-dimensional rendering of ROV *SuBastian* with a model of an organism, Ellie Hannon paints on the aft deck at sunset on the Timor Sea, and Tanya Young uses watercolors to capture a deep-sea jellyfish imaged by *SuBastian*.

ARTIST-AT-SEA

Beyond scientific operations, SOI continued to expand community engagement through its Artist-at-Sea program. R/V *Falkor* hosted nine regional artists during its 2021 expeditions. Artists included Jessica Leitmantis, Lea Kanner-Lichtenberger, Ellie Hannon, Constance Sartor, Tanya Young, Shona Kitchen, Ale de la Puente, and collaborative team Carol Mickett and Robert Stackhouse. A piece from each respective artist has been added to our virtual and traveling exhibit. Works of previous Artists-at-Sea were exhibited at the 2021 United Nations Climate Change Conference (COP26) in Glasgow and a solo exhibition titled "The Soul Expanding Ocean #1" by Taloi Havini was presented at the Ocean Space venue of the Venice Biennale.

DEEPENING COLLABORATIONS

In 2021, SOI formalized several new partnerships, including one with Nekton to present the Ocean Rising Workshop and white paper (https://schmidtocean.org/ocean-rising/), a new avenue for engaging public audiences through popular culture outlets like music, fashion, and gaming. Another partnership with the Marine Technology Society and IEEE Oceanic Engineering Society focused on student and early career marine technology professionals, and sponsored the OCEANS Student Poster Competition. SOI also provided grants to support the first hybrid MATE ROV Competition with a virtual reality component, and developed a virtual aquarium in collaboration with the World Ocean Observatory. In addition, SOI contributed to a special film on 2020 deep sea discoveries and an interactive display along with ROV footage for the Australian National Maritime Museum's "One Ocean, Our Futures" exhibit.

MATE Director Jill Zande (right) helps to coordinate the hybrid MATE ROV International Competition, which included both in-person and remote testing.

Schmidt Ocean Institute hosted "Climate and the Deep Sea World: Schmidt Ocean Institute's Global Efforts—A Visual Journey and Panel" in the Green Zone at COP26. The two-hour event featured exclusive, award-winning video content from the deep sea showcasing new species and underwater features. Scientists from around the world discussed the impact of climate change on these fragile ecosystems.

PART 4. Collaborative Projects and Partners

Advancing Technologies Through the OCEAN EXPLORATION COOPERATIVE INSTITUTE

By Adam Soule

The Ocean Exploration Cooperative Institute (OECI) is a consortium of five organizations that work together to advance ocean exploration technology, operations, and training in concert with NOAA Ocean Exploration: University of Rhode Island (URI) Graduate School of Oceanography, Ocean Exploration Trust (OET), Woods Hole Oceanographic Institution (WHOI), University of New Hampshire (UNH), and University of Southern Mississippi (USM).

Following its launch in 2019, and with some restrictions from COVID-19 finally reduced, the OECI accelerated into its third year with a significant uptick in activities. Our array of projects spans the gamut of ocean exploration and includes the acquisition and development of novel autonomous systems (e.g., Figure 1), new approaches for cooperative exploration by humans and robots, innovative uses of telepresence, and the application of machine learning and cloud computing to ocean exploration data. These programs are layered with an active ocean exploration program that utilizes E/V *Nautilus* to explore the US Exclusive Economic Zone in the Central Pacific and leverages OET's world-class outreach capabilities, real-time streaming of exploration to students and audiences worldwide, and deep engagement with stakeholders, including the stewards of the Papahānaumokuākea Marine National Monument and Polynesian cultural leaders.

The imperative to explore the ocean is driven by both the quest for fundamental knowledge and the health, wealth, and security of nations. However, a central challenge in ocean exploration is the vast area of ocean that remains unexplored, even within the national and territorial boundaries of the United States. A key goal of the OECI is to accelerate the pace of ocean exploration through the development and advancement of new ocean exploration technologies that enable coordinated and simultaneous multi-vehicle operations to access the three-dimensional volume of the ocean and ensure that every ocean exploration mission acquires as much information as possible.

In 2021, the OECI made some key steps toward that goal. First, UNH accepted and began testing of the *DriX*, an 8 m autonomous surface craft that will effectively double the mapping capacity of an expedition and can serve as a communications hub for submerged vehicles, allowing them to operate away from a research vessel. Initial tests included collaborative exercises with WHOI's autonomous underwater vehicle (AUV) *Mesobot*, a robotic vehicle designed for midwater operations that utilizes novel sensors and eDNA samplers targeted at exploring life in the mesophotic zone. In the past year, *Mesobot* conducted trials from E/V *Nautilus*, demonstrating novel behaviors, such as following an isolume (lines of equal light intensity), that are central to defining an approach to midwater exploration. These trials were conducted during the 2021 OECI Technology

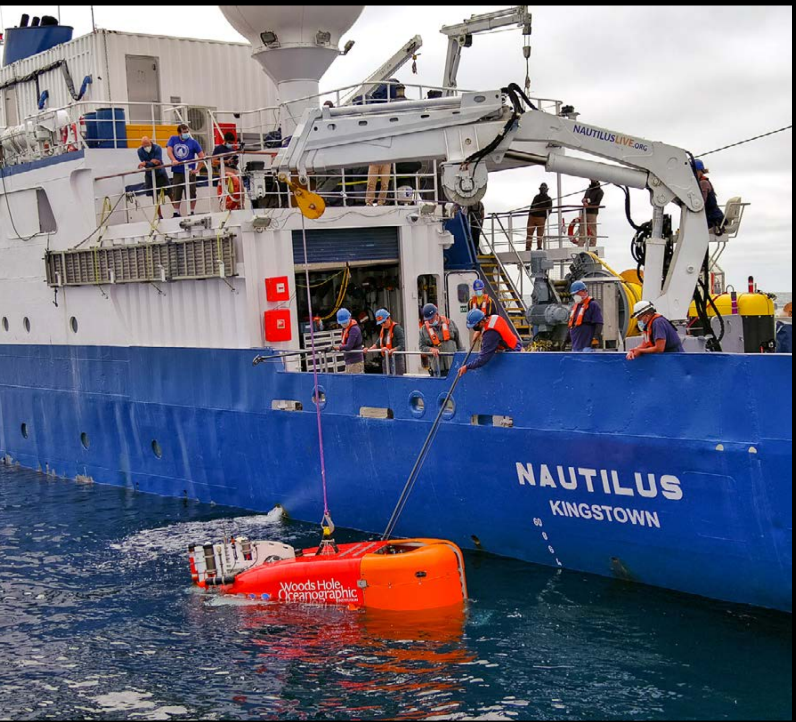


FIGURE 1. Launching Woods Hole Oceanographic Institution's hybrid remotely operated vehicle *Nereid Under Ice* (*NUI*) from E/V *Nautilus*. *Photo credit: OET*

FIGURE 2. Research activities (testing AUV technologies) in the Gulf of Mexico aboard R/V *Pt. Sur* in September 2021. *Photo credit: ISC*

FIGURE 3. Darielle Williams (far left; veterinary science major, class of 2022, Tuskegee University) the first OECI intern, spent 10 weeks at USM and was also an active participant in a research cruise. *Photo credit: NOAA OECI, URI Inner Space Center, Patrick Flannagan*

Challenge, which provided a critical opportunity for field testing new technologies, following a deliberate progression from concept to operations. This expedition also featured tests of tele-operations and tele-engineering that are aimed at expanding research vessel operational expertise beyond those working aboard the ship. The WHOI hybrid ROV/AUV *Nereid Under Ice* (*NUI;* Figure 1) was used as a platform to develop protocols for shore-based engineering support and vehicle operation, including autonomous manipulation guided from shore. The participants supported ship-side engineering tasks and remote, autonomous manipulations from Illinois and Massachusetts while the ship and vehicle operated off California.

