NEW FRONTIERS IN OCEAN EXPLORATION

The Ocean Exploration Trust 2022 Field Season

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Contents

In 2022, the Ocean Exploration Trust started a partnership with the National Geographic Society focused on the scientific exploration of shallow-water habitats, a first for E/V *Nautilus*.

Introduction

By Daniel Wagner and Allison Fundis

March 2023 marks the thirteenth year of the partnership between *Oceanography*, the Ocean Exploration Trust (OET), and other organizations to co-develop an annual supplement to the journal highlighting advancements in ocean exploration. This issue summarizes work conducted as part of the 2022 field season aboard OET's E/V *Nautilus*. Since OET first launched expeditions aboard *Nautilus* in 2009, our work has centered on exploring the ocean and making discoveries, while pushing the boundaries of technological innovation, education, and outreach. During the 2022 field season, *Nautilus* undertook 11 multidisciplinary expeditions to explore some of the most remote and poorly surveyed areas in the Central Pacific. Several of these integrated emerging exploration technologies, and all included efforts to share expedition stories with diverse audiences across the globe.

As in previous years, E/V *Nautilus* began its 2022 operations with a shakedown cruise to complete a series of engineering tests in preparation for the field season, and then conducted several expeditions focused on mapping and remotely operated vehicle operations in US waters surrounding the Hawaiian Islands and the Pacific Remote Islands. Two of these expeditions also included deployments of vehicles from partners of the Ocean Exploration Cooperative Institute, a consortium of oceanographic institutions that brings together the expertise and capabilities of the University of Rhode Island, University of New Hampshire, Woods Hole Oceanographic Institution, University of Southern Mississippi, and OET to advance the core priorities of NOAA Ocean Exploration. These technology-focused expeditions demonstrated the value of combining complementary ocean exploration technologies, as well as the benefits of inter-institutional collaborations, for accelerating the pace by which we can effectively explore our ocean. The 2022 *Nautilus* season ended with three back-to-back expeditions that combined the complementary missions of OET and the National Geographic Society to undertake a new shallow-water exploration program for *Nautilus*.

Stories and discoveries from the 2022 season were shared with public audiences via various avenues that collectively reached several million people around the world. Across the 2022 field season, expedition teams hosted 569 live interactions from the broadcast studio onboard *Nautilus*, welcomed aboard over 50 students and educators, grew the program's social media presence, developed dozens of new STEM education resources, and promoted *Nautilus* work through more than 1,200 media stories.

The accomplishments of the E/V *Nautilus* 2022 field season were only possible thanks to the many partners that contributed to this work, including both ship-based and shore-based personnel. In 2022, OET continued to build on its collaborations with NOAA Ocean Exploration, the Ocean Exploration Cooperative Institute, the National Geographic Society, the Office of Naval Research, the National Marine Sanctuary Foundation, and many others that are detailed throughout this supplement to *Oceanography*. These partnerships focused not only on gaining new knowledge about our largely unexplored ocean, but also on how to meaningfully share this knowledge with a wide array of ocean stakeholders, particularly those from geographies where *Nautilus* operated. In particular, we continued our ongoing collaboration with our partners in Hawai'i—including Papahānamokuākea Marine National Monument staff and representatives of the Office of Hawaiian Affairs-facilitated Papahānamokuākea Cultural Working Group—to ensure our expeditions to places that hold cultural significance to Native Hawaiians incorporated Hawaiian worldview, participation, and input.

Technology

E/V NAUTILUS

The Exploration Vessel (E/V) *Nautilus* is an efficient 68-meter ship, with berthing for 17 permanent crew members in addition to 33 berths for rotating members of the *Nautilus* Corps of Exploration. The ship is equipped with remotely operated vehicles (ROVs), acoustic mapping sonars, and various other state-of-the-art technologies. *Nautilus* has a data lab for processing digital data, as well as a wet lab for processing physical samples. As part of the Ocean Exploration Trust's effort to share expeditions with the world, 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.

GENERAL

BUILT. 1967, Rostock, Germany

LENGTH. 68.23 meters (224 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 horsepower) controllable pitch main thruster; 280 kilowatt bow tunnel thruster; 300 kilowatt jet pump stern thruster

SHIP SERVICE GENERATORS. Two 585 kilovolt-ampere generators, one 350 kilovolt-ampere generator

PORTABLE VAN SPACE. Four 6.1-meter (20-feet) 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
- Hawbolt painter boom with winch safe working load, 1.5 metric tons with 7-meter reach off starboard side
- Two air tuggers, safe working load 900 pounds each
- A-frame, safe working load 8 tons
- Two rescue boats, crane and davit, safe working load 0.9 metric tons
- Oceanscience UCTD 10-400 profiling system; maximum 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 megabits per second (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

CAMERAS. 24 high-definition cameras: aft port, amid and starboard (pan/zoom/tilt), 180° wide aft, transom, bow, command center (8), 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 the ship
- Full Internet connectivity from shipboard LAN and Wi-Fi
- 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. Eight workstations for seafloor mapping and other data processing

RACK ROOM

AREA. 17.3 square meters (185 square feet)

DATA STORAGE. 50 terabyte onboard storage for non-video data, 150 terabyte 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. 10-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-feet) stainless steel bench and 2.3-meter-long (7.6-feet) 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

MICROSCOPE. Zeiss Primo Star Binocular Microscope, 4x, 10x, 40x, 100x

ROV HANGAR

AREA. 24 square meters (258.3 square feet)

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

PERSONAL PROTECTIVE EQUIPMENT. Hard hats, personal flotation devices, 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 workstations, typical configuration for ROV operations includes workstations for ROV pilot, co-pilot, navigator, video engineer, data logger, educator, and 2-4 for scientists

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 linear tape-open-6 archive media drives, 2x linear tape-open-8 archive media drives

ACOUSTIC SYSTEMS

KONGSBERG EM 302 MULTIBEAM ECHOSOUNDER

The EM 302 is a hull-mounted 30-kilohertz multibeam echosounder composed of two long transducer arrays mounted in a T-shape on the hull of E/V *Nautilus*. The EM 302 can map the seafloor in water depths from 10 to 7,000 meters (33 to 22,965 feet) at ship speeds up to 12 knots.

FREQUENCY. 30 kilohertz

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

PULSE FORMS. CW and FM chirp

ANGULAR RESOLUTION. 1° × 1°

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

SOUNDINGS PER SWATH. Up to 423 in single swath mode, 864 in dual swath mode

APPROXIMATE GRID RESOLUTION. 1%–5% water depth (e.g., 10–50 meters [33–164 feet] at 1,000 meters [3,281 feet] depth)

KNUDSEN 3260 SUB-BOTTOM PROFILER AND ECHOSOUNDER

The Knudsen 3260 is a sub-bottom echosounder mounted inside the hull of E/V *Nautilus*. It operates at low frequencies (3.5 and 15 kilohertz) so that emitted sound can penetrate layers of sediment to about 100 meters below the surface.

OPERATING FREQUENCY. Dual frequency, 3.5 and 15 kilohertz

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

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

KONGSBERG SIMRAD EC150-3C TRANSDUCER

The Kongsberg Simrad EC150-3C 150 kilohertz is a hull-mounted transducer that combines an acoustic Doppler current profiler (ADCP) and an EK80 split-beam fisheries sonar into one instrument. The ADCP measures the speed and direction of currents underneath the ship, whereas the split-beam echosounder maps features found within the water column.

FREQUENCY. 150 kilohertz (130-170 kilohertz range)

DEPTH RANGE. <400 meters (1,312 feet)

BEAMWIDTH. 3° at 150 kilohertz

PULSE FORMS. CW or FM

ADCP NUMBER OF BEAMS. 4

ADCP DEPTH BIN CELL SIZE. 2-16 meters (6.5-52.5 feet)

ULTRA-SHORT BASELINE NAVIGATION SYSTEMS

SYSTEM. Sonardyne Ranger 2 with Lodestar GyroUSBL transceiver deployed from the moonpool for USBL tracking

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

POSITIONING ACCURACY. 0.5% of slant range

OPERATIONAL COVERAGE. ±90°

OPERATING FREQUENCY. 19–34 kilohertz

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

REMOTELY OPERATED VEHICLE (TOWSLED) *ARGUS*

ROV *Argus* is a deep-tow system capable of diving to 6,000 meters. *Argus* is mainly used in tandem with ROV *Hercules*, hovering 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 surveys.

GENERAL

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

CABLE. 7,000 meters (23,000 feet) of 1.73 centimeter (0.681 inch) diameter electro-optic Rochester cable, 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)

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 megapixel 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

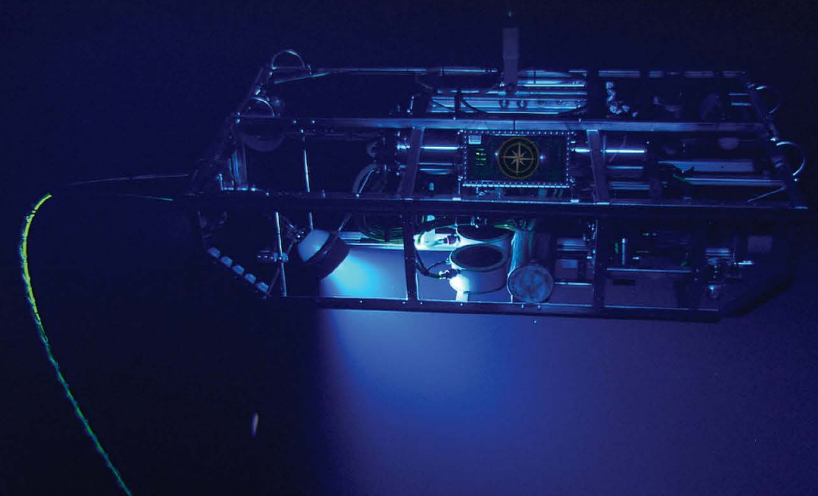
FORWARD-LOOKING SONAR. Mesotech 1071, 300 kilohertz, 0.5–100 meter (1.6–328.1 feet) range

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

SCIENTIFIC INSTRUMENT SUPPORT

POWER. 110 volt 60 hertz AC, 24 VDC and 12 VDC power options

DIGITAL DATA CHANNELS. Ethernet



REMOTELY OPERATED VEHICLE *HERCULES*

ROV *Hercules* works in tandem with towsled *Argus* or *Atalanta* to explore the deep sea. *Hercules* is equipped with a high-definition video camera, LED lights, two manipulator arms, and a variety of oceanographic sensors and samplers. A suite of high-resolution mapping tools is available upon request. *Hercules* can deliver up to 113 kilogram (250 pounds) 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 pounds) 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. Range 30 meters/minute (98.4 feet/minute) to 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 kilowatt (20 horsepower), 207 bar (3,000 pounds power square inch) hydraulic system
- Fore/Aft & Vertical – Four 27.94 centimeter (11 inch) ducted thrusters, each providing 900 Newton (200 pounds of force) thrust
- Lateral – Two 22.86 centimeter (9 inch) ducted thrusters, each providing 450 Newton (100 pounds of force) thrust

VEHICLE SENSORS & NAVIGATION

SYSTEM. NavEst integrated navigation system solution

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

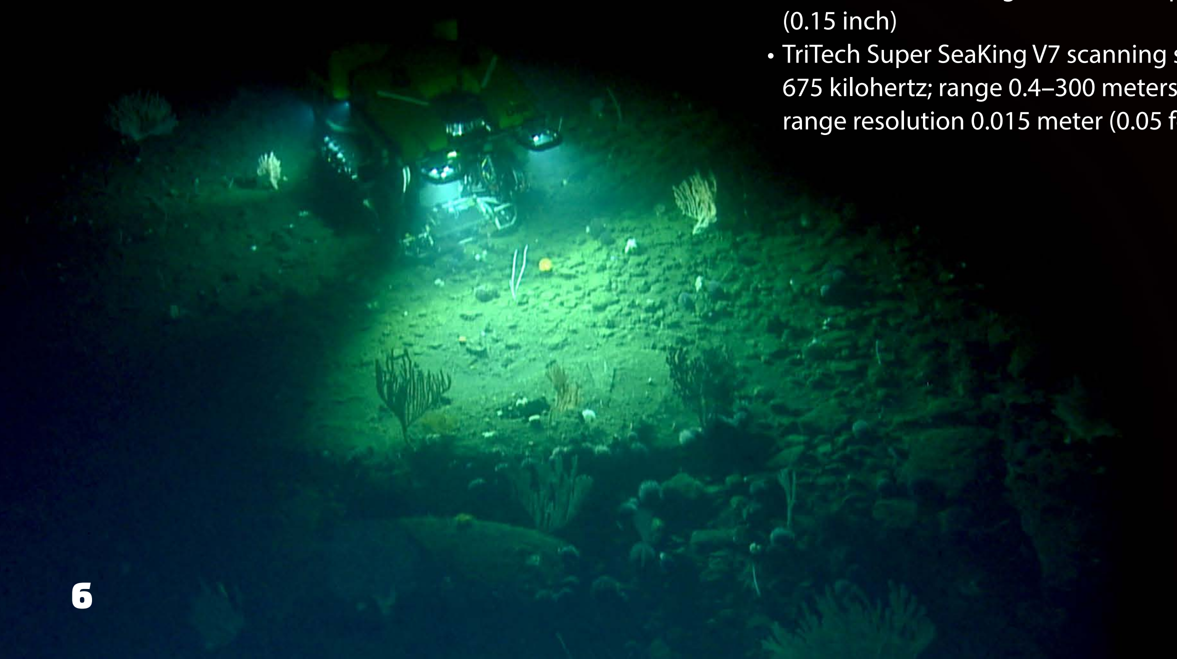
CTD. Sea-Bird FastCAT 49

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 kilohertz, 0.7–90 meter range (2.3–295.3 feet)

FORWARD-LOOKING SONARS
- Kongsberg Mesotech 1071 scanning sonar, tunable from 400–1,000 kilohertz; range to 200 meter (656 feet) at 450 kilohertz; range resolution up to 3.75 millimeter (0.15 inch)
- TriTech Super SeaKing V7 scanning sonar, 325 and 675 kilohertz; range 0.4–300 meters (1.3–984 feet); range resolution 0.015 meter (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-meter rated, Zeus Plus with 10× zoom lens, Ikegami HDL-45A with zoom/pan/tilt/extend, 1080i SMPTE 292M output format
- Insite Pacific, 6,000-meter 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 Spheres

LED lights, 6,000 lumens, mounting configurable

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

MANIPULATORS & SAMPLING

MANIPULATORS

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

SUCTION SYSTEMS

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

SAMPLING TOOLS. Mission configurable:

- Up to five 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 × 33 × 25 centimeters (17.7 × 13 × 9.8 inches)
- Forward sample tray (outboard): 68 × 35 × 30 centimeters (26.8 × 13.8 × 11.8 inches)
- Starboard sample drawer: 65 × 50 × 30 centimeters (25.5 × 19.7 × 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 volt, 60 hertz alternating current
- 24 volt direct current
- 12 volt direct current

DIGITAL DATA CHANNELS

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

HYDRAULIC. Proportional and solenoid hydraulic functions:

- 1,150 pounds per square inch at 5 gallons per minute
- 1,850 pounds per square inch at 5 gallons per minute
- 3,000 pounds per square inch at 5 gallons per minute (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 multibeam sonar—forward or downward facing
- 18 megapixel Ethernet connected digital still camera
- Low-light camera
- Modular soft grippers

REMOTELY OPERATED VEHICLE (TOWSLED) *ATALANTA*

Atalanta is a smaller version of *Argus* and 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 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)

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 kilohertz altimeter

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

SCIENTIFIC INSTRUMENT SUPPORT

POWER. 110 volt 60 hertz alternating current, 24 volt direct current, and 12 volt direct current power options

DIGITAL DATA CHANNELS. Ethernet, RS-232

REMOTELY OPERATED VEHICLE *LITTLE HERCULES*

ROV *Little Hercules* is a smaller sister to *Hercules* with 6,000-meter capability, 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.

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) maximum

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

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.

VEHICLE SENSORS & NAVIGATION

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

PRESSURE SENSOR. Paroscientific Digiquartz 8CB series

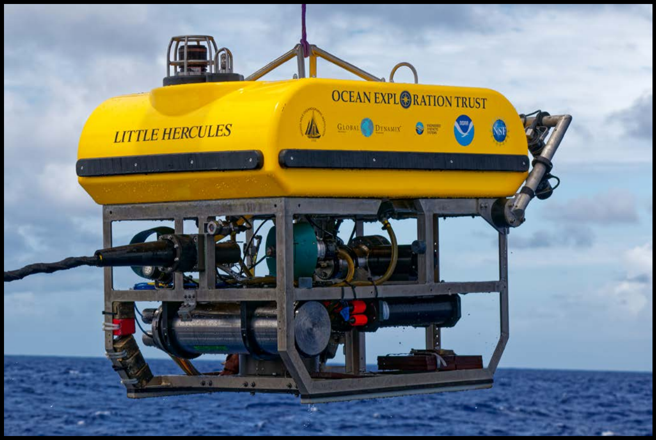
ALTIMETER. Valeport VA500 500 kilohertz altimeter

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

SCIENTIFIC INSTRUMENT SUPPORT

POWER. 110 volt 60 hertz alternating current, 24 volt direct current, and 12 volt direct current power options

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



2022 Technology Collaborations

UNIVERSITY OF NEW HAMPSHIRE. USV *DriX* and Universal Deployment System
WOODS HOLE OCEANOGRAPHIC INSTITUTION. AUV *Mesobot* and HROV *Nereid Under Ice*
OREGON STATE UNIVERSITY. Sexton still camera (on ROV)
UNIVERSITY OF RHODE ISLAND. Norbit wideband multibeam sonar (on ROV)
SOFAR OCEAN. Spotter 3 ocean buoys

E/V *Nautilus*'s Two-Body ROV System

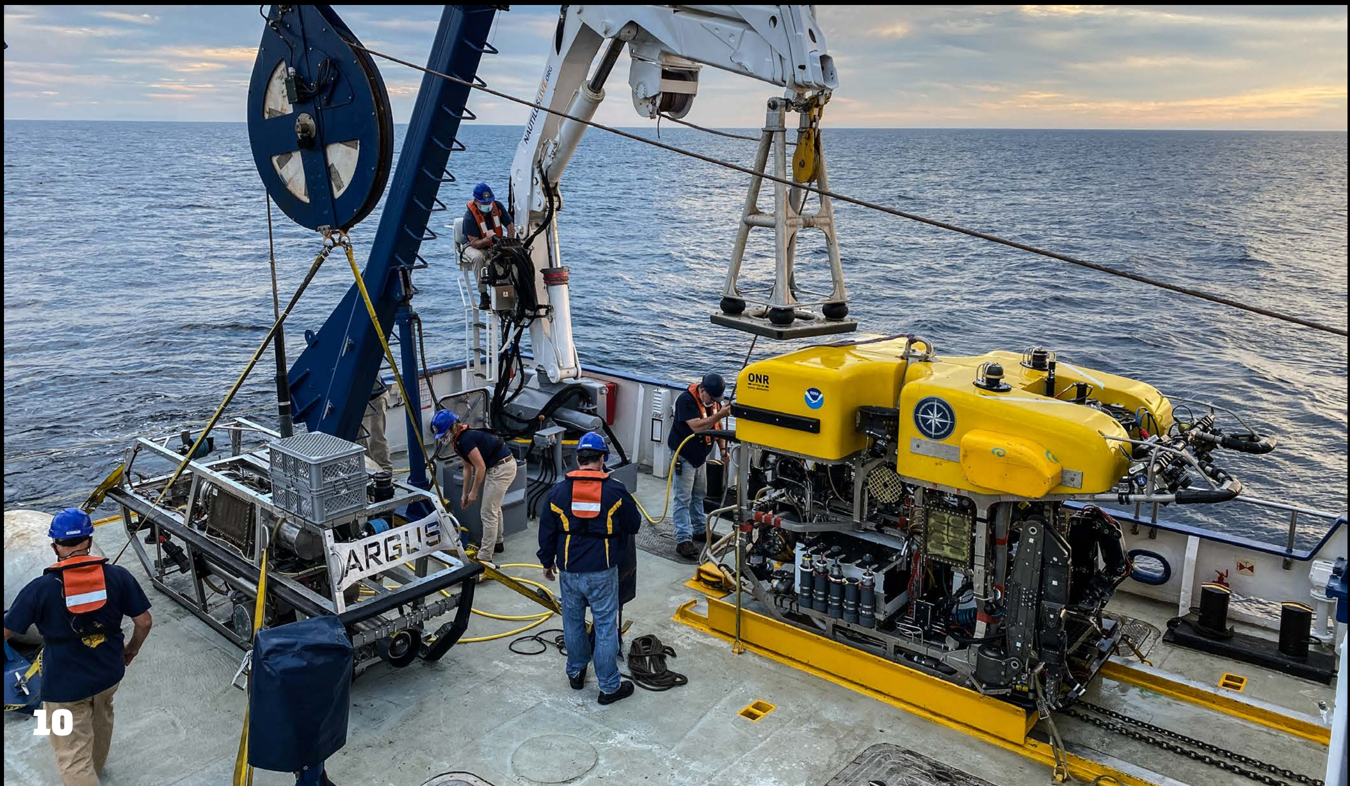
By Josh Chernov

A unique feature of Ocean Exploration Trust (OET) operations is the use of a two-body remotely operated vehicle (ROV) system (Figure 1). ROV *Hercules* operates in tandem with a tow sled, either *Argus* or *Atalanta*. The negatively buoyant tow sled dangles at the end of an armored cable connected to a winch onboard E/V *Nautilus*. The tow sled's movements are controlled horizontally by moving the ship and vertically using the winch to pay out or pay in cable. Thrusters on the tow sled allow the pilots to control heading and thereby aim cameras and lights toward *Hercules* and features on the seafloor. A soft 30 m tether connects the tow sled to *Hercules*, and the pair of vehicles is arranged in such a way that *Hercules* is decoupled from the ship's movements. *Argus* carries a high-definition video camera similar to the one on *Hercules*, as well as bright lights that illuminate the area around *Hercules*. This powerful feature allows pilots, scientists, and our home audiences a bird's-eye view of *Hercules* working on the seafloor. It also creates stunning visuals and allows for a much higher level of situational awareness for all who are involved with subsea operations.

Hercules is one of a handful of ROVs specifically designed to be used as a deep ocean science tool. Custom built for the OET, *Hercules* is equipped with special features that allow it to perform intricate tasks on the seafloor to a maximum depth of 4,000 m. The vehicle carries an array of cameras and sensors that are used to gather video, still images, and ocean sensor data during each dive (Figure 2). A combination of cameras is used to collect high-definition video, ultra-high-definition video, and high-resolution photos that allow scientists to closely examine the seafloor, while ROV pilots maneuver the vehicles to execute the objectives of the mission.

Designed to withstand the enormous pressure at its maximum depth rating, most of *Hercules*'s onboard electronics are built into cylindrical titanium pressure housings. Any air exposed to the outside pressure will be compressed to one four-hundredth of its original volume at depth, which can destroy components. To avoid this, electrical components not enclosed in pressure housings are immersed in mineral oil, which does not compress significantly under pressure and does not conduct electricity or cause corrosion. Electric motors, transformers, electrical junction boxes, and much of the external wiring are filled with oil, and similar oil is used in the electric motor and pump that hydraulically activate the vehicle's manipulator arms and thrusters.

FIGURE 1. Ocean Exploration Trust's two-body system consisting here of ROV *Hercules* and tow sled *Argus* is shown prior to deployment from E/V *Nautilus*.



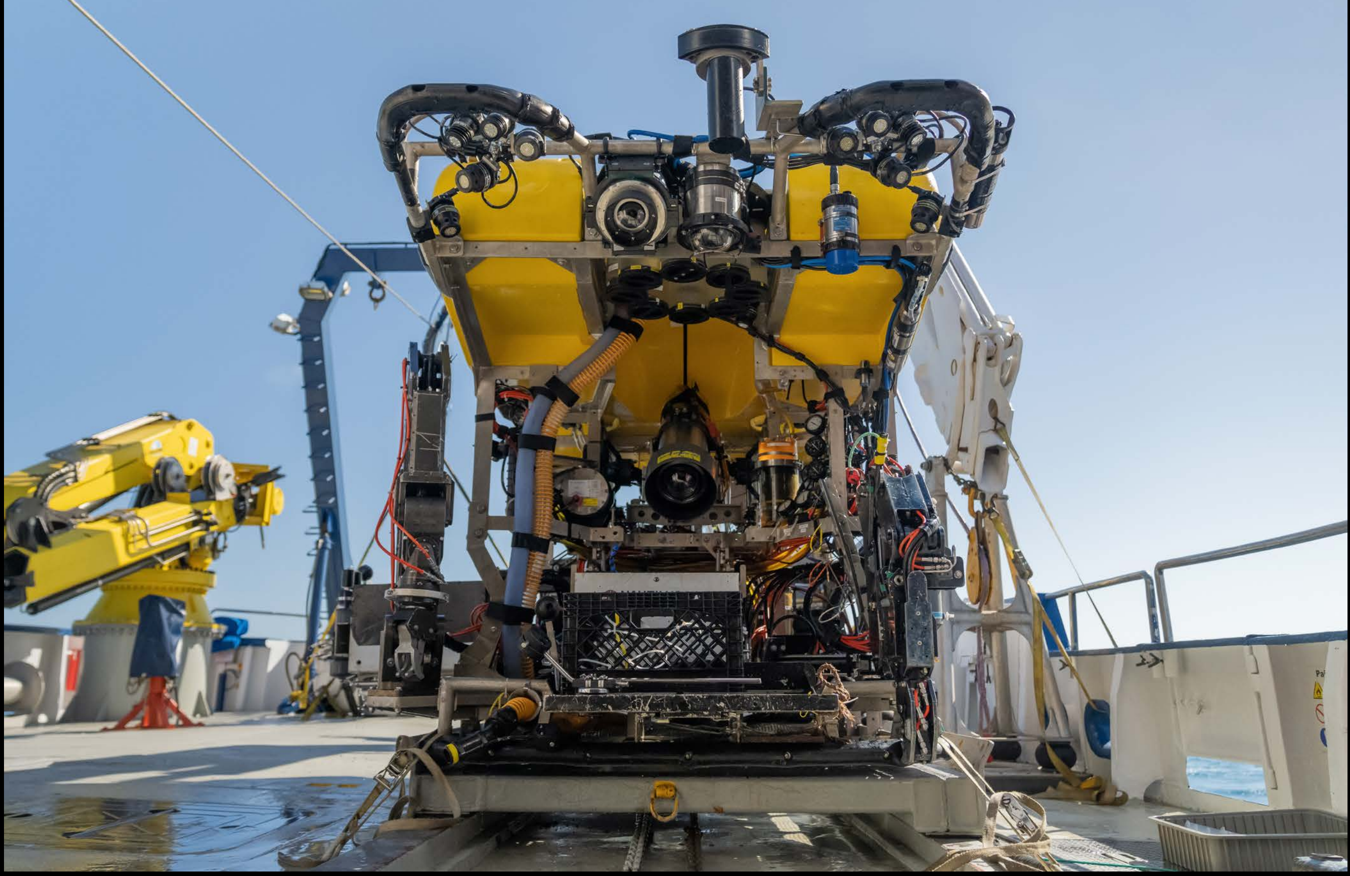


FIGURE 2. This view of ROV *Hercules* on the back deck of E/V *Nautilus* shows its array of cameras and other instruments.

A yellow flotation package, or buoyancy module, supports the vehicle when in seawater and decreases the average density of *Hercules* to less than that of seawater, allowing it to float on the ocean surface. Overall buoyancy can be controlled by adding lead blocks so that a small force generated by the vertical thrusters can drive the ROV down or up. The buoyancy module is made of syntactic foam, which is composed of tiny, hollow glass balls mixed into epoxy resin. The foam is heavy in air, with a density about half that of seawater, but it can withstand the pressure of more than 6,000 psi exerted at a depth of 4,000 m.

Although *Hercules* was originally designed primarily to study and recover artifacts from ancient shipwrecks, it was later modified to better study and sample within many other science disciplines, such as geology, biology, and chemistry. *Hercules*'s standard set of science tools includes a pair of manipulator arms that are used to collect physical samples, a water suction sampler with the ability to "slurp" softer samples into individual jars, two large boxes for storing samples, a set of sediment push cores to sample soft bottom substrates, and Niskin bottles for taking water samples. *Hercules* also carries CTD (conductivity, temperature, depth) and oxygen sensors to measure water properties throughout each dive. Another feature of the *Hercules* platform is its flexibility to integrate guest sensors and instrumentation to allow scientists and engineers from all backgrounds to add their cutting-edge technologies.

At the end of the 2022 field season, *Hercules* was refitted with a new custom aluminum frame and a new buoyancy module along with a few system upgrades that will increase efficiency both in and out of the water, thus allowing more time on the seafloor.

In addition to *Hercules*, *Atalanta*, and *Argus*, OET possesses *Little Hercules,* a much smaller, simpler ROV that is capable of working at depths up to 6,000 m. Although *Little Hercules* has no arms or other sampling tools, when there is a need to survey deeper areas, it can gather ultra-high-resolution video and images similar to those collected by *Hercules*.

Data collected by these ROVs are transmitted to the *Nautilus* control van in real time. A shipboard satellite system then connects these live streams from the seafloor to the Inner Space Center located in Rhode Island (see pages 16–17), where they are made available to all viewers over the internet. This telepresence technology allows anyone with an internet connection to follow OET's missions as they happen. By coordinating all of these technologies, OET is nurturing the development of far-reaching connections and a worldwide interest in ocean science, engineering, and technology.

Collaborating for Ocean Stewardship

Examples of OET Partnerships in 2022

By Allison Fundis, Daniel Wagner, Megan Cook, and Robert D. Ballard

A major goal of the Ocean Exploration Trust (OET) is to explore the ocean in order to provide the foundational knowledge needed to inform the sustainable stewardship of its resources and to share that information broadly. Given the magnitude and complexity of this task, partnerships are critical to OET's work. In 2022, OET continued to build on its long-standing collaborations—in addition to our primary expedition partner NOAA Ocean Exploration—and initiated new partnerships focused on meaningfully connecting OET's work to a wide array of ocean stakeholders, particularly those from geographies where E/V *Nautilus* operates.

Operations in 2022 included the first of what we hope will become a longstanding collaboration between the National Geographic Society and OET to conduct at-sea expeditions aboard *Nautilus*. In September and October 2022, the National Geographic Society and OET conducted three back-to-back expeditions for a total of 35 days at sea aboard *Nautilus* to support National Geographic Explorer-led research projects in the Main Hawaiian Islands (Figure 1). These expeditions conducted shallow-water surveys, a first for *Nautilus*, to support field research projects designed to increase our scientific understanding of marine mammal communication and soundscapes, shark communities, microplastic pollution, and maritime heritage, as well as an Indigenous data sovereignty project. By combining the complementary resources and missions of both organizations, these expeditions (see pages 40–41) brought together highly accomplished explorers, early career scientists, local community collaborators, storytellers, and educators.