As the OECI builds toward new paradigms of ocean exploration, we maintain a steady pace of exploration using state of the art ship- and ROV- and AUV-based exploration through expeditions aboard *Nautilus*. In the past year, *Nautilus* transited from the US West Coast to Hawai'i and initiated a campaign of exploration in the vast unexplored areas of US territorial waters located in the central Pacific. During this time, OECI-supported expeditions mapped 107,246 km^2 of seafloor, filling gaps in bathymetry and supporting the National Ocean Mapping, Exploration, and Characterization (NOMEC) Strategy and Seabed2030 objectives for complete mapping of the seafloor. In addition, ROV *Hercules* spent 490 hours submerged (45 dives) in order to make critical observations of benthic habitats and resources. Twelve deployments of uncrewed systems were supported at the surface, in the midwater, and at the seafloor (e.g., Figures 1 and 2).

The OECI strongly emphasizes engaging the next generation of ocean explorers and Blue Economy workers throughout its activities at sea and onshore. We strongly believe that introducing students to potential career pathways in ocean science, support, and storytelling will be critical to executing an increased pace of ocean exploration and doing so with a workforce that more closely resembles the ethnic, cultural, and racial makeup of the United States. One OECI core program core program that exemplifies this ambition is the OECI Tuskegee University (TU) Internship Program in partnership with the USM. In this program, OECI has helped to establish an Ocean Club that brings together interdisciplinary TU students to learn about ocean science and engineering from experts within OECI and offers opportunities to join the ocean exploration enterprise. The first OECI intern, Darielle Williams (veterinary science major, class of 2022) spent 10 weeks at USM in Leila Hamdan's microbial ecology laboratory conducting original research and participating in a research cruise using USM's AUV technology in the Gulf of Mexico (Figure 3). Williams was an outstanding contributor to this pilot program and continues to engage in the oceanographic community, including presenting the results of her internship at the AGU Ocean Sciences meeting.

In addition, a new internship program was established at URI with students from the New England Institute of Technology (NEIT), which offers a range of degrees, including associates degrees, in technical fields. The internship program was designed to appeal to students who might not have the capacity to spend an intensive summer away from work, education, and family responsibilities. Four NEIT students are participating in a paid, part-time externship program and contributing their skills to projects ranging from machine learning to three-dimensional model and animation development.

OECI continues to provide opportunities for OET's Office of Naval Research-funded interns to join OECI expeditions, and the OECI and the UT and URI programs also introduce students from underrepresented groups toward exciting career pathways in STEM and maritime fields.

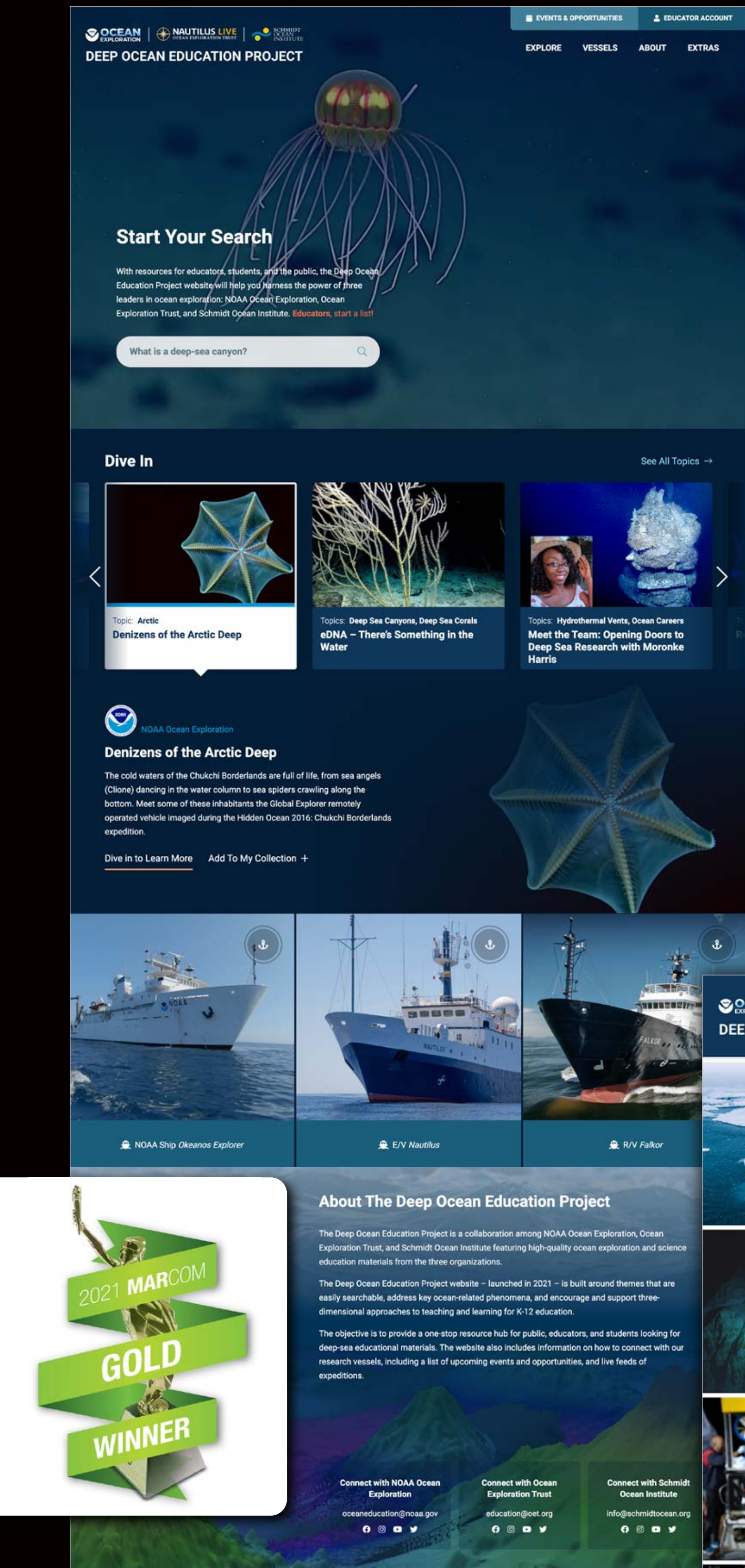
THE DEEP OCEAN EDUCATION PROJECT

An Online Hub for Ocean Science and Exploration-Themed Educational Resources

By Hannah Nolan and Liz Hoadley

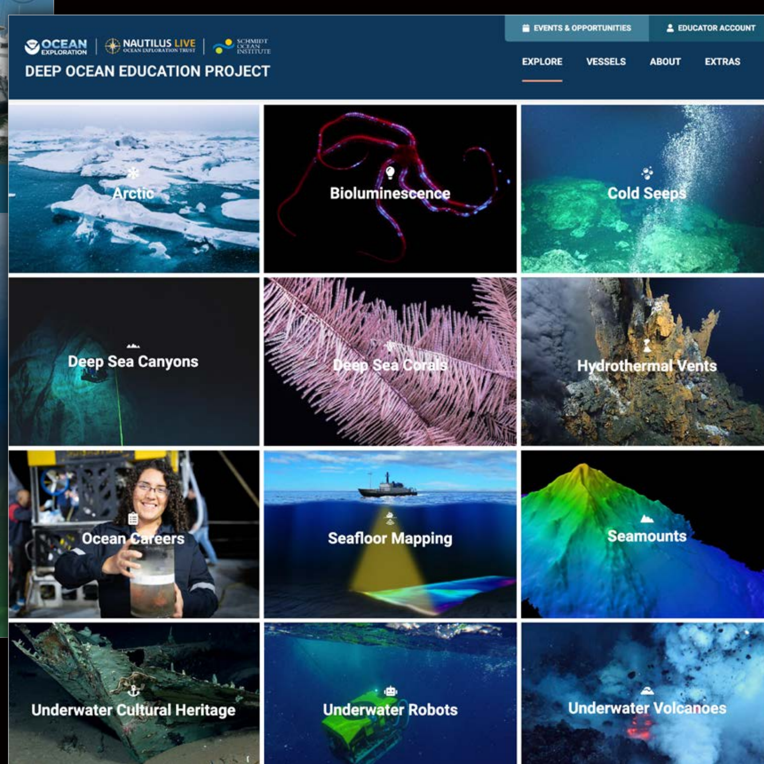
For the past two years, NOAA Ocean Exploration, the Ocean Exploration Trust, and Schmidt Ocean Institute have been collaborating to build a single online hub for ocean science and exploration-themed educational resources developed by our three organizations. Called the Deep Ocean Education Project, the website launched on World Ocean Day in 2021 (June 8; https://deepoceaneducation.org). The goal of the Deep Ocean Education Project is to help educators find and use resources that will aid them in teaching about the deep ocean in order to build greater ocean literacy for students worldwide.

The Deep Ocean Education Project website features standards-aligned student activities, images, and videos; stories from the field; and information on current events and expeditions from our three organizations on one central website. Users can explore educational tools for



The Deep Ocean Education Project website features high-quality ocean exploration and science education materials.

The website's "Explore" page invites visitors to dive into ocean exploration educational materials designed to support diverse learners, offering image galleries, video highlights, student activities, and more.



The website's "Events & Opportunities" page provides information on everything from live ship-to-shore interactions to inspiring summer internships. Educators can check out webinars, workshops, ship tours, and other ways to engage with our exploration teams. *Photo credits: (left) NOAA Ocean Exploration; (below) Ocean Exploration Trust*

topics ranging from hydrothermal vents to seafloor mapping, learn about upcoming expeditions and connect to live-streaming remotely operated vehicle dives, and discover such opportunities as internships and ship-to-shore interactions. The website has additional features tailored for educators in informal and K–12 learning environments and includes resources in Spanish as well as in English.

By creating accounts with the Deep Ocean Education Project website, educators can build and share collections for teaching about deep-ocean phenomena and customize their saved resources to fit their teaching needs. Since the website's launch, over 300 educators have created accounts and built over 350 collections. The top five countries utilizing the website include the United States, the United Kingdom, Australia, Germany, and Canada.

Feedback since the website launch has been positive overall, with teachers showing appreciation for having resources condensed into one visually appealing and user-friendly space. In addition, the website won a MarCom Gold award in 2021, recognizing its excellence in design and communication. Moving forward, all three organizations will continue to develop and share new resources to link learners with underway expeditions, phenomena, and role models. For example, NOAA Ocean Exploration is working to develop new educational materials that support the Next Generation Science Standards and Ocean Literacy Essential Principles. This year's other goals for the Deep Ocean Education Project include raising website awareness and use among educators to better promote deep-sea learning.

The Deep Ocean Education Project is grateful to the NOAA Office of Education, whose funding initiated the development of the new educational materials and the website. The project was created in cooperation with the National Marine Sanctuary Foundation, under a cooperative agreement with NOAA Ocean Exploration—a nearly two-decade partnership supporting ocean exploration education initiatives.

INNER SPACE CENTER MEDIA PRODUCTION

Continuing the Evolution of Creative Science Communication in the Cloud

By Holly Morin, Alex DeCiccio, Ryan Campos, Jessica Kaelblein, and Dwight Coleman

In response to the COVID-19 pandemic and a corresponding shift to work-from-home activities, the Inner Space Center (ISC) media and production team took time to reflect on best practices and evolve workflows to better suit remote media creation methods. The team has since fully embraced an apparent paradigm shift in ocean exploration media production and science communication, migrating systems and processes to cloud-based environments. The team has also renewed its commitment to prioritizing patience, flexibility, and consistent communications.

During the 2021 exploration season, the ISC team continued to refine its virtual production workflows and dialogues. The "collaborative planning document," developed in 2020, formed a common-ground foundation for all production efforts, providing efficient and consistent inputs at the start of each project. In a deliberate transparent process, we brought more members from partner institutions into pre-production efforts. Involving partners early in the production process encourages open and collaborative information exchange, with all participants learning from one another. This exchange allows individuals to approach the process from an engaged perspective—as well as to have fun producing the media.

The team continued its successful support of NOAA Ocean Exploration's virtual professional development (PD) programming. Although many schools returned to in-person learning in 2021, much uncertainty remained, and accessible, virtual PD opportunities were designed to meet teacher needs during this time of persistent flux. Informative ocean science videos and newly developed instructional resources were paired with web-based, conversational-style PD programs featuring ocean science experts from across the globe. Providing educators with direct access to engaging deep-sea content and experts is key to the success of these programs. In 2021, over 800 educators from across the continental United States and its associated territories participated in live, virtual PD programming on hydrothermal vents, seafloor mapping, and bioluminescence. The reach of these programs is expanded through additional views of archived PD events on YouTube (>2,500 views as of November 2021). Teachers and other stakeholders can also access the Deep-Sea Dialogues PD videos on the NOAA Ocean Exploration Education website (https://oceanexplorer.noaa.gov/edu/multimedia-resources/dsd/dsd.html). The ISC will offer new PD programming in 2022 in cooperation with NOAA Ocean Exploration Education, covering topics such as deep-sea corals, seamounts, and marine archeology.

The collaborative efforts between the ISC and NOAA Ocean Exploration Education were highlighted in a submission to the Technical Education Research Center's NSF-funded 2021 STEM for All Video Showcase. With a focus on COVID, equity, and social justice, the 2021 program featured federally funded projects aimed at improving STEM education, highlighting strategies to engage students during COVID, and addressing educational inequities. With over 2,400 views during the 2021 event, which attracted more than 280 submissions, the three-minute, ISC/NOAA Ocean Exploration collaborative video *Deep Dives: Transforming Ocean Education During COVID-19* was awarded a Facilitator's Choice designation, recognizing "extraordinary creativity in the use of video to share innovative work" (Figure 1).

As COVID protocols began to allow for in-person learning in many locations, the same applied for seagoing activities. With oceanographic exploration ramping back up in 2021, the ISC worked with Ocean Exploration Cooperative Institute (OECI) partners to document research and innovations in remotely operated and autonomous vehicles.

FIGURE 1. In 2021, the Inner Space Center (ISC) Media Team continued its collaborative media production efforts with NOAA Ocean Exploration Education to create engaging and informative, virtual professional development (PD) programs. These efforts were highlighted in a 2021 National Science Foundation STEM for All Video Showcase submission titled *Deep Dives, Transforming Ocean Education During COVID*. This video, as well as the PD programming and its associated media resources, produced by the team while working remotely from home, highlights the ISC's commitment to innovation with cloud-based tools. The video, among more than 280 Showcase entries, was awarded a Facilitator's Choice designation.