FIGURE 1. Participants of the inaugural From Shore to the Abyss program, intended to become a longstanding collaboration to conduct at-sea expeditions aboard E/V *Nautilus*. The program brings together the complementary capabilities of the National Geographic Society and the Ocean Exploration Trust, particularly the ability to engage a broad spectrum of the exploration community.

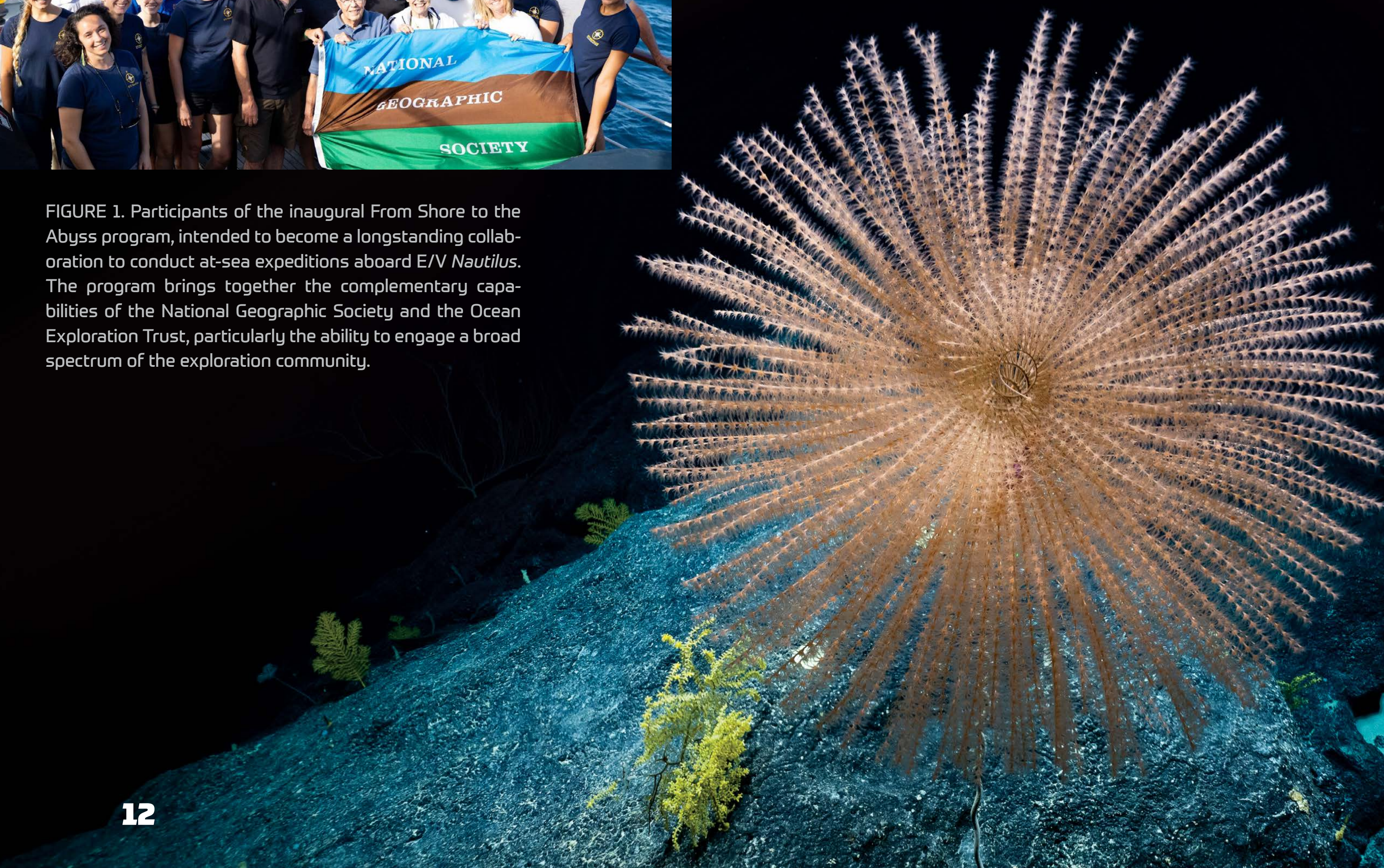


FIGURE 2. Hawaiian student interns conduct a seafloor mapping survey during E/V *Nautilus* expedition Luʻuaeaahikiikapāpahākuʻiwawā to Papahānamokuākea Marine National Monument.

Building on collaborations with the staff of Papahānamokuākea Marine National Monument developed when E/V *Nautilus* first operated within the Monument in 2018, in 2022 OET continued to work with NOAA, the US Fish and Wildlife Service, the State of Hawaiʻi, and the Office of Hawaiian Affairs to co-develop culturally relevant content for communities throughout Hawaiʻi. Activities included working closely with Native Hawaiian language practitioners to (1) incorporate Hawaiian cultural values into expedition implementation, as well as developing (2) an original mele (chant) and Hawaiian expedition names reflecting Hawaiian relationships with mission themes, (3) educational videos in Hawaiian language, and (4) a curated Hawaiian language vocabulary glossary of ocean science and technology terms. Further efforts encompassed (5) outreach to the local Department of Education charter and Hawaiian immersion schools, (6) live ship-to-shore interactions and promotion in the Hawaiian language, (7) paid internships for Native Hawaiian students and educators, and (8) a paid at-sea position for a cultural liaison to incorporate cultural protocol and practices into expedition operations. These strategic and collaborative efforts resulted in content from *Nautilus* expeditions reaching students at nearly 40% of all kula kaiapuni Hawaiian language immersion schools, and many thousands of others across the State of Hawaiʻi. In 2022, several Hawaiian student interns sailed on *Nautilus* (Figure 2).

Since 2019, OET has been partnering with NOAA Ocean Exploration and the Schmidt Ocean Institute on the Deep Ocean Education Project, an award-winning website (https://deepoceaneducation.org/) developed with support from the National Marine Sanctuary Foundation that features a curated collection of educational resources, including lesson plans, informational videos, photo galleries, ship schedules, event announcements, and more (Figure 3). Content generated during 2022 E/V *Nautilus* expeditions was used to add new educational videos, classroom activities, and image galleries to the website. Through this partnership, the OET, Schmidt Ocean Institute, and NOAA Ocean Exploration co-convened the *In Kupe's Wake: A Voyage of Exploration from Hawaiʻi to Aotearoa* virtual

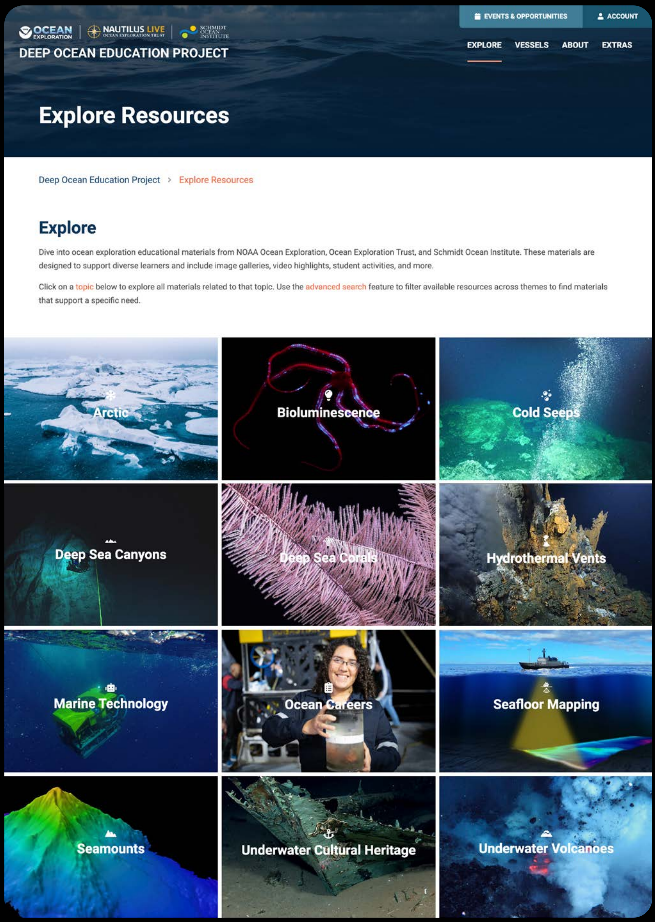


FIGURE 3. Over the last three years, OET has partnered with NOAA Ocean Exploration and the Schmidt Ocean Institute on the Deep Ocean Education Project, an award-winning website that features a curated collection of educational resources.

FIGURE 4. NA138 expedition team aboard E/V *Nautilus*, led by Beth Orcutt, principal investigator of the National Science Foundation-funded Crustal Ocean Biosphere Research Accelerator (COBRA) project. Using telepresence technology, the expedition connected with students in COBRA's Master Class, providing them with an opportunity to learn more about planning and executing deep-sea oceanographic research.

workshop that brought together Pacific Island community leaders, Indigenous practitioners, and educators from Pacific Island communities throughout Polynesia to discuss best practices for ocean exploration entities to engage with Pacific communities and build collaborative partnerships that serve island needs. The workshop resulted in a series of values, principles, and guidelines for creating meaningful opportunities and partnerships with local communities.

Since 2021, OET has been partnering with the Crustal Ocean Biosphere Research Accelerator (COBRA) project, an international network-of-networks focused on generating new knowledge and informing decision-making related to emergent human uses of the deep ocean. With funding from the National Science Foundation, COBRA regularly convenes experts and organizations engaged in deep-sea exploration and research to generate science-based policy recommendations and accelerate research and sound decision-making regarding deep-sea resources. Additionally, COBRA provides dedicated training opportunities for early career professionals through leadership training and international research exchanges that promote collaboration. In 2022, OET partnered with COBRA on the Master Class, a 13-week course focused on designing, proposing, and executing deep-sea field research (Figure 4). This included connecting Master Class students with personnel aboard E/V *Nautilus*, as well as involving them in the planning and execution of an expedition via telepresence technology.

Finally, in 2022 OET continued working with Seabed 2030, a collaborative project led by the Nippon Foundation and the General Bathymetric Chart of the Oceans that aims to bring together all available bathymetric data to produce a complete map of the global seafloor by 2030. As in 2021, all seafloor mapping data collected by *Nautilus* in 2022 was submitted to Seabed 2030 data centers shortly after the field season.

These are just a few of the partners that OET collaborated with during the 2022 field season in an effort not only to explore the largest portion of our planet, but also to meaningfully connect diverse audiences to this work to catalyze positive change.

The Ocean Exploration Cooperative Institute

By Adam Soule and Aurora C. Elmore

Given the vast undersea regions remaining to be explored and the great diversity of expertise and experience needed to do so, NOAA initiated the Ocean Exploration Cooperative Institute (OECI) to facilitate coordination, cooperation, and execution of ocean exploration activities. Established in 2019, the OECI brings together five research organizations: the University of Rhode Island, the Woods Hole Oceanographic Institution, the University of New Hampshire, the University of Southern Mississippi, and the Ocean Exploration Trust. Together with NOAA Ocean Exploration, these partners are dedicated to developing and advancing ocean exploration technology, executing ocean exploration activities, and training the next generation of ocean scientists and blue economy workers.

This past year, the third season of OECI activities, further validated the tremendous benefits of merging the expertise of the partner institutions in support of NOAA Ocean Exploration's mission. The Ocean Exploration Trust's E/V *Nautilus* provides the expeditionary platform for OECI activities. Over the past year, the vessel mapped nearly 200,000 km^2 of seafloor and deployed uncrewed ocean exploration vehicles 120 times. In addition, exciting new technologies and approaches being piloted by the OECI will increase the pace and capabilities of ocean exploration in the future. Among them are annual Technology Challenge cruises that involve the simultaneous operation of multiple uncrewed and autonomous systems to explore the ocean from top to bottom. This past year we simultaneously deployed the uncrewed surface vehicle *DriX* at the sea surface, the autonomous underwater vehicle *Mesobot* in the midwater, and the hybrid remotely operated vehicle *Nereid Under Ice* at the seafloor. Not only was each vehicle exploring a different ocean layer, their observations helped guide other vehicles to specific areas where we could learn the most. With all of this surveying occurring independent of *Nautilus*, we glimpsed a future of increased exploration efficiency, as well as improvements to the quality and value of the data collected.

Collaborations among OECI partners ensure that advanced technologies are deployed at the same time as traditional exploration activities, enabling new tools to be more quickly integrated into standard ocean exploration practices. The addition of new federal, commercial, and academic partnerships to the OECI in the past year will further accelerate the transfer of innovations from within and outside of OECI to the ocean enterprise.

The OECI ensures that a diverse group of students can access the opportunities presented by our activities. Internship programs conducted with the Community College of Rhode Island and Tuskegee University are providing pathways toward a diverse blue economy workforce. The OECI provides students and the public front-row seats and hands-on experiences so the next generation will be ready to put new advances into action and drive the field beyond what we can even conceive.

The simultaneous operation of several exploration technologies is one of several avenues by which OECI-funded expeditions aboard E/V *Nautilus* seek to accelerate the pace of ocean exploration.

Inner Space Center

Telepresence Support for E/V *Nautilus* in 2022

By Dwight Coleman, Christopher Knowlton, Rachel Simon, Derek Sutcliffe, and Webb Pinner

The Inner Space Center (ISC) at the University of Rhode Island Graduate School of Oceanography has been the shore-based hub for telepresence operations since the first season of the E/V *Nautilus* in 2009. Thirteen seasons later, the ISC continues to collaborate with the Ocean Exploration Trust (OET) to livestream expeditions, enable remote participation by wide audiences, and assist with data management needs. The technical support provided to *Nautilus* operations by the ISC broadly fits within five categories: satellite engineering, network engineering, video engineering, data engineering, and general expedition support.

Satellite engineering support took a major turn during 2022 as OET changed satellite service providers from Verizon to Marlink. The ISC had been working with Marlink on a number of projects, mostly supporting vessels operating under the University-National Oceanographic Laboratory System (UNOLS), a US organization that coordinates oceanographic ships' schedules and facilities. The timing was right for the switchover, especially as the onboard technology for satellite operations had recently changed to a more robust, technically simpler, and more straightforward system compared to previous years. ISC engineers worked closely with OET engineers to bring several new systems online. We were able to eliminate the expensive dedicated Multiprotocol Label Switching fiber-optic network and rely on Marlink's New York City co-location facility and data center to deliver reliable network services. The University of California San Diego, which runs HiSeasNet for UNOLS and has supported ISC and OET operations in the past, was a key partner in enabling this transition.

Network engineering support also took a major turn in 2022, primarily because of the satellite service changes, but also with the addition of a next generation firewall onboard E/V *Nautilus* (see pages 42–43). A new Fortigate network appliance was integrated, providing much more control over bandwidth utilization, wide area network management, and cybersecurity. The ISC had previous experience with these systems onboard other ships, and

Inner Space Center facilities at the University of Rhode Island Graduate School of Oceanography.

Scientists and engineers collaborate at the Inner Space Center to support telepresence operations during an E/V *Nautilus* expedition.

HiSeasNet reported positive experiences working with Fortigate systems on other vessels. The integration of this firewall onboard *Nautilus* allowed OET and ISC to manage a much-improved workflow for simultaneous live streaming, data transfers, live video teleconferencing, and live ship-to-shore interactions.