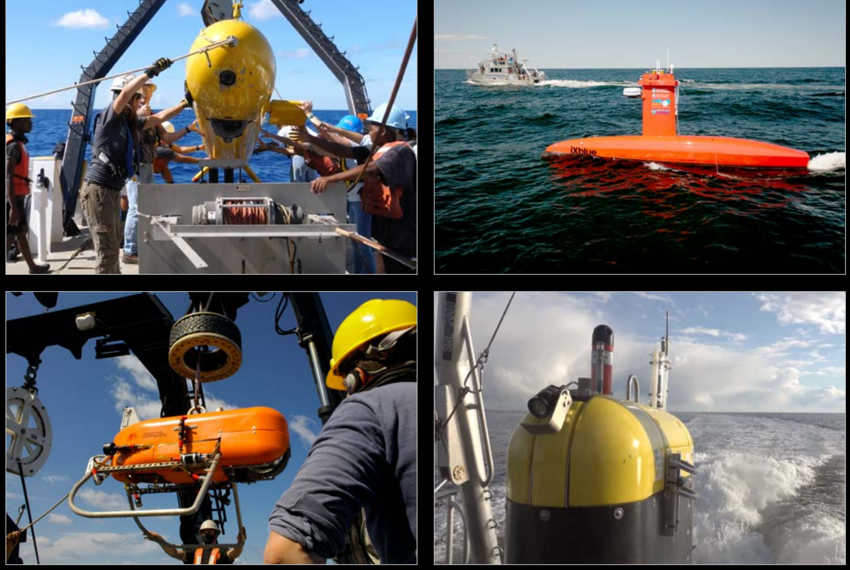


FIGURE 2. Images taken by ISC documentarians during 2021 Ocean Exploration Cooperative Institute (OECI) at-sea trials and field operations. (a) Autonomous underwater vehicle (AUV) *Eagle Ray* is launched in the Gulf of Mexico (University of Southern Mississippi, September 2021). (b) Autonomous surface vehicle (ASV) *DriX* operates in the Gulf of Maine (University of New Hampshire, July 2021). (c) Hadal class AUV *Orpheus* is shown in the southeast Atlantic (Woods Hole Oceanographic Institution, May 2021). (d) AUV *Mesobot* with ASV *DriX* works in the Gulf of Maine (University of New Hampshire and Woods Hole Oceanographic Institution, November 2021).

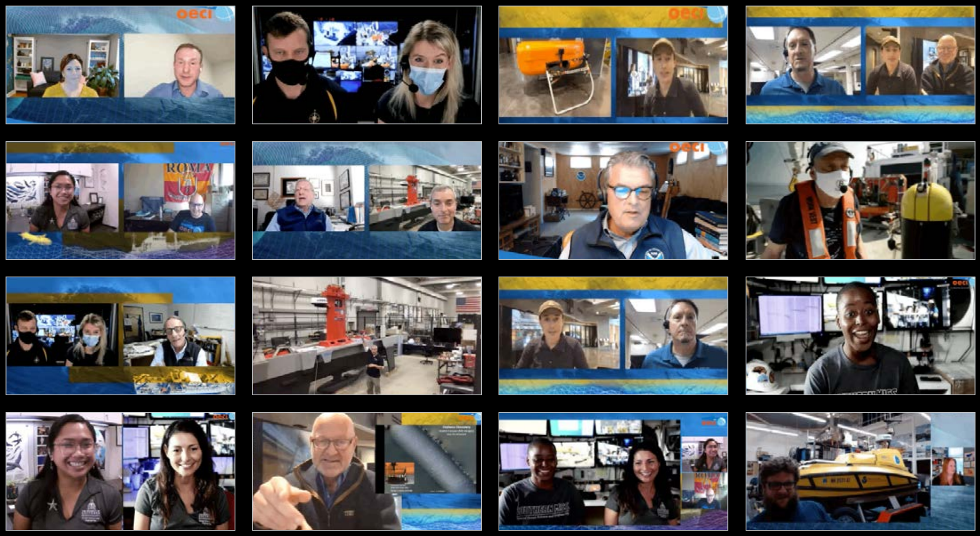


FIGURE 3. Snapshots from six OECI-themed NOAA Science Seminar events. Beginning in August 2021, the ISC collaborated with OECI partners to create and virtually produce monthly 60-minute seminar events that were live-streamed through YouTube. Each event focused on the exploration efforts of individual OECI partners, including at-sea connections to E/V *Nautilus* and R/V *Point Sur*.

Tasked with chronicling field operations, creating produced packages, and delivering OECI-focused live programming, ISC documentarians set sail and/or traveled to field sites to film with OECI partners (Figure 2). Over 750 gigabytes of media were collected and then curated into shared folders of select imagery and videos, with short highlight reels developed for each at-sea trial and field operation event. In addition to media collection, important protocols for media documentation with multiple stakeholders were developed; this was key in providing clarity for efficient workflows and defined communication protocols for additional media production projects within the OECI. These processes continue to evolve and strengthen the ISC's relationships with its partners.

In addition to filming OECI ocean science and technology activities, the ISC worked with each partner in the production of a six-part, OECI-focused NOAA Seminar Series. Leveraging its experiences with cloud-based production of online, conversational PD programming, the ISC applied similar communications and workflow protocols for production of the OECI seminar series. The live seminar events (Figure 3), which have been archived to the ISC's YouTube channel, have received over 10,000 collective views and were a great success in telling new audiences about the OECI mission, the exploration activities of its partner institutions, and the technological benefits and innovative synergies that occur when member institutions work together.

This constant evolution of relationships with partners and the clear success of these new processes has allowed the ISC production team to move from a place of necessity to a place of style. Instead of merely figuring out "how" to produce in the cloud, the team has focused on media refinement and high-quality video production, creating an ever-improving product for viewers. In total, during 2021, the ISC media and production team completed over 75 cloud-based, live-streaming events in support of ocean science and exploration. These efforts more than double what was produced (in the loud) in 2020 and speak to the ISC's commitment to evolving best practices in media production.

What's Next

By Robert D. Ballard, Jeremy Weirich, and Carlie Wiener

As we plan for another year of operations impacted by a global pandemic, we are frequently reminded that collaboration is a vital element of ocean exploration. Ongoing and new partnerships help broaden participation by connecting expedition teams with shoreside scientists and education communities, and by encouraging technological innovation that maximizes operational time at sea. Read on to learn how the Ocean Exploration Trust, NOAA Ocean Exploration, and Schmidt Ocean Institute are moving forward with our annual expeditions in collaboration with many other organizations.

OCEAN EXPLORATION TRUST

After the conclusion of a successful 2021 E/V *Nautilus* field season that included 148 days at sea over the course of 11 expeditions, the Ocean Exploration Trust is transitioning to an eight-month-long field season set to begin early in 2022. Our focus for 2022 and the next couple of years will be on the central Pacific as we continue to concentrate our expeditions on the underexplored areas of the US Exclusive Economic Zone and build collaborative relationships within the communities local to the areas we will explore.

Along with our partners at NOAA Ocean Exploration, NOAA Office of National Marine Sanctuaries, and Ocean Exploration Cooperative Institute (OECI), our next E/V *Nautilus* field season will include expeditions to Papahānaumokuākea Marine National Monument and sites within the Pacific Remote Islands Marine National Monument, including Johnston Atoll, Palmyra Atoll, and Kingman Reef. Additionally, we will continue work with OECI partners Woods Hole Oceanographic Institution (WHOI), University of New Hampshire (UNH), University of Rhode Island, and University of Southern Mississippi to advance autonomous vehicle systems to more efficiently and effectively map and characterize underexplored regions of the ocean. Our focus on technological advancements will include simultaneous operations of multiple uncrewed systems—UNH's surface vehicle *DriX*, WHOI's autonomous underwater vehicle *Mesobot*, and WHOI's hybrid remotely operated vehicle *NUI*. By increasing the range and independence of autonomous systems from their support vessels, they become a force multiplier for autonomous data collection. Among other targets, we plan to use these novel systems to explore specific regions of the full water column.

In 2022, the Ocean Exploration Trust will launch a new initiative, partnering with the National Geographic Society to expand our exploration program from the deep sea into shallower coastal coral ecosystems by utilizing E/V *Nautilus* as a scuba diving platform for the first time. This new program being launched offshore Hawai'i in 2022 will include a variety of research projects, such as examining coral, fish, and shark biodiversity; collecting acoustic recordings of underwater soundscapes; detecting microplastic concentrations within the monument; collecting three-dimensional photogrammetry of archeological sites; and ensuring Indigenous data sovereignty.

NOAA OCEAN EXPLORATION

NOAA Ocean Exploration operations have been at peak performance since NOAA Ship *Okeanos Explorer* was underway again in April 2021. The pace and efficiency in exploration and mapping operations increased, major milestones were reached, and the complexities of marine operations amidst a pandemic were navigated. In addition, a cloud computing project was initiated with the aim of blazing a trail for future synchronous global data usage that will provide equity and access as well as robust succession planning and risk mitigation. This year, we also pushed the boundaries of technology by testing and applying emerging uncrewed systems, optimizing sonar systems, and improving 'omics and eDNA sampling. The NOAA Ocean Exploration 2022–2027 Strategic Plan lays out a path for us to continue to advance operations, build science capabilities, support technology development, and enhance outreach and education efforts.

In 2022, we will complete exploratory mapping in the Caribbean Sea with a focus on Puerto Rican waters, then work along the Mid-Atlantic Ridge with European and US partners to complete mapping and ROV exploration of the Charlie-Gibbs Fracture Zone, Mid-Atlantic Ridge, and Azores Plateau. *Okeanos Explorer* will then transit the Panama Canal in August to begin systematic exploration of the Pacific Ocean in partnership with OECI. NOAA Ocean Exploration's Pacific preparation work has begun, and the initial focus for *Okeanos Explorer* for the next two years will be primarily to meet domestic-focused National Strategy for Mapping, Exploring, and Characterizing (NOMEC) objectives off the US West Coast and the remote Aleutian Island chain in Alaska. Additionally, we plan to initiate discussions with the Australian government to establish a bilateral agreement to advance ocean technologies and standards and develop programs to train early career professionals on ships in the high seas of the Pacific Basin. To address future challenges in 2022 and beyond, we will enhance investments in emerging technologies, including in situ sensors, autonomous vehicles, the cloud, machine learning, and artificial intelligence. Participants in this spring's National Ocean Exploration Forum worked together to envision near- and long-term actionable milestones to guide the community in identifying and addressing shared exploration priorities over the next decade.

Our work with external partners will continue in 2022 through the OECI and our competitive grants program. We anticipate work starting this summer and expect to include projects that target deep-ocean acoustics, water column exploration, submerged cultural resources, and the use of autonomous and other innovative technologies. We are also particularly interested in projects that focus on innovative sensors and technologies that could increase the capabilities of autonomous seagoing systems, along with artificial intelligence and machine learning applications that could improve ocean exploration data usability and accessibility. Moving ahead, NOAA Ocean Exploration will continue to leverage federal, state, academic, philanthropic, and industry partnerships to advance our operations, science, and technologies. We will also expand our partnerships to enhance education and outreach efforts through implementing an education mini-grant project, leveraging the recently launched Deep Ocean Education website, and identifying new ways to engage and reach audiences.

SCHMIDT OCEAN INSTITUTE

The next year will bring a sea change for Schmidt Ocean Institute as we eagerly anticipate delivery of our new vessel, *Falkor (too)*, in the fall, and look forward to implementing our new strategic framework to support the vision of boldly exploring our unknown ocean.

Schmidt Ocean Institute will continue to work with strategic partners to broaden the impactful science and outreach completed aboard our research vessel to new and expanded audiences. We are thrilled to be working with the United Nations Decade of Ocean Sciences for Sustainable Development, Nekton, the Marine Technology Society, the IEEE Ocean Engineering Society, and the Guy Harvey Ocean Foundation.

Additionally, Schmidt Ocean Institute has plans to continue collaborations with the MATE ROV competition, the National Ocean Science Bowl, *Nautilus* magazine, the Australian National Maritime Museum, the World Ocean Observatory, and Thyssen-Bornemisza Art Contemporary (TBA21), with the goal of bringing the ocean to students and the public globally. Through these partnerships, collaborations, and growing goals, Schmidt Ocean Institute will continue to evolve, deepening our understanding of, and connection to, our ocean.