Video engineering support was provided in the same manner as in previous years. The ISC operates and maintains all the onboard and onshore video streaming devices to ensure the live feeds remain online with little down time, especially during ROV dives. These devices exist not only at the ISC facility itself, but also at the Marlink co-location data center, and there is a plan to migrate content to the cloud on servers and storage devices hosted by Amazon Web Services. These devices stream to YouTube for the public and also to several private websites for higher resolution and lower latency access for tele-operations and remote science. The quad-view video feed and location map with live ship position and ship tracks continued to be created and maintained for the entire season.

Data engineering support was similar to that of previous years, but included more experimentation with processing and managing data in new and innovative ways. Linear tape-open tapes were used to backup all expedition data onboard E/V *Nautilus* and were then transferred to the ISC for archiving. Quality-control processes were implemented prior to archiving the data, which ranged from several to dozens of terabytes per expedition. Processed data were then transferred to various repositories (YouTube, Rolling Deck to Repository, and NOAA's National Centers for Environmental Information, among others) for permanent archiving. Many requests for copies of video data were filled by ISC staff, as in previous years. Lastly, the ISC continued to support the integration of Sealog and other software tools on board to assist with science and engineering workflows.

General expedition support included managing the ISC facility to meet the needs of OET and providing occasional assistance to the Doctor-On-Call program and to OET's educational outreach programs for Science Communication Fellows and others. ISC assisted with maintaining and operating the OET Scientist Ashore Portal and supported various Exploration Command Centers, as well as other special OET projects related to telepresence and data management.

Reaching the World through Ocean Exploration and Education

By Megan Cook, Jamie Zaccaria, Kelly Guarino, Jonathan Fiely, and Jacob Ottaviani

The Ocean Exploration Trust (OET) continues to be inspired by sharing ocean exploration with learners from around the world. Across the 2022 field season, the team reached millions with engaging live-streaming from the seabed, welcomed over 50 students and educators aboard E/V *Nautilus*, grew our ship-to-shore live interaction program to reach over 72,000 learners, expanded social media storytelling by launching a TikTok channel, and cultivated partnerships to deepen the impact of our work.

While operating in the Pacific, we continue to work closely with partners to ensure that our expeditions are guided by Indigenous knowledge. Building upon relationships with the Papahānaumokuākea Marine National Monument and the Office of Hawaiian Affairs-facilitated Papahānaumokuākea Cultural Working Group, we worked to learn from and listen to priorities of Pacific Island communities. After two years of developing Hawaiian expedition names for visits to Papahānaumokuākea, the partnership supported composition of a mele oli (chant) that reflects relationships of expeditions to place. This collaboration also developed a paid, cultural liaison position on expeditions to support outreach and incorporate Indigenous protocol into operations.

Early in 2022, OET partnered with the Schmidt Ocean Institute and NOAA Ocean Exploration to host the In Kupe's Wake workshop designed to explore principles that deepen Indigenous relationships with ocean exploration. Building on previous events within the oceanographic community, this workshop brought together Pacific Island community leaders, Indigenous practitioners, and educators from Hawaiʻi, Samoa, Cook Islands, and New Zealand to develop relationships among educators interested in ocean exploration (see pages 12–14). The virtual gathering focused on how exploration organizations can equitably engage Polynesian communities and build collaborative partnerships that serve such Indigenous priorities. With wisdom from traditional knowledge holders and community leaders, the In Kupe's Wake event and report (https://nautl.us/InKupesWake) gathered advice for exploration organizations operating in the Pacific on how to best work with and serve local communities, reinforcing that true reciprocal collaboration can connect individuals to their heritage and the natural world.

FIGURE 1. The at-sea team of the Deep Sea Biodiversity & Ancient Volcanoes near Johnston Atoll expedition (NA141) included three professional educators and ten university students.

FIGURE 2. Science and Engineering Internship participants have key roles in vessel operations. Here, Video Engineering Intern Rian Leung operates and maintains E/V *Nautilus*'s video systems.

IMMERSING EDUCATORS AND STUDENTS IN AT-SEA LEARNING

OET's at-sea programs invest in the next generation of ocean professionals and stewards by providing hands-on experiences that enrich their practical skills and boost their confidence in interpreting cutting-edge science (Figure 1). The Science Communication Fellowship brings together educators for a cohort-based, year-long experience that includes several weeks at sea building science communication skills and fostering ocean exploration excitement in their communities. Fellows gain exposure to the applications of science, technology, engineering, art, and mathematics (STEAM) in the field of ocean exploration. They also bring expeditions to life for learners all over the world through ship-to-shore broadcasts from E/V *Nautilus*. A total of 14 educators from eight states participated this year with one fellow describing the experience as follows:

This experience has brought me back to my passion, full circle. I don't know what to do next, but whatever it is, I want it to be enriching, the way my OET experience was. I have never been in such a collegial, focused, supportive, and super-smart group of individuals. It's really changed me in a wonderful way.

OET also supports young professionals interested in ocean science and engineering by providing internship opportunities for community college, undergraduate, and graduate students to sail on E/V *Nautilus*. Interns learn through mentoring relationships with professionals at different career stages (Figure 2). Twenty young professionals were trained within the Science and Engineering Internship Program in 2022, including eight students from Pacific Islands where the ship operated.

At-sea programs continued to create supportive and enriching opportunities for individuals from historically marginalized backgrounds, as well as provided opportunities for these individuals to serve as role models in their communities. In the words of one participant:

As a minority in my community, young girls now see a representation of possibilities. (Through me) teachers and staff will witness where taking a risk and true exploration can take you.

Another participant highlighted the importance of being part of ocean exploration:

Black people in my community were so in awe and intrigued as they followed along with me at sea. I believe it has expanded what young black people can be.

Over 60% of 2022 Science Communication Fellows self-identified as coming from historically marginalized ethnic and racial backgrounds, and many teach at majority low-income (Title-1 eligible) schools. Over 73% of internship participants (n=14) self-identified as members of racial and ethnic groups historically underrepresented in STEAM.

GROWING OET'S DIGITAL FOOTPRINT

The Nautilus Live website offers many ways for public audiences to engage with ocean exploration, including career pages that highlight pathways to roles aboard an exploration vessel, education resources, and an expedition log with updates from the team on board. Science pages detail the often long route to scientific discovery, the need for data accessibility, and the various partners involved. Across our 2022 season, our live streams attracted over 1.65 million views, with an average watch time of over eight minutes—an extremely high metric for educational content. Additionally, the team received and answered over 27,000 questions from global audiences through our website.

Video highlights from ROV dives remain a signature of our education and outreach program. During the season, the team produced 54 original videos that showcase content from our 11 expeditions. The growing video library of thrilling ocean discoveries continues to garner millions of views—over 8.7 million this year. Beyond highlights from the seafloor, these videos explain basic ocean exploration concepts in a relatable way.

Efforts to expand the accessibility of ocean exploration content included diversifying language offerings. OET published a series of Hawaiian-language narrated videos and expanded Spanish and English subtitling to over 200 of our most popular media pieces. Across our channels, approximately 25% of viewers used captions while watching our content, validating support for this inclusive practice. To expand the on-demand ability to replay full ROV dives, we host a YouTube channel that features complete ROV dive recordings. The channel includes integrated video bookmarks from ROV dive logs that allow quick reference to observations throughout our archived dives. Due to its wide accessibility, YouTube proved its value as a global engagement platform, and our viewership grew substantially.

REACHING STUDENTS IN CLASSROOMS AND COMMUNITIES

Ship-to-shore interactions remain one of the most dynamic and direct ways OET brings the deep sea to the public. From a broadcast studio onboard, Science Communication Fellows and STEAM professionals link one-on-one with learners in K–12 classrooms, universities, museums, and community events. Sharing the latest discoveries and insights into life aboard an exploration vessel, the team engages through dialog rather than formal presentations, building familiarity with diverse STEAM role models and bringing ocean exploration to everyone (Figure 3).

During the 2022 season, the team hosted a remarkable 569 ship-to-shore interactions with over 70% of expedition team members participating as role model hosts. These programs connected with more than 72,000 people in 40 US states, American Samoa, Guam, Northern Mariana Islands, Puerto Rico, the US Virgin Islands, and 14 countries across four continents. This capacity for connecting with global audiences was showcased by interactions that connected *Nautilus* with prominent events like the European Space Foundation's European Rover Challenge, professional development workshops hosted by NASA's Jet Propulsion Laboratory, the Hawaiʻi STEMWorks state STEM Conference, and secondary schools throughout Greece during an event hosted by the Ministry of Education.

Building on a partnership begun in 2021 with the Papahānaumokuākea Marine National Monument and the Office of Hawaiian Affairs, live ship-to-shore interactions continue to be offered in ʻŌlelo Hawaiʻi (Hawaiian language), connecting learners to the deep ocean realm. This year, our international team also hosted programs in Spanish, Greek, Italian, Catalan, and American Sign Language.

OET also supports student learning by hosting free online educational resources in English, Spanish, and ʻŌlelo Hawaiʻi (https://nautiluslive.org/education/resources). Our suite of over 125 educational resources written by educators

FIGURE 3. Expedition team members Daniel Kinzer and Jamie Zaccaria connect from the ship's broadcast studio with a classroom through the live ship-to-shore interaction program.

FIGURE 4. In 2022, we published 13 new educational resources for learners on the OET website, including an immersive virtual field trip to E/V *Nautilus*.

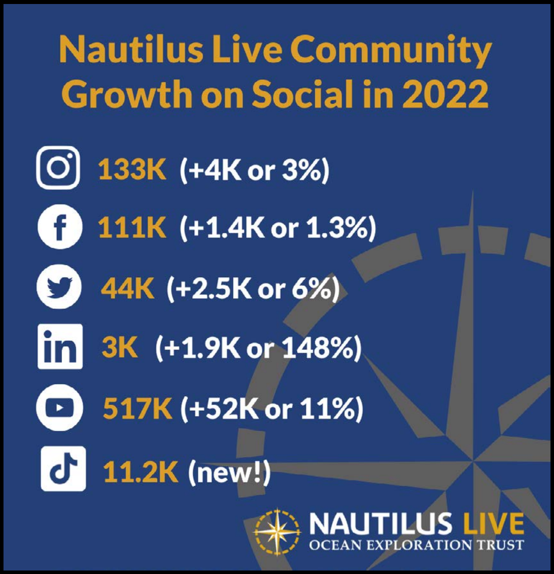


FIGURE 5. The deep sea continues to attract curious new fans. Audiences on all of OET's social media platforms grew in 2022, with over 800 K accounts engaged in deep sea discovery.

for educators includes lessons, engineering challenges, video playlists, and more, linking ocean exploration with national standards. In 2022, we added 13 new resources, including:

- A virtual field trip immersive ship tour (Figure 4) (https://nautiluslive.org/resource/virtual-fieldtrip-exploration-vessel-nautilus),
- A Hawaiian seafloor vocabulary resource (https://nautiluslive.org/resource/na-huaolelo-huakai-aumoana-visual-vocabulary-olelo-hawaii-english
- The Storytime at Sea series with children's books read by explorers paired with lessons (https://nautiluslive.org/resource/storytime-sea-ocean-speaks)
- A classroom warm-up series of Next Generation Science Standard teaching frameworks (https://nautiluslive.org/resource/seeing-science-and-engineering-practices)

In order to expand access, these resources were also contributed to the Deep Ocean Education Project (https://deepoceaneducation.org/), a one-stop educational resource library developed by NOAA Ocean Exploration, Schmidt Ocean Institute, and OET with support from the National Marine Sanctuary Foundation.

BROADENING THE OCEAN EXPLORATION COMMUNITY

OET supports press and media partnerships by licensing footage to promote open-access scientific data and share stories about the largest habitat on the planet. In 2022, OET's work was featured in over 1,200 media pieces in 53 countries, including *Newsweek*, *Vice*, *IFLScience*, and MSN. Our top press stories included the "yellow brick road" spotted in the Papahānaumokuākea Marine National Monument (see pages 30–31), which was featured in over 190 articles with a combined reach of over 1.4 billion, the first-in-the-Pacific witnessing of two *Solumbellula* sp. sea pens near Johnston Atoll, and the story of the fossilized *Megalodon* shark tooth (see pages 32–33) revealed in post-cruise sample processing by collaborators at the University of Rhode Island.

Social media continues to be one of our most popular tools for reaching audiences, especially in real time. We actively cultivate communities on six platforms to share ongoing exploration operations with everyone. As audiences grew on all platforms, the biggest achievement was a half-million subscribers to our YouTube channel. OET also launched a new social channel on TikTok, a platform with a rapidly growing user group in early career age demographics. Since launching this channel in March 2022, we have already reached over 10,000 followers (Figure 5).

OET continues to identify new paths for bringing the excitement of discovery and STEAM careers to the daily lives of audiences around the globe. Transporting audiences to the largest and least explored portion of our planet, we look forward to continue engaging communities around the world for many years to come. In 2022, OET's education and outreach program was supported by the Office of Naval Research, the National Marine Sanctuary Foundation, CITGO, NOAA Ocean Exploration via the Ocean Exploration Cooperative Institute, the Nippon Foundation GEBCO Scholars Program, and the NOAA Educational Partnership Program.

2022 E/V *Nautilus* Field Season Overview

By Daniel Wagner

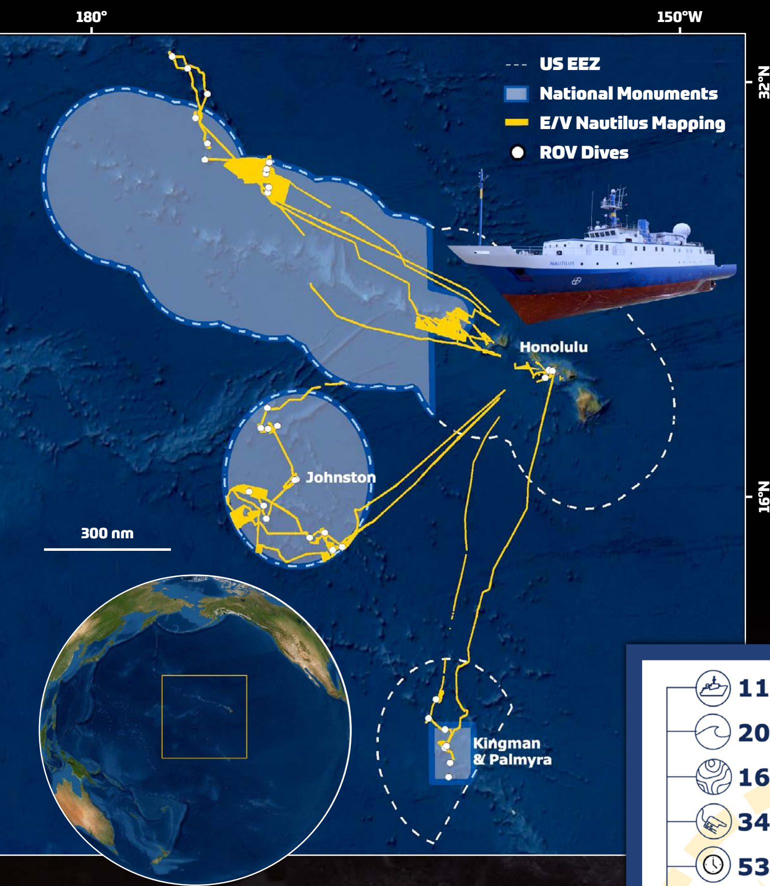


FIGURE 1. Map showing the locations explored by E/V *Nautilus* during the 2022 field season in the Central Pacific Ocean.