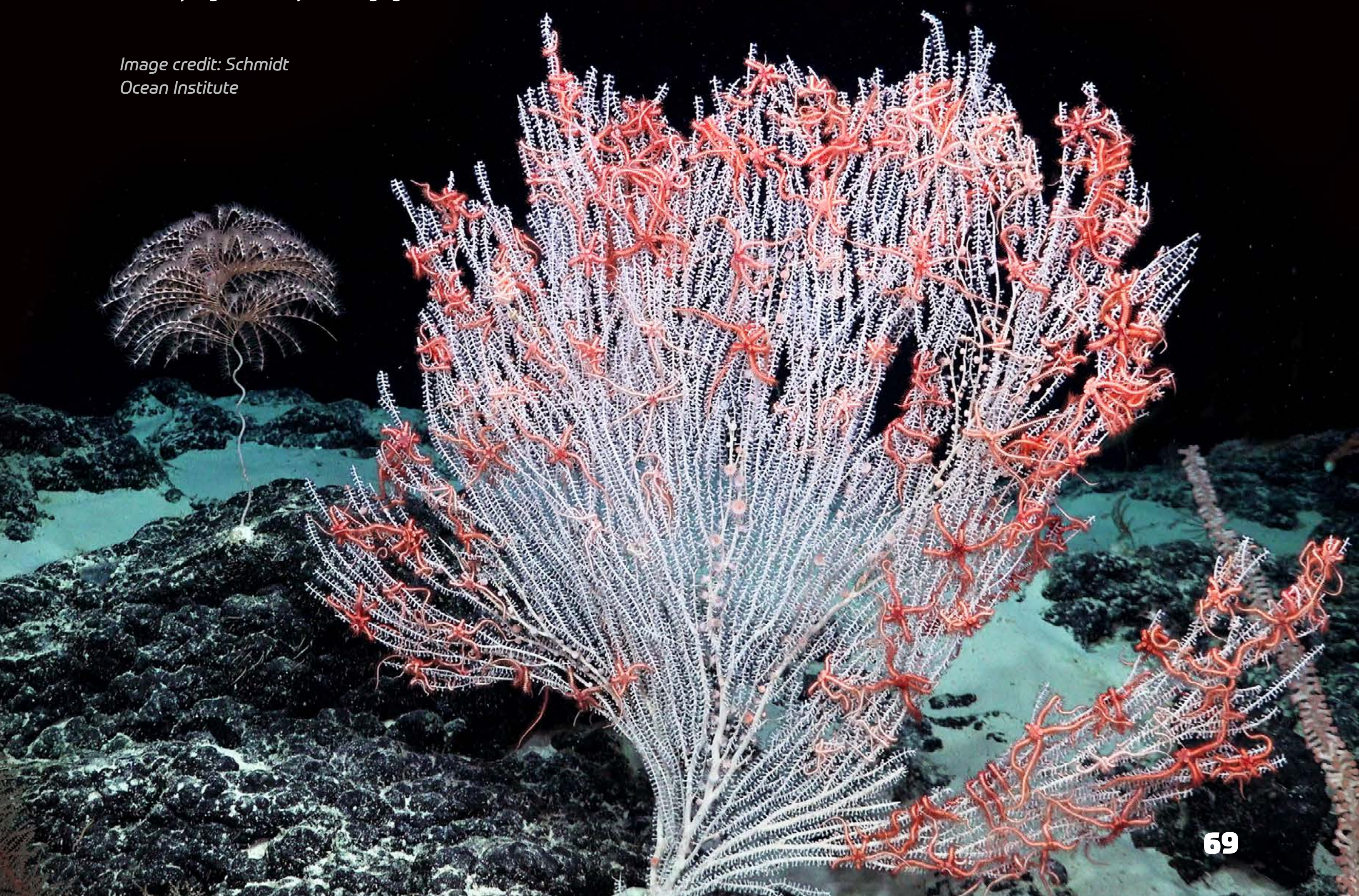


Image credit: Schmidt Ocean Institute

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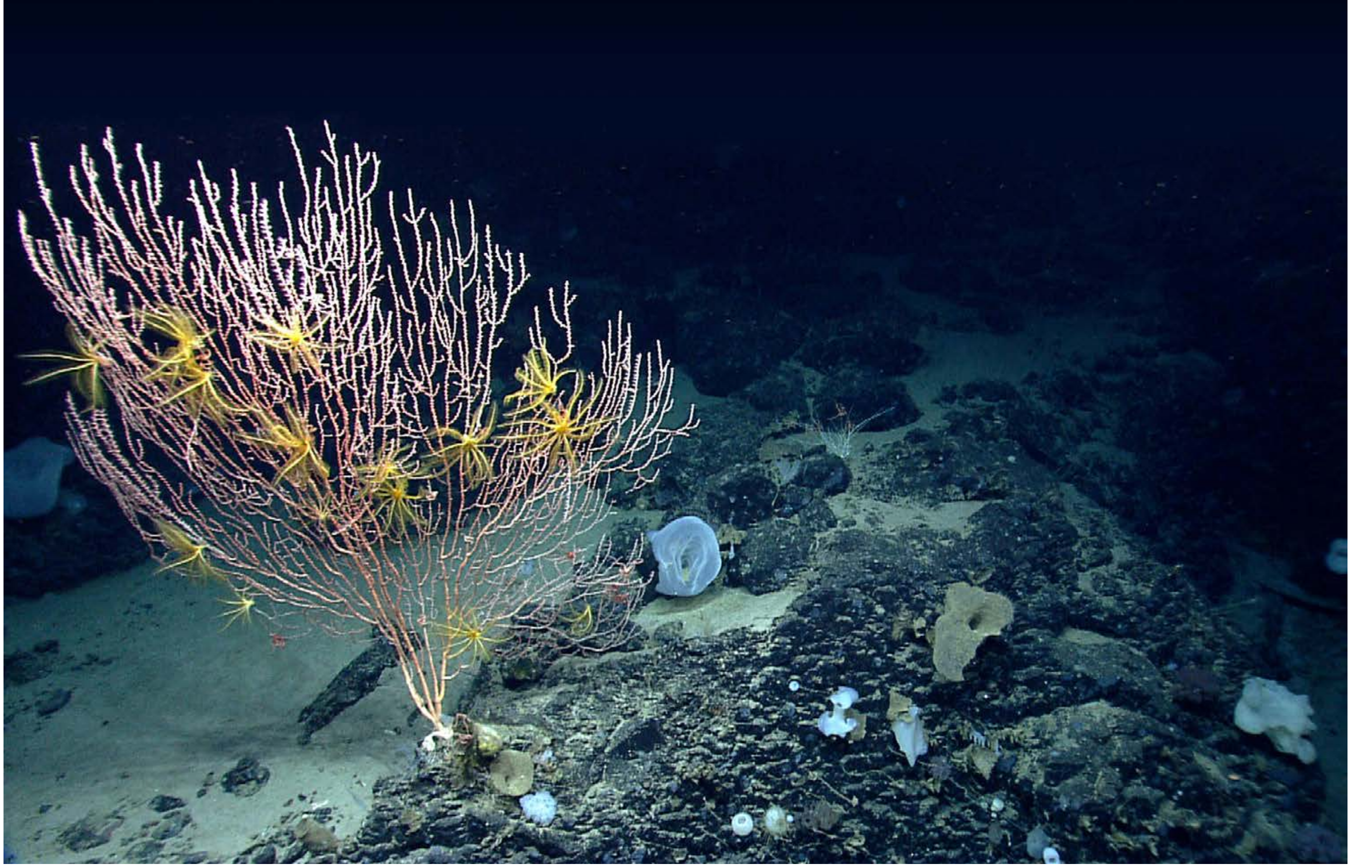
A well camouflaged Wobbegong shark was seen at 69 m depth on Ashmore reef off northwest Australia. *Image credit: Schmidt Ocean Institute*



A colony of bamboo coral with crinoids on Mytilus Seamount, which is within both the Northeast Canyons and Seamounts Marine National Monument and the Georges Bank Deep-Sea Coral Protection Area. *Image credit: NOAA Ocean Exploration*