In 2022, E/V *Nautilus* successfully completed an eight-month field season consisting of 11 expeditions that explored the Central Pacific Ocean for a total of 202 days at sea (Figure 1). The ship's field season began with a shakedown cruise around the Main Hawaiian Islands. It was followed by a series of expeditions focused on seafloor mapping and ROV explorations, testing and integrating emerging exploration technologies, and conducting shallow-water surveys as part of a new partnership with the National Geographic Society. Collectively, 2022 expeditions mapped over 162,000 km^2 of seafloor and surveyed a diversity of habitats and geological features that ranged from coral reefs just a few meters below the surface to abyssal depths approaching 4,000 m.

- **11** expeditions
- **202** days at sea
- **162,172** km^2 of seafloor mapped
- **34** successful ROV dives
- **534** hours of seafloor exploration
- **562** samples collected
- **36** students at sea
- **21** educators at sea
- **111** scientists participated remotely
- **1,180** media stories
- **569** live ship-to-shore interactions
- **>72,000** ship-to-shore participants
- **>1,800,000** live stream views
- **>6,500,000** highlight video views

2022 SHAKEDOWN (NA136)

The shakedown expedition was conducted on March 1–10 to complete engineering tests in preparation for the 2022 field season (Figure 2). This nine-day voyage included routine testing of the ship's mapping, ROV, and telepresence systems, as well as incorporating the University of New Hampshire's uncrewed surface vehicle (USV) *DriX* into *Nautilus* operations. The vehicle was integrated with the ship's infrastructure, launches and recoveries of the vehicle were fine-tuned, and the team was trained in operating USV *DriX* and emergency scenarios. Many lessons learned during the mission were pivotal to the success of two cruises later in the season that included USV *DriX*.

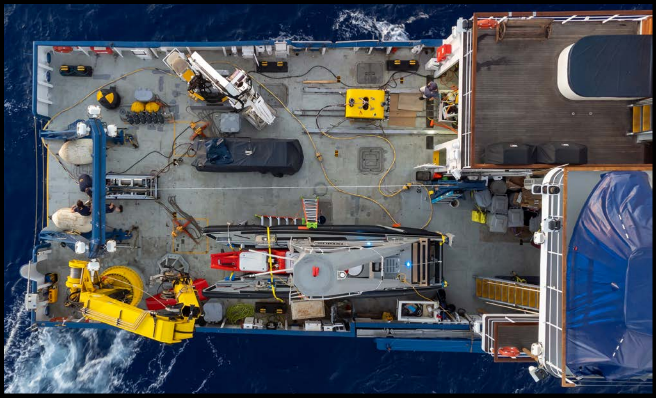


FIGURE 2. Scientists and engineers conduct engineering tests on the fantail of E/V *Nautilus* during the 2022 shakedown expedition.

FIGURE 3. Enigmatic sedimentary deposits, which may be turbidites deposited after slump failure, were documented on a dive to 2,756 m on an unnamed guyot located north of Palmyra Atoll.

KINGMAN AND PALMYRA UNIT OF THE PACIFIC REMOTE ISLANDS MARINE NATIONAL MONUMENT (NA137)

Between March 14 and April 5, a 22-day E/V *Nautilus* expedition investigated deep-sea habitats in the US exclusive economic zone (EEZ) surrounding Kingman Reef and Palmyra Atoll. Despite weather challenges, eight successful ROV dives were completed, six within the current boundaries of the Monument and two in an area that may be considered for Monument expansion in the future. During one of the dives, the ROVs documented an enigmatic sedimentary deposit that may represent turbidites deposited after a slump failure, a phenomenon that has not been recorded in this region (Figure 3). In addition to executing ROV dives, the expedition mapped over 19,507 km^2 of previously unmapped seafloor, including 3,450 km^2 within the Pacific Remote Islands Marine National Monument.

PAPAHĀNAUMOKUĀKEA MARINE NATIONAL MONUMENT (NA138, NA142, AND NA143)

Between April 7 and September 13, E/V *Nautilus* conducted three expeditions for a combined 72 days at sea in and around Papahānaumokuākea Marine National Monument. The first of these included ROV explorations, and the other two were dedicated to seafloor mapping. Noteworthy ROV observations included a "yellow brick road" at 1,029 m depth that likely represents the fractured crust of a hyaloclastite (a deposit consisting of volcanic glass fragments formed when hot magma hits cold water), where the fractures intersect at right angles (Figure 4). While this formation is a result of natural causes, its resemblance to a human-made structure resulted in a story that garnered close to 1.5 billion in media reach. The three expeditions mapped a combined area of 89,330 km^2, including 72,118 km^2 inside the Monument.

FIGURE 4. This "yellow brick road" was found at 1,029 m depth near the summit of Nootka Seamount inside Papahānaumokuākea Marine National Monument. While this formation is a result of completely natural causes, its resemblance to human-made structures resulted in a story that drew substantial media attention.

JOHNSTON UNIT OF THE PACIFIC REMOTE ISLANDS MARINE NATIONAL MONUMENT (NA140 AND NA141)

During 47 days at sea between May 25 and July 13, two back-to-back expeditions explored the deep-water geology and biology inside the Johnston Unit of the Pacific Remote Islands Marine National Monument. Over 55,275 km^2 of seafloor were mapped, including 42,493 km^2 inside the Monument where several seamounts and larger ridge features were detailed for the first time. These mapping data were key to the successful execution of 13 ROV dives, which explored diverse habitats and geological features, including the deeper flanks of Johnston Atoll, as well as those of offshore seamounts and guyots (Figure 5). Noteworthy ROV observations included recording basalt atop most guyots overlying limestone. This juxtaposition suggests that many guyots in this region were created during multiple phases of volcanism. Other noteworthy observations included the discovery of a fossilized *Megalodon* tooth, fossilized whale bones, and the first record of the sea pen genus *Solumbellula* from the Pacific (see pages 46–47).

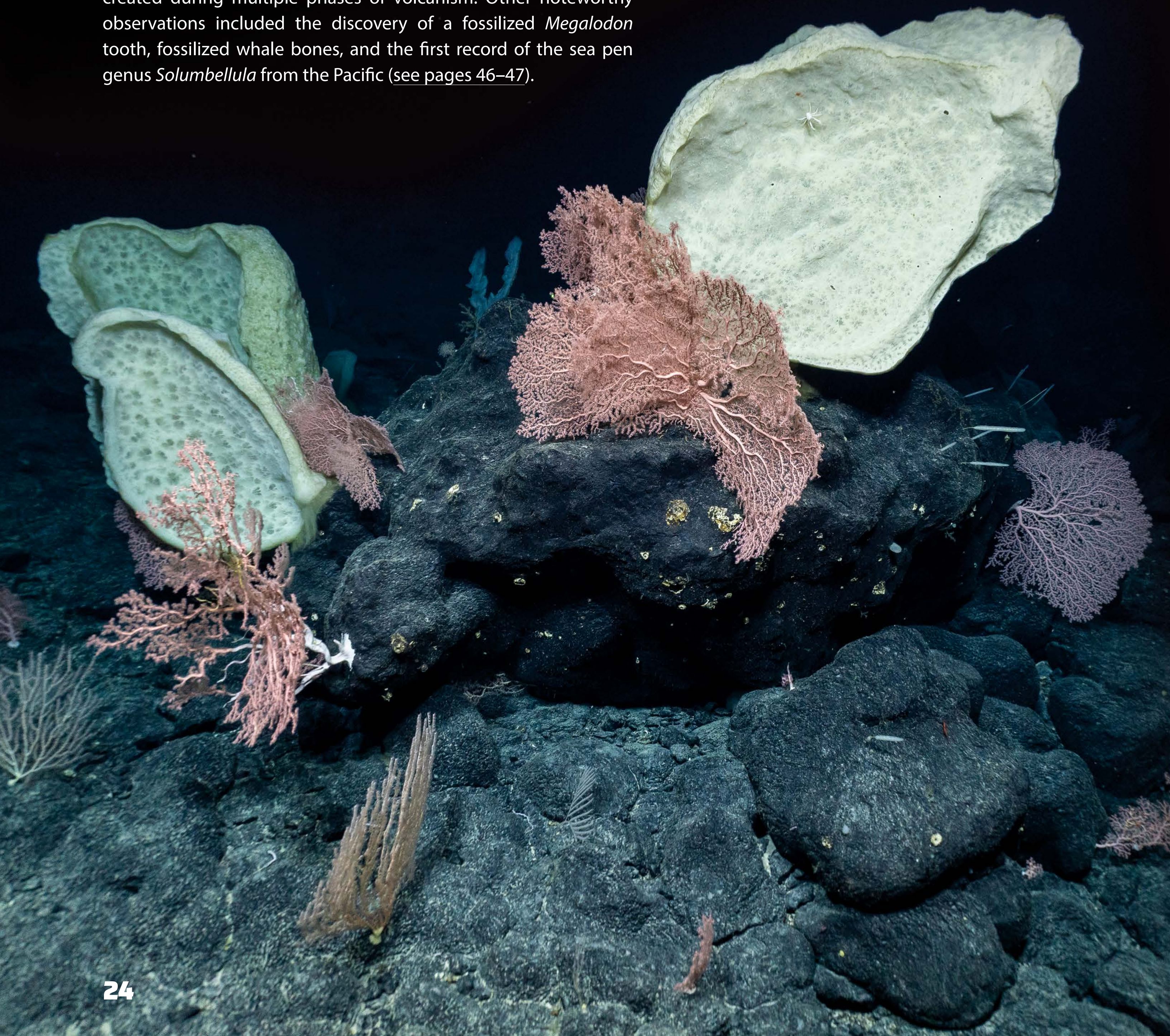


FIGURE 5. A diverse assemblage of deep-sea corals and sponges were documented on a dive to 2,500 m depth on a seamount located about 200 km southwest of Johnston Atoll.

TECHNOLOGY CHALLENGE (NA139)

From May 6 to 22, E/V *Nautilus* supported an expedition that combined various exploration technologies, including the University of New Hampshire's USV *DriX* (Figure 6), as well as Woods Hole Oceanographic Institution's autonomous underwater vehicle *Mesobo*t and hybrid vehicle *Nereid Under Ice*. Over the course of this 16-day expedition, the team successfully demonstrated the complementary capabilities of these technologies. Expedition accomplishments included the three vehicles communicating with each other while they were simultaneously deployed, shipboard personnel re-tasking the vehicles based on information gained from partner vehicles, and personnel back on shore operating the vehicles.

FIGURE 6. A drone photo shows E/V *Nautilus* launching USV *DriX*.

FIGURE 7. USV *DriX* operates with E/V *Nautilus* in the background.

DUAL-TECHNOLOGY SEAFLOOR MAPPING (NA142)

Sonars on both E/V *Nautilus* and USV *DriX* (Figure 7) were used to map the seafloor around the Northwestern Hawaiian Islands between July 16 and August 8. Over the course of six *DriX* deployments, its shallow-water mapping capabilities were progressively integrated into simultaneous mapping operations with the deep-water sonars of *Nautilus*. In addition to developing important new protocols for multi-vehicle exploration, the expedition also demonstrated inter-institutional collaboration; the mission was co-funded by NOAA Ocean Exploration via the Ocean Exploration Cooperative Institute and the NOAA Office of Coast Survey via the Center for Coastal and Ocean Mapping/Joint Hydrographic Center.

FROM SHORE TO ABYSS (NA144, NA145 & NA146)

Between September 15 and October 24, three back-to-back expeditions supported the new From Shore to the Abyss program, with funding from the National Geographic Society. The team quickly adapted to this new shallow-water focus, a first for *Nautilus,* to facilitate the deployment of divers, snorkelers, and sampling equipment in nearshore waters around the islands of Maui, Lāna'i, and Hawai'i (Figure 8). These expeditions included field surveys to support studies on marine mammal communication, shark communities, maritime heritage, and microplastic pollution, along with an Indigenous data sovereignty project. In total, 116 scuba and 40 small boat surveys were conducted over the course of these expeditions.

FIGURE 8. Underwater photographer Jenny Adler conducting a scuba survey during an E/V *Nautilus* expedition that supported the new From Shore to the Abyss program.

Building the Foundation for Deep-Sea Exploration in the Central Pacific

E/V *Nautilus* Seafloor Mapping in 2022

By Daniel Wagner, Erin Heffron, Renato Kane, and Derek Sowers

E/V *Nautilus* expeditions in 2022 explored some of the most remote areas in the Central Pacific, focusing on deep-water explorations in US waters surrounding the Hawaiian Islands, Johnston Atoll, Palmyra Atoll, and Kingman Reef (Figure 1). Because most of the seafloor in this region had not been mapped with modern technologies, acquiring high-resolution seafloor mapping data was a main objective. Collectively, 2022 expeditions mapped over 162,000 km^2 of seafloor, including 143,557 km^2 in the US exclusive economic zone of the Pacific Island Region.

The primary targets were areas in Papahānaumokuākea Marine National Monument and the Pacific Remote Islands Marine National Monument. These mapping operations not only acquired new data in largely unexplored regions, but also were key to follow-on explorations using E/V *Nautilus*'s remotely operated vehicles. As is standard protocol on *Nautilus* expeditions, mapping operations were designed specifically to cover previously unmapped or poorly mapped seafloor and thus contributed directly to the primary goals of the National Strategy for Mapping, Exploring, and Characterizing the United States Exclusive Economic Zone; the Nippon Foundation-GEBCO Seabed 2030 Project; and the UN Decade of Ocean Science for Sustainable Development (2021–2030).

Mapping operations inside Papahānaumokuākea Marine National Monument were conducted during three separate *Nautilus* expeditions (NA138, NA142, and NA143). These operations focused on acquiring high-resolution data on seamounts and ridge features associated with the Liliuokalani Ridge, as well as various other features toward the southeastern boundary of the Monument (Figure 2). Building on previous mapping efforts inside

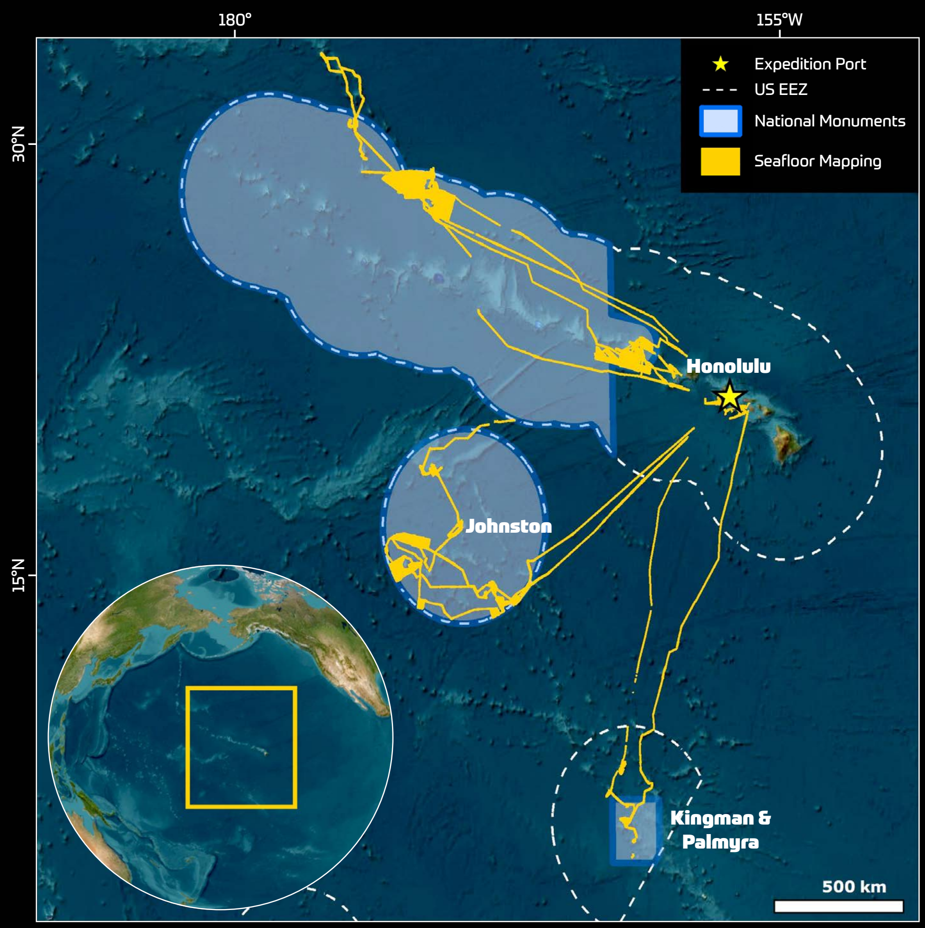


FIGURE 1. Map showing seafloor mapped by E/V *Nautilus* in 2022.

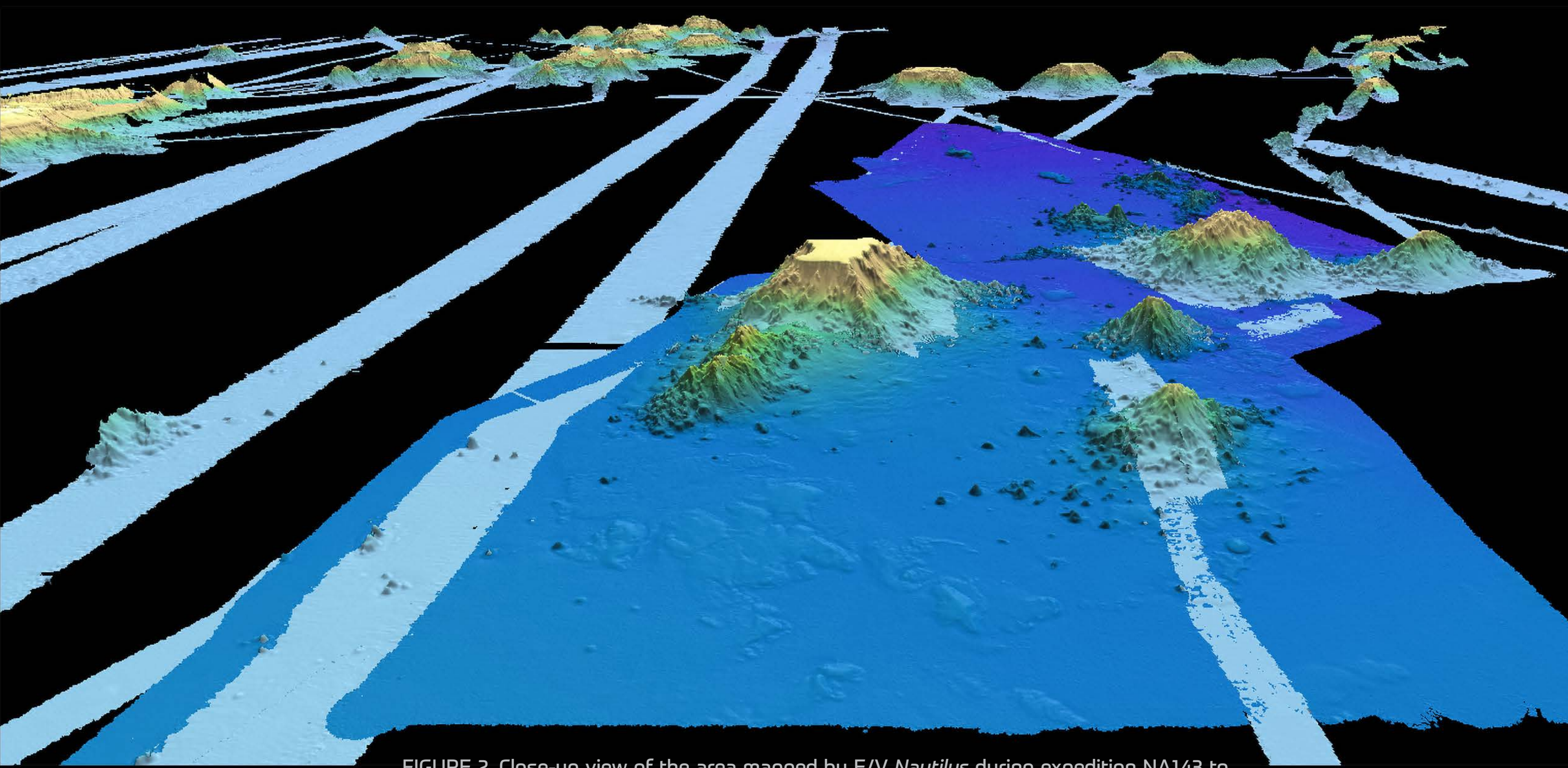


FIGURE 2. Close-up view of the area mapped by E/V *Nautilus* during expedition NA143 to Papahānaumokuākea Marine National Monument. Lighter colors represent areas that had previously been mapped, and darker colors show data collected by *Nautilus* in 2022.

the Monument by other programs, *Nautilus* mapped a combined 89,330 km^2 in 2022 (an area larger than the state of Maine), including 72,118 km^2 inside the Monument. Collectively, over half of the seafloor inside the Monument has now been mapped at high resolution, providing an important foundation for follow-on exploration, research, and management activities.

Mapping operations inside the Pacific Remote Islands Marine National Monument occurred during three separate E/V *Nautilus* expeditions, including one in the Kingman and Palmyra Unit (NA137) and two in the Johnston Unit (NA140–141). Collectively, these expeditions mapped over 74,782 km^2 of seafloor, including 45,943 km^2 inside the Monument. Seafloor mapping focused on filling multibeam gaps around the Mid-Pacific Mountains toward the southwestern extent of the Johnston Unit, as well as on various seamounts located north of Palmyra Atoll.

In addition to using the hull-mounted sonars of E/V *Nautilus* (Kongsberg EM302 multibeam sonar and Knudsen 3260 sub-bottom profiler), 2022 expeditions employed two other sonars from collaborating institutions. During the ROV expedition to Johnston Atoll (NA141), a Norbit ultra-compact wideband multibeam sonar mounted on ROV *Hercules* produced centimeter-scale seafloor maps of select targets identified during dives. The Dual Technology Mapping Expedition (NA142) included deployments of the University of New Hampshire's uncrewed surface vehicle *DriX* equipped with a Kongsberg EM 2040 multibeam sonar capable of mapping the seafloor to maximum depths of about 500 m (see pages 36–37). During the 160 hours *DriX* was deployed on this expedition, its shallow-water mapping capabilities were progressively integrated into simultaneous mapping operations with the deep-water sonars of *Nautilus*.

Making seafloor mapping data publicly available continued to be a priority. To this end, mapping data collected during 2022 expeditions were submitted to the Rolling Deck to Repository, the Marine Geoscience Data System, the Global Multi-Resolution Topography data synthesis, and the GEBCO Seabed 2030 data centers.

At the conclusion of the 2022 field season, a Kongsberg Simrad EC150-3C 150 kHz transducer was installed into the hull of E/V *Nautilus*. This new sonar is the first of its kind to combine an acoustic Doppler current profiler (ADCP) and an EK80 split-beam fisheries sonar into one instrument. The ADCP will be used to measure the speed and direction of currents at various depths beneath the ship to a maximum depth of approximately 400 m. These data will support safe and efficient ROV operations, as well as provide data for improving oceanographic current models. The integrated split-beam echosounder can be calibrated to measure absolute backscatter values, which are useful for mapping and characterizing features found within the water column, such as fish aggregations, scattering layers, and bubble plumes.

Exploration of the Pacific Remote Islands Marine National Monument

Kingman Reef, Palmyra Atoll, and Seamounts of the Surrounding US EEZ

By Steven Auscavitch, Emil Petruncio, Erin Heffron, Amber Ciravolo, Coralie Rodriguez, Mary Deere, Megan Lubetkin, Rebecca Lippitt, Leilani Sablan, Dwight Coleman, Katherine A. Kelley, Adam Soule, and Daniel Wagner

For the first time since 2019, E/V *Nautilus* returned to the northern Line Islands region of Kingman Reef and Palmyra Atoll within the Pacific Remote Islands Marine National Monument (PRIMNM). Using ROVs *Hercules* and *Argus*, the expedition completed a total of eight dives to seafloor depths ranging between 659 m and 3,771 m, targeting previously unexplored seamounts and ridges. The original expedition plan focused on exploring sites external to the PRIMNM within the US exclusive economic zone (EEZ), but poor sea state conditions associated with strong trade winds forced operations into southern portions of the Monument. Six ROV dives occurred within the boundaries of the PRIMNM, and two dives targeted newly mapped seamounts northwest of Kingman Reef (Figure 1). The deepest ROV dive to date (to 3,771 m) in the Kingman and Palmyra Unit of the PRIMNM was H1908 on an unnamed seamount south of Palmyra Atoll. Seafloor mapping operations were conducted throughout the expedition, typically during transits between ROV dive sites, but also to fill mapping gaps when weather conditions did not permit ROV operations. In all, 19,507 km^2 of seafloor were mapped, including never-before-mapped seamounts, and 11,453 km^2 of the total were within US EEZ boundaries.

Across 95 hours of ROV bottom time, 80 biological, 37 geological, and 24 water samples for environmental DNA (eDNA) were recovered. Biological samples primarily consisted of deep-water corals, sponges, and other invertebrate megafauna, along with associated commensal organisms. Collections of corals and sponges revealed unknown but characteristic species of a site, potential range extensions of known taxa, and species unknown to science. At least one candidate new species of coral in the genus *Calyptrophora* has since been identified from a specimen collected near Kingman Reef at 1,375 m depth.

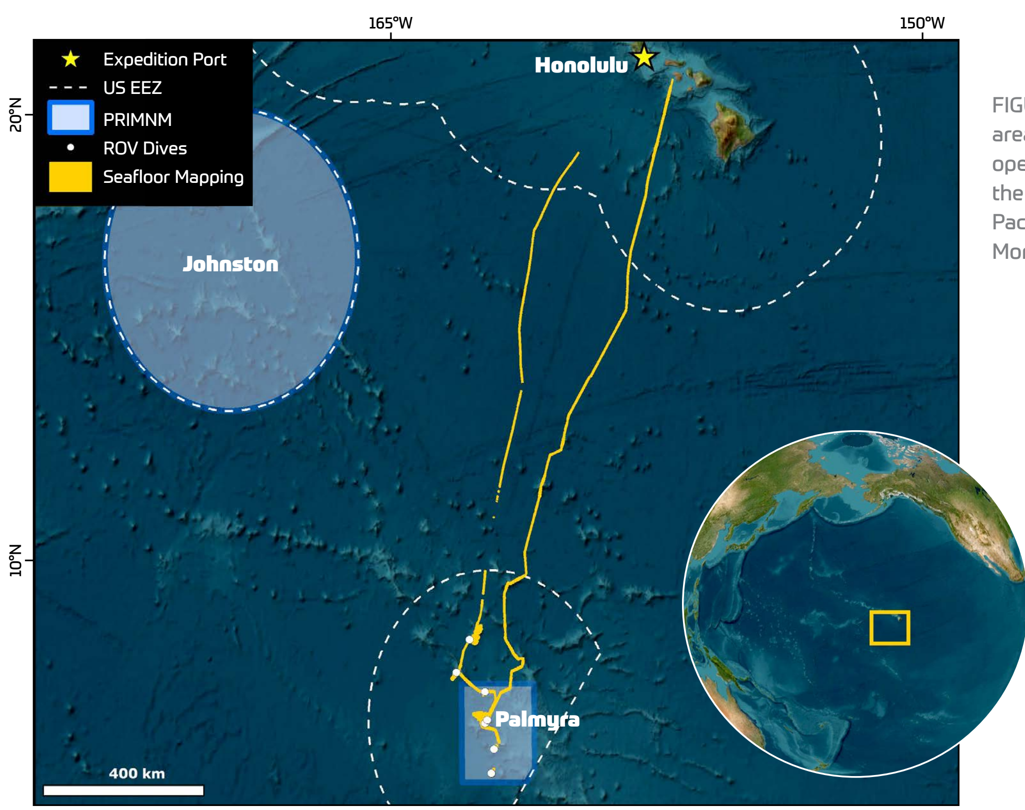


FIGURE 1. Map showing the locations of areas mapped by E/V *Nautilus* and ROV operations during expedition NA137 to the Kingman and Palmyra Unit of the Pacific Remote Islands Marine National Monument (PRIMNM).

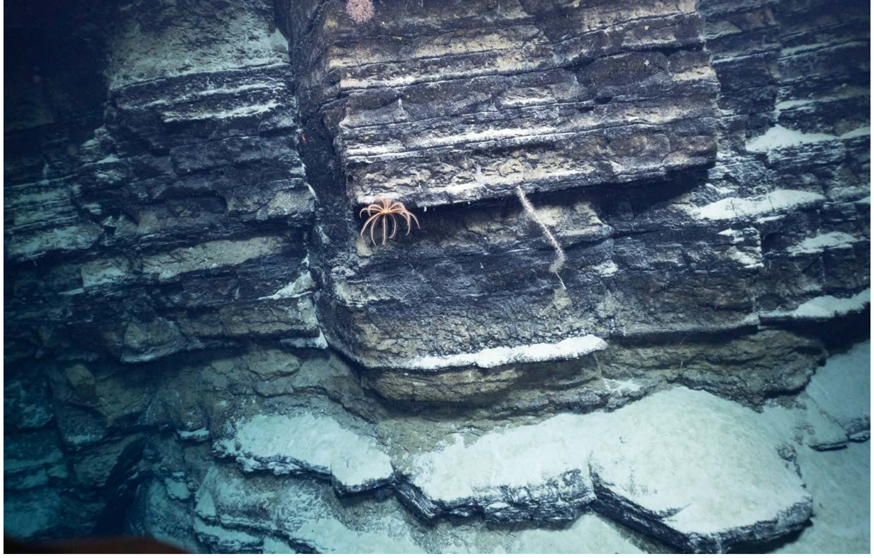


FIGURE 2. Enigmatic geological stratification across a steep rocky face observed at dive site H1912. These observed layers may indicate turbidites deposited after a slump or slope failure.

FIGURE 3. An image taken by ROV *Hercules* shows a dense and diverse coral and sponge community often associated with vertical surfaces at an unnamed seamount north of Kingman Reef in the PRIMNM.

Geological sampling targeted rocks that can provide insights into the geological context for the Northern Line Islands region and information about ferromanganese crust geochemistry. With the exception of a shallower dive site at Kingman Reef, the seafloor environment was dominated by ferromanganese-coated pillow lavas, sheet flows, and occasional enigmatic rock formations (Figure 2). Of the 37 geological samples collected, 11 contained abundant clinopyroxene, plagioclase, and amphibole phenocrysts. They are currently being processed for age determinations using $^{40}Ar/^{39}Ar$ geochronology and whole rock geochemistry.

Interesting findings included a conglomerate from an unnamed guyot (dive H1911) that contained subrounded basalt clasts and fresh amphibole in the matrix. Amphibole was also found in a volcanic sample collected during dive H1913 on an unnamed guyot. This mineral has rarely been identified in *Nautilus* cruise samples from the Kingman/Palmyra area.