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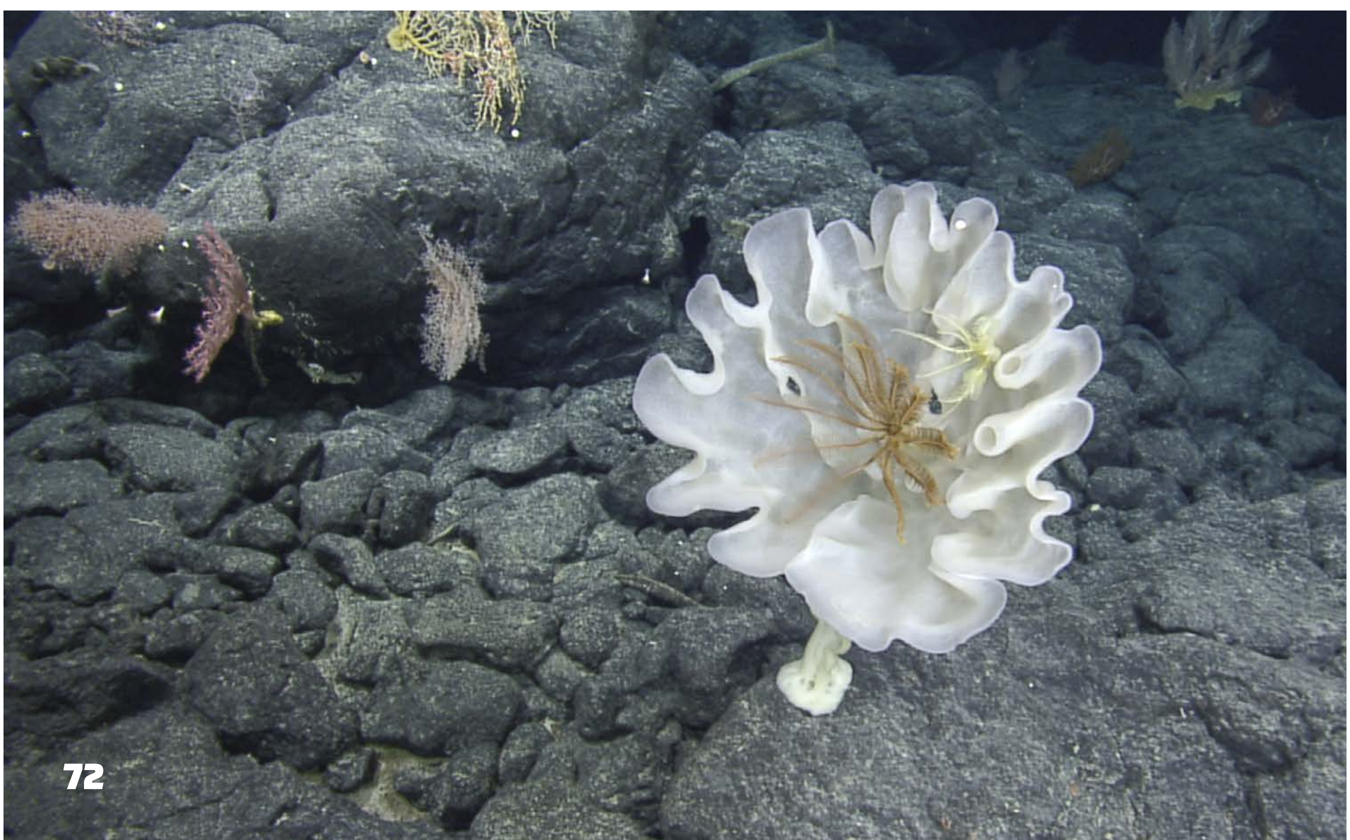
This golden yellow feather star within the family Thalassometridae sits in the middle of this beautiful glass sponge. A crinoid is also taking advantage of this prime feeding location. The sponge, spotted during a dive on Mercury Seamount, may be a new species. *Image credit: OET*



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ROV *Hercules* imaged deepwater corals with associates, including brittle stars and crabs, during E/V *Nautilus* expedition NA135 on an unnamed seamount chain south of the Hawaiian Islands. *Image credit: OET*

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ABOVE. Once ROV *Hercules* returns from the seafloor with samples, like this delicate coral, the E/V *Nautilus* science team carefully processes subsamples for further study at partner institutions. *Image credit: OET*

LEFT. ROV *Hercules* imaged an octopus along the Cascadia Margin while the E/V *Nautilus* team searched for methane seeps during expedition NA128. *Image credit: OET*

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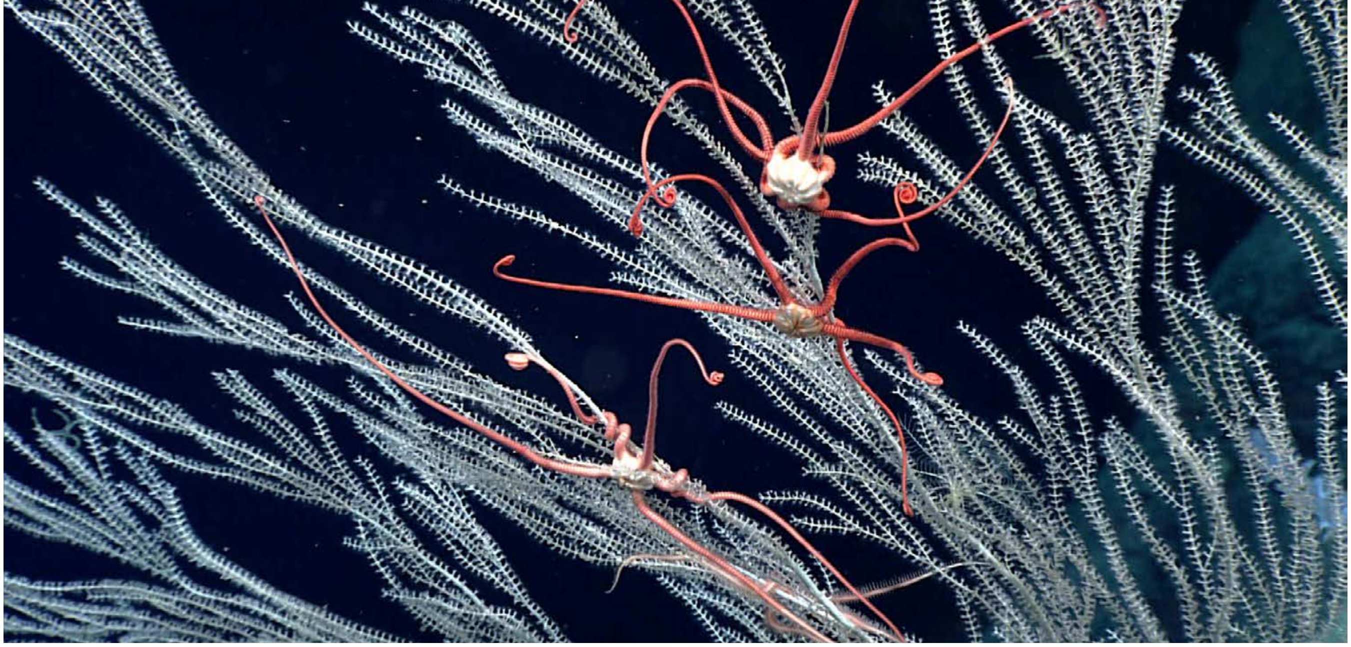
- National Ocean Mapping, Exploration and Characterization Council
- National Oceanographic Partnership Program, Arlington, VA
- National Science Teaching Association, Arlington, VA
- New Mexico BioPark Society, Albuquerque, NM
- NOAA Communications, Washington, DC
- NOAA National Environmental, Satellite, Data, and Information Service, Silver Spring, MD
  - National Centers for Environmental Information
- NOAA National Ocean Service, Silver Spring, MD
  - NOAA Studio, Silver Spring, MD
  - Office of Coast Survey, Silver Spring, MD
  - Office of National Marine Sanctuaries, Silver Spring, MD
- NOAA Ocean Exploration Advisory Board
- NOAA Office of Education, Washington, DC
- NOAA Office of Marine and Aviation Operations, Silver Spring, MD
  - NOAA Ship *Okeanos Explorer*
- NOAA Office of Oceanic and Atmospheric Research
  - Office of Communications, Silver Spring, MD
  - Pacific Marine Environmental Laboratory, Seattle, WA, and Newport, OR
- Ocean Exploration Cooperative Institute, Narragansett, RI
- Ocean Exploration Trust, New London, CT
- Office of Science & Technology Policy, Washington, DC
- Oregon Museum of Science and Industry, Portland, OR
- Oregon State University, Corvallis, OR
  - Oregon State University Marine and Geology Repository
- Saildrone Inc., Alameda, CA
- Schmidt Ocean Institute, Palo Alto, CA
- Smithsonian Institution
  - National Air and Space Museum, Washington, DC
  - National Museum of Natural History, Washington, DC
- South Carolina Aquarium, Charleston, SC
- The Oceanography Society, Rockville, MD
- Tuskegee University, Tuskegee, AL
- United States Geological Survey
- University Corporation for Atmospheric Research, Boulder, CO
- University-National Oceanographic Laboratory System
  - Multibeam Advisory Committee
- University of Dallas, Irving, TX
- University of Hawai'i/Hawai'i Institute of Marine Biology, Kaneohe, HI
- University of New Hampshire Durham, NH
  - Center for Coastal and Ocean Mapping/Joint Hydrographic Center
- University of Rhode Island, Graduate School of Oceanography, Narragansett, RI
  - Inner Space Center
- University of South Florida, St. Petersburg, FL
- University of Southern Mississippi, Ocean Springs, MS
- Virgin Islands Marine Advisory Service, University of Puerto Rico Sea Grant College Program, University of the Virgin Islands, St. Thomas, USVI
- Waikīkī Aquarium, Honolulu, HI
- Woods Hole Oceanographic Institution, Woods Hole, MA

ABOVE. Remotely operated vehicle *Deep Discoverer* images the wreck of what is likely SS *Bloody Marsh* off the coast of South Carolina, explored during Windows to the Deep 2021. *Image credit: NOAA Ocean Exploration*

RIGHT. Ensign Abby Letts standing watch during the Technology Demonstration expedition. The NOAA Corps is one of the nation's eight uniformed services and provides opportunities in engineering, Earth sciences, oceanography, meteorology, fisheries science, and other science-related disciplines. Officers operate ships, fly aircraft, conduct diving operations, work on research projects, and staff positions throughout NOAA. *Image credit: Art Howard Photography/GFOE*



The branches of this primnoid octocoral supported several beautiful brittle stars with their arms outstretched in an effort to catch food floating by in the water column. *Image credit: NOAA Ocean Exploration*

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Acronyms

ASV..................Autonomous Surface Vehicle
AUV.................Autonomous Underwater Vehicle
DEI&A.............Diversity, Equity, Inclusion, and Accessibility
eDNA..............Environmental DNA
EEZ..................Exclusive Economic Zone
E/V...................Exploration Vessel
GFOE..............Global Foundation for Ocean Exploration
ISC....................Inner Space Center
LED..................Light Emitting Diode
NOAA.............National Oceanic and Atmospheric Administration
NOMEC..........National Ocean Mapping, Exploration, and Characterization
NSF..................National Science Foundation
NUI..................*Nereid Under Ice*
OECI................Ocean Exploration Cooperative Institute
OET.................Ocean Exploration Trust
ONC................Ocean Networks Canada
PD....................Professional Development
ROV.................Remotely Operated Vehicle
R/V...................Research Vessel
SOI...................Schmidt Ocean Institute
STEM...............Science, Technology, Engineering, and Mathematics
TBNMS...........Thunder Bay National Marine Sanctuary
UNH................University of New Hampshire
UNOLS...........University-National Oceanographic Laboratory System
URI...................University of Rhode Island
USM................University of Southern Mississippi
WHOI.............Woods Hole Oceanographic Institution

Methane seep bubbles are seen floating in the foreground as ROV *Hercules* pilots operate a gas-tight sampler along the Cascadia Margin during E/V *Nautilus* expedition NA128. *Image credit: OET*

This sea spider, or pycnogonid, was observed crawling up a colony of bamboo coral overgrown by yellow zoanthids at 2,623 m depth during the 2021 North Atlantic Stepping Stones expedition. *Image credit: NOAA Ocean Exploration*

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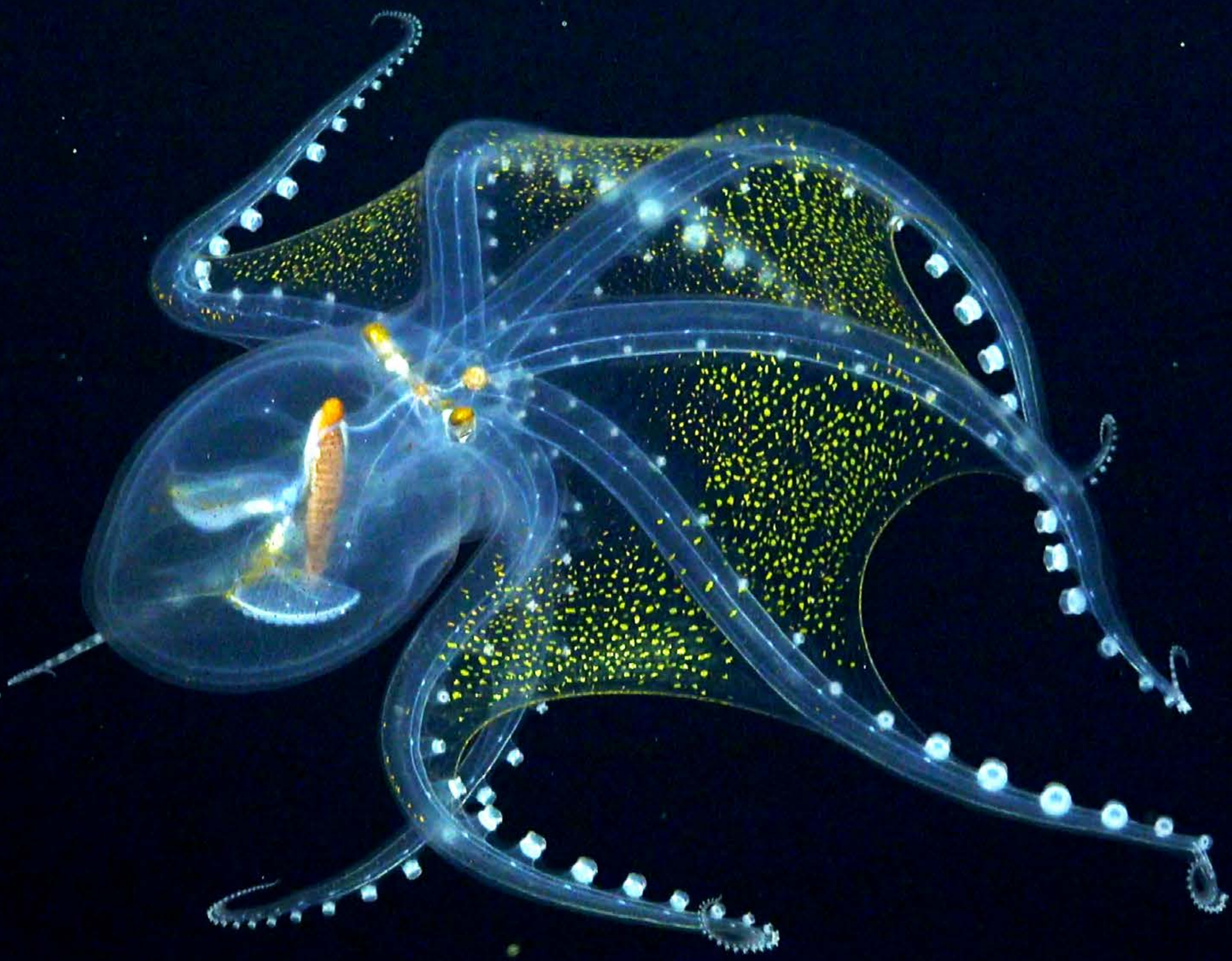

During the R/V *Falkor* expedition to the Phoenix Islands Archipelago, scientists made two rare sightings of a glass octopus, a nearly transparent species. *Image credit: Schmidt Ocean Institute*

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