Analyses of biological and geological collections from this expedition support various regional research projects. Geochemistry work is ongoing, using samples to compare crust accumulation and composition to others previously collected from the Pacific Islands Region. Six rocky crust fragments were sampled to enable DNA sequencing of microbial communities living within them. DNA from bamboo coral specimens are being sequenced to explore the biodiversity of this taxonomic group across the Central Pacific. Finally, eDNA obtained from filtered seawater captured adjacent to high-density deep-water coral communities, as well as collected coral tissues, are being sequenced to support the development of eDNA characterization tools and a genetic reference library for the Central Pacific.

High-density coral and sponge communities were observed to be patchy across the seafloor landscapes, but were encountered at each ROV dive site, including at Kingman Reef and off the southwest of Palmyra Atoll. Bamboo corals (Keratoisisdae), several primnoid coral genera (primarily *Calyptrophora* spp., *Narella* spp., *Paracalyptrophora* spp.), golden corals (Chrysogorgiidae), and black corals (multiple families) dominated high-density coral communities. Glass sponges (*Atlantisella* sp., *Poliopogon* sp., *Farrea* spp.) dominated deeper depths, and *Sericolophus* sp. was observed where soft sediment covered the seafloor. A noteworthy observation of the expedition was a high-density and high-diversity community documented on steep vertical slopes and overhangs at an unnamed seamount north of Kingman Reef (Figure 3).

In addition to the science objectives, the expedition focused on education and outreach activities. Educators and scientists conducted 69 ship-to-shore interactions from the *Nautilus* studio broadcast in both Hawaiian language and in English, reaching more than 2,700 students.

Luʻuaeaahikiikekumu: Ancient Seamounts of Liliʻuokalani Ridge

By Beth N. Orcutt, Valerie Finlayson, Dwight Coleman, Renato Kane, Justin Umholtz, Lila Ardor Bellucci, Ryan Gasbarro, Annabelle Adams-Beyea, Malanai Kāne Kuahiwinui, Hoʻoipo Bertelmann, Christopher Kelley, and Randall Kosaki

As part of the Luʻuaeaahiki Waikoloa expedition series conducted by the Ocean Exploration Trust in partnership with NOAA's Papahānaumokuākea Marine National Monument (PMNM), E/V *Nautilus* expedition Luʻuaeaahikiikekumu (NA138) used ROVs *Hercules* and *Atalanta* to explore seamounts of the Liliʻuokalani Ridge in the northern expansion zone of the Monument. The expedition used new bathymetric maps created during the 2021 field season on NA133 to guide sampling of these seamount ecosystems, following techniques similar to those used on the Luʻuaeaahikikapapakū NA134 expedition that visited seamounts in the southern extent of the PMNM. Of particular interest was obtaining a greater understanding of the puzzling bifurcation in the Liliʻuokalani Ridge seamount trail by sampling rocks from these seamounts.

Eleven ROV dives were completed on nine seamounts at depths ranging from 718 m to 3,536 m, including eight dives within the boundaries of the PMNM and another three dives just north of the Monument (Figure 1). In addition, the expedition conducted mapping operations using the E/V *Nautilus* sonars. Over 28,559 km^2 of seafloor were mapped over the course of the expedition, 23,456 km^2 within the US exclusive economic zone and 19,853 km^2 within the Monument.

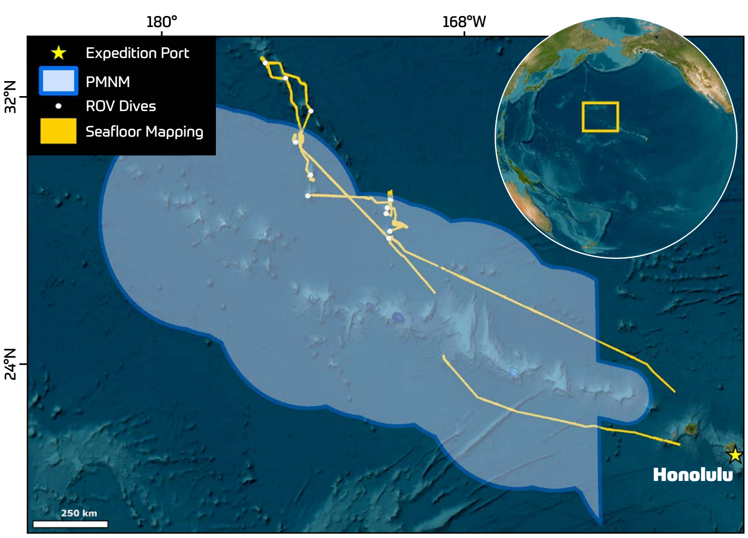


FIGURE 1. Map showing the location of seafloor mapping and ROV operations conducted during E/V *Nautilus* expedition NA138 to Papahānaumokuākea Marine National Monument.

There were several significant geological discoveries on NA138. First, a "yellow brick road" was observed at a depth of 1,029 m near the summit of Nootka Seamount inside the PMNM (see page 23, Figure 4). Preliminary interpretations indicate that this formation likely represents the fractured crust of a hyaloclastite (a deposit consisting of volcanic glass fragments formed when hot magma hits cold water), where the fractures have locally intersected at 90° to one another. The yellowish color is likely due to low temperature hydrothermal alteration of the volcanic glass to iron-oxyhydroxide. While these rocks formed naturally, their resemblance to a human-made brick sidewalk resulted in the story being picked up by numerous media outlets. Over 120 news stories were released, collectively garnering close to 1.5 billion in media reach.

A second discovery was the broad pattern displayed in the mineral content of basalts sampled along the seamount chain surveyed on the expedition. Seamounts in the western fork exhibited a mixture of olivine basalts and ankaramites (basalts with abundant pyroxene and olivine crystals), while the eastern fork had only olivine basalts. The presence of ankaramites roughly corresponded with larger seamount size, suggesting that mantle sources for basalts in the eastern and western forks were subjected to different degrees of melting. A mixture of both rock types was present in seamounts in the junction area, as well as north of the junction.

A third significant observation concerned the volcanic plumbing system of Loudoun Seamount, which was exposed at a steep fault plane where dikes were aligned parallel to the rift axis (Figure 2). Finally, we observed several pieces of pumice throughout the region, indicating transport from far away eruptions (Figure 3). A total of 85 samples (>272 kg cumulative) were collected for

FIGURE 2. Loudoun Seamount provided a rare look at its internal plumbing. The columnar jointing at near 90° angles in the basalt formed when magma within the seamount's dikes (its "plumbing system") cooled and solidified.

FIGURE 3. The light color in this rock collected from Nootka Seamount indicates that it may be pumice, a lightweight, porous volcanic rock. The rock's color suggests it may have floated to Lili'uokalani Ridge as part of a pumice raft that originated from a volcanic eruption in the Aleutian Islands or Marianas arc.

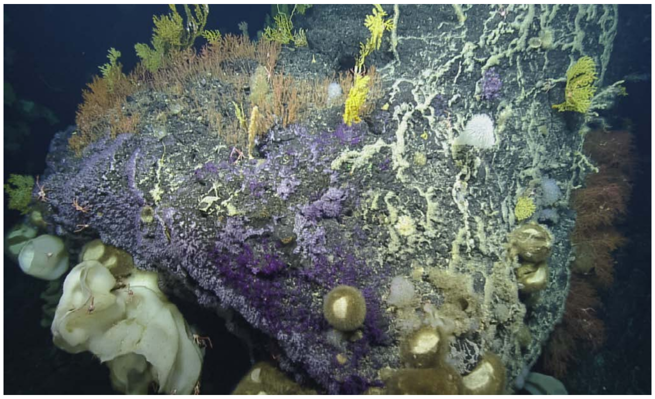


FIGURE 4. Diverse and dense communities of deep-sea corals and sponges were observed on King George Seamount.

geological analyses. Cross sections of some of these will be displayed at Mokupāpapa Discovery Center, providing more effective interpretive tools for deep-sea science.

In addition to geological sampling, ROV surveys were used to document the biological communities that live on these seamounts. The focus was on finding high-density coral and sponge communities similar to those previously discovered in the PMNM and surrounding region (Figure 4). Large specimens of *Poliopogon* and *Caulophacus* sponges—commonly seen during the 2021 E/V *Nautilus* field season—were primarily evident at the southernmost seamounts (Figure 5). We observed potentially new feeding behaviors of sea stars (Figure 6). Mobile fauna such as groundfish were observed on the tops of larger flat-topped seamounts, as was lost fishing gear. In support of these biological observations, 77 macrobiology specimens were collected, some of which may prove to be new species or new records for the PMNM. Forty-four water samples were collected to support an environmental DNA study of deep-sea coral habitats in the Monument that began in 2018 during *Nautilus* expedition NA101. Finally, a subset of the geological rock samples and sediment push cores was collected to determine microbial ecosystem services and mineral content in order to describe microbe-mineral interactions in ferromanganese crusts.

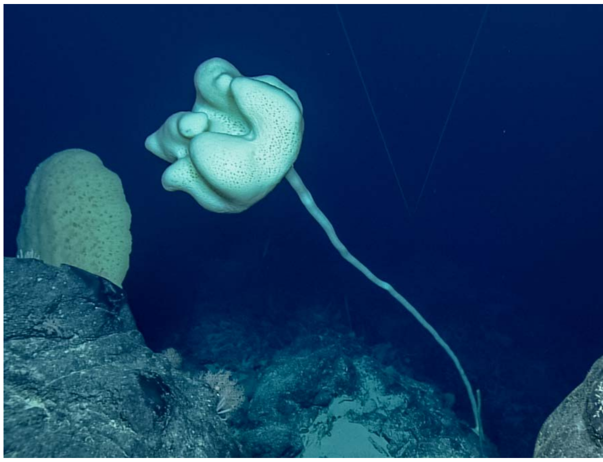


FIGURE 5. Large sponges, like the *Poliopogon* and *Caulophacus* shown here, were primarily observed on more southern seamounts.

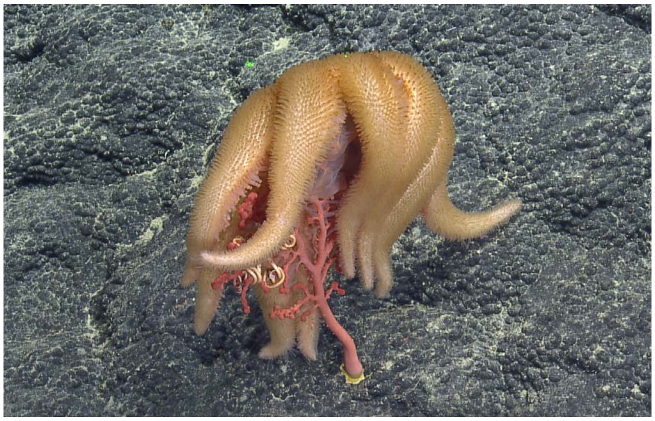


FIGURE 6. There were numerous sightings of sea stars feeding on corals, including this sea star engulfing a bubblegum coral at Nootka Seamount.

A total of 71 scientists and students participated in the expedition as scientists ashore through telepresence technology, including 12 early career researchers enrolled in the National Science Foundation-funded COBRA Deep Sea Expedition Leadership Master Class (see pages 12–14). 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 science operations 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 the ʻŌlelo Hawaiʻi language helped visiting scientists and crew to learn these protocols and also led engagement with Hawaiian audiences during the expedition. Hawaiian language materials developed during the expedition with the PMNM will be used to increase deep-sea science programming and interpretation in collaboration with Hawaiian language immersion schools.

This expedition summary is dedicated to the memory of Jasper Konter, whose passion for understanding volcanism in the Pacific Ocean inspired many.

Exploration of Deep Seamount Biology and Geology

The Johnston Atoll Unit of the Pacific Remote Island Marine National Monument

By Rob Pockalny, Steve Auscavitch, Megan Cook, Meredith Everett, Renato Kane, Kevin Konrad, Elizabeth Miller, Brandon Scott, Allison Fundis, Erin Heffron, and Lindsay Gee

Between May 25 and July 13, 2022, E/V *Nautilus* mapped and explored four regions within the Johnston Atoll Unit of the Pacific Remote Islands Marine National Monument (PRIMNM) during two back-to-back expeditions (Figure 1). While the focus of these expeditions revolved around maximizing near-bottom observations and sampling of geology and diverse biology, a combined total of 42,493 km^2 of previously uncharted seafloor was also mapped within the Monument.

A total of 13 ROV dives amassed over 210 hours of bottom time and traversed ~40 km of seafloor. Bottom time of dives ranged from 9 to 27 hours across 1 to 2.5 km of seafloor and covered 100 to 1,500 m of vertical relief.

A record number 278 samples were collected on this expedition. Biological samples accounted for the majority (60%), followed by geological samples (38%) and fossilized biological material (2%). Biological samples included 53 corals, sponges, and anemones; 39 sea cucumbers, urchins, and sea stars; 27 Niskin bottle water samples for environmental DNA; and six potential fossils including a *Megalodon* tooth, whale bones, and sponges. Geological samples included 90 rock samples of mostly iron-manganese encrusted basalt with one limestone sample, 10 collections of marble- to softball-sized iron-manganese encrusted nodules (Figure 2), and four push cores. Selective sampling of biota and rocks was a priority to better characterize the biodiversity and geologic settings of the four regions.

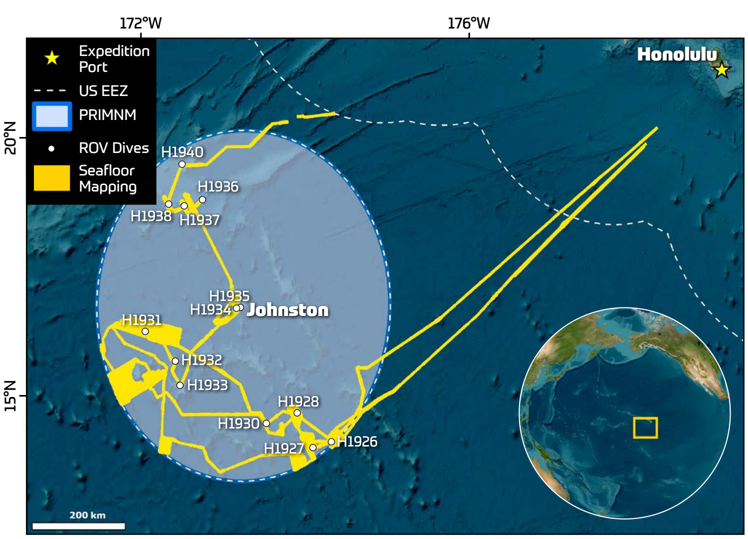


FIGURE 1. Track lines show areas that were mapped and explored via ROV during expeditions NA140 and NA141 aboard *E/V Nautilus*.

Several different morphologies of seamounts, guyots, and elongate ridges were explored in the four regions (e.g., Figure 3). In the southeastern region, three dives were located along ridges radiating from a seamount (H1926, H1928, H1930), and another dive was along a ridge consisting of a series of subtle cones flanking a guyot (H1927). In the western region, one dive was located along a section of a 100 km-long east-west trending ridge (H1931). Two other dives (H1932, H1933) explored ridges radiating from guyots that may be remnants of slope failures or mass-wasting events. Dives at Johnston Atoll (H1934, H1935) provided a continuous transect up the western flank of a prototypical atoll, with basalt transitioning to coral reef material up the slope. Seamount morphologies in the northern region did not have the radiating ridge patterns observed in the other regions, but were more circular in shape. Their cross sections were different, with one seamount presenting a more classic conical shape (H1936), another with more of a pancake morphology (H1938), and another with a possible caldera at the top (H1937). The final dive of the expedition (H1940) was along the northern flank of a guyot capped by a 15 km-diameter plateau. An interesting morphology seen in this northern region was an abundance of numerous, <500 m-high cones flanking the seamounts and guyots.

Preliminary observations indicate that the majority of rocks recovered represent a mixture of alkalic and highly silica undersaturated (e.g., trachytic) lithologies, consistent with previous reports from the region. The presence

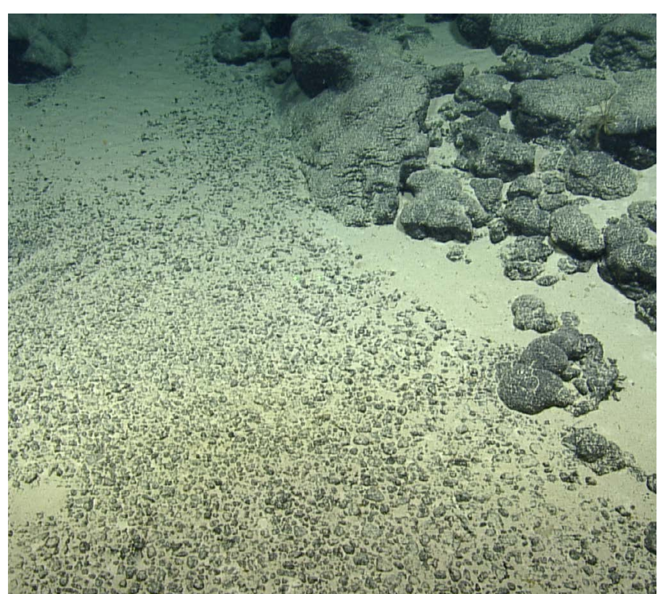
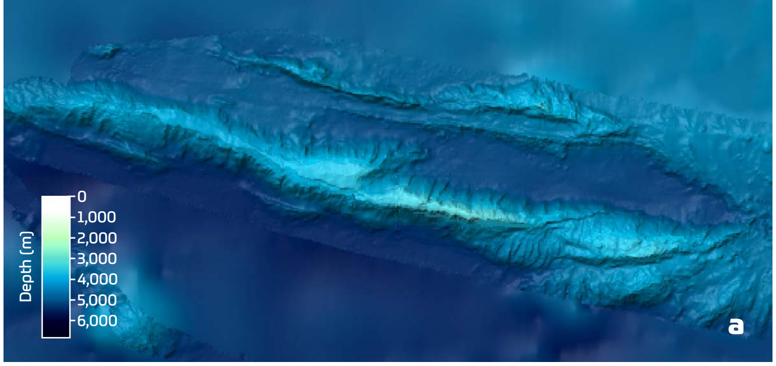


FIGURE 2. A drift of marble- to softball-sized iron-manganese encrusted nodules observed and collected during the NA141 expedition.



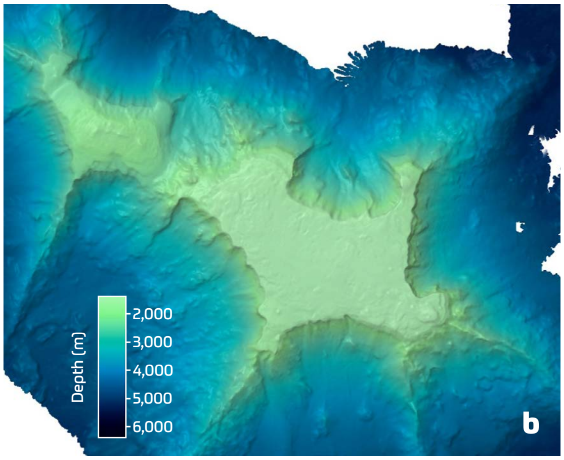


FIGURE 3. (a) Newly mapped elongate ridges of unknown origin. (b) Wetmore Seamount, an example of a guyot with radiating ridge morphology.

of basalt atop some guyots (e.g., Guyot S4 East unnamed guyot, H1940) and the occurrence of basalt morphologies overlying limestones (e.g., Wetmore Seamount, H1933) suggests that some guyots in the region may have undergone multiple, discrete volcanic phases. The origin and history of both the enigmatic ridge and the anomalous guyots require subsequent geochemical and geochronological analyses for interpretation. The long dive transects, coupled with relatively dense sampling (6–10 rocks per dive), will allow for novel insights into how these ancient volcanoes were constructed, for example, via a continuous event or multiple discrete pulses of volcanism.

Biology was notably sparse during the first two dives at unnamed seamounts (H1926, H1927), possibly owing to relatively sluggish current flow in the area. Sponges that dominated the benthic fauna across these seamount landscapes included glass sponges (*Caulophacus* sp. and *Poliopogon* sp.) and those in the family Farreidae. Corals, which more commonly exhibited high-density patches compared to sponges, were represented by golden, bamboo, and black corals (Figure 4). Small nodule patches observed across these sites were found to be populated by sponges in the genus *Semperella*.

In the western and southern portions of the Johnston Unit of the PRIMNM, exploration of a deep unnamed ridge summit (H1931) identified the presence of bamboo coral (Keratoisididae) and sponge (*Poliopogon* sp.) dominated communities. Higher density and more diverse coral and sponge communities were observed at H1932 and H1933 on guyots with prominent northeastward trending ridges. Patchy but high-density sea pen communities (*Balticina* sp.) were found on Johnston Atoll (H1935) along heavily sedimented slopes off the deeper western flank between 1,600 m and 1,800 m depth.

At seamount sites explored north of Johnston Atoll, high-density and diverse deep-water coral and sponge communities were observed on two unnamed seamounts (H1936, H1937), with highest densities often associated with vertical rock surfaces or overhangs. Among the most noteworthy species encountered during this expedition was the sea pen *Solumbellula* during dive H1938 at 2,993 m depth (see page 46, Figure 2a). It is both the first observation and the first collection of this abyssal genus in the Pacific Ocean basin.

Fossilized skull remains of beaked whales coated in ferromanganese crusts were encountered across multiple sites (Figure 5), suggesting a previous ecological relationship between seamount biological resources in this region and these transient marine mammals.

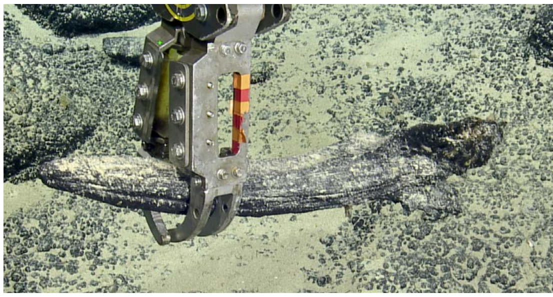


Figure 5. ROV *Hercules* recovering a portion of a fossilized beaked whale skull.

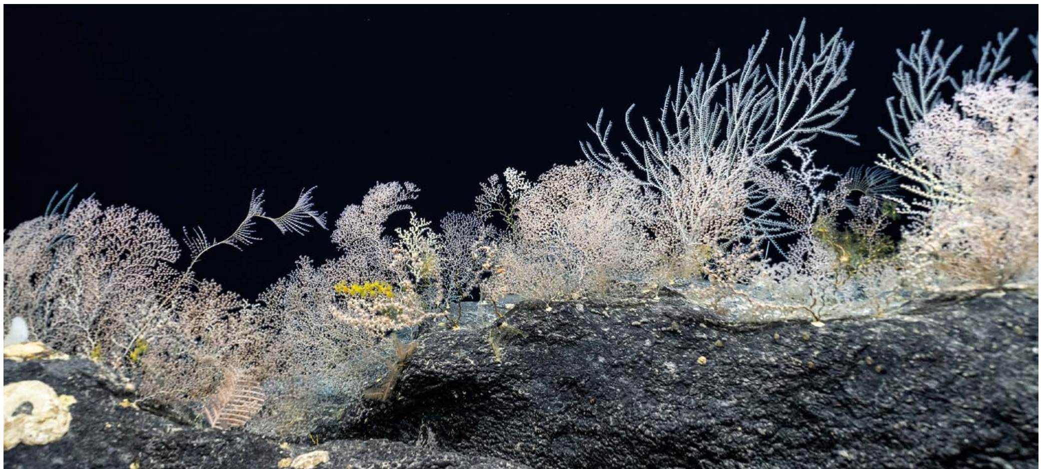


FIGURE 4. An outcrop observed at 1,895 m depth on an unnamed seamount during dive H1930 harbors a high density of golden and bamboo corals, as well as *Poliopogon* sp. glass sponges.

Mesobot Operations from E/V *Nautilus*

By Eric Hayden, Dana Yoerger, Annette Govindarajan, Allan Adams, Jacob Bernstein, Lui Kawasumi, William Pardis, M. Jordan Stanway, and Sara Stover

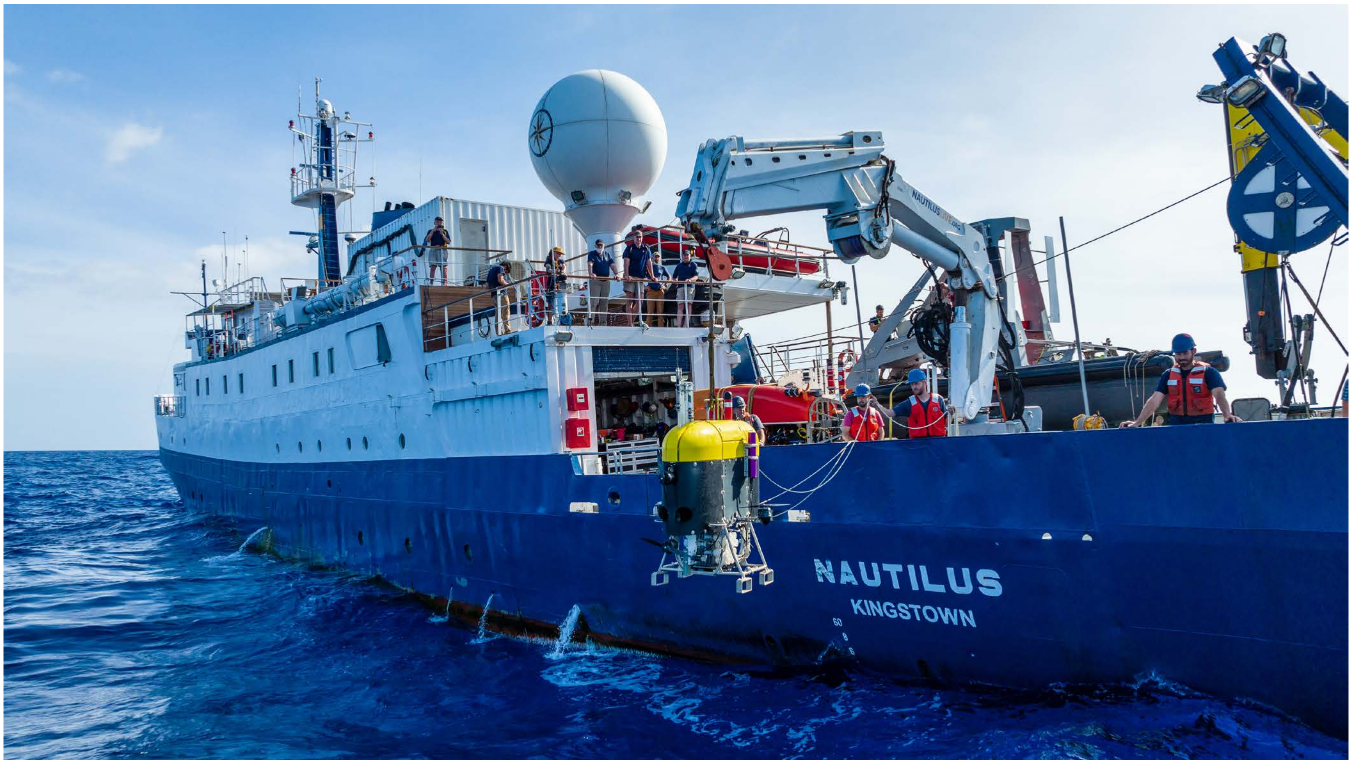
Mesobot is an ocean exploration vehicle specifically designed to survey midwater environments with minimal disturbance at depths to 1,000 m (Figures 1 and 2). Operating as either a remotely operated vehicle or an autonomous underwater vehicle, *Mesobot* can collect environmental data like turbidity and ambient light, while simultaneously collecting samples and surveying pelagic biodiversity with cameras.

Because of its unique midwater survey capabilities, *Mesobot* was a perfect addition to the multi-vehicle expedition (NA139) that also featured Woods Hole Oceanographic Institution's hybrid submersible *Nereid Under Ice* (*NUI*) and the University of New Hampshire's uncrewed surface vehicle *DriX*. With *DriX* on the surface and *NUI* exploring the seafloor, *Mesobot* complemented the mission by surveying midwater environments. Its main scientific goals were to characterize fauna engaging in a daily light-driven migration up and down through water column, known as diel vertical migration. *Mesobot* surveys were particularly focused on the operation of two subsystems that were recently added to the vehicle: a pair of radiometers and an environmental DNA (eDNA) multisampler.

Radiometers are highly sensitive devices that allow *Mesobot* to detect light levels far beyond what humans can see. This capability is crucial to understanding the behavior of animals that undertake diel vertical migration, which is driven by very small changes in light levels. Because radiometers are so sensitive, they need to be fine-tuned to the environments they survey. That is why they are used in pairs, with one unit collecting data in deeper water, while the other has a filter that allows it to work well in shallower regions where light levels are much brighter. In the first half of the NA139 expedition, *Mesobot* radiometers were used as passive sensors, continually collecting light data that could then be cross referenced to video and eDNA samples collected on the same dive.

As the expedition progressed, the team began to use the radiometers in a more active manner to direct *Mesobot*, as it can be programmed to move vertically to follow a constant light level, also known as an isolume. Midway through the

Mesobot is ready to be lifted from the pier in Honolulu prior to the multi-vehicle expedition aboard E/V *Nautilus*.



E/V *Nautilus* scientists and crew deploy *Mesobot* for a midwater survey.

cruise, we attempted to follow a dawn isolume. We first deployed *Mesobot* at a relatively shallow depth before dawn so that it could latch onto that light level, and then *Mesobot* descended through the water column to follow that light level as the sun rose. The attempt was successful, as *Mesobot* started to follow the isolume at about 100 m depth, with the moon still above the horizon. The vehicle rose slightly as the moon set, and then as the sun rose, it slowly descended until settling at a depth of 470 m a couple of hours later. Plotted over time, *Mesobot*'s motion draws a curve very much like the one known for vertically migrating species.

For the remainder of the expedition, we continued to follow dawn and dusk isolumes. To this end, we first had to adjust the gain setting to reduce lag and more tightly regulate isolume-following behavior. Next, we attempted—with good success—a simultaneous isolume follow with a camera survey. The inherent challenge here is that cameras require lights that would blind the radiometers. The way around this was to alternate between active isolume following and camera usage. When the cameras were on, *Mesobot* was no longer driven by the radiometers. Instead, its trajectory was controlled by interpolating previously collected light data. Once the camera survey ended and the camera lights were turned off, the radiometers once again took over to drive the vehicle based on detected light levels. This is an exciting new ability that we look forward to improve, and thereby increase, the time available for camera surveys.

Mesobot can carry up to three multisampler units, each of which can collect 16 eDNA samples. These samplers filter the water in situ, rather than bringing the water to the surface for filtration. In contrast to traditional forms of surveying pelagic biodiversity, eDNA sampling increases the chance of detecting fast-moving fish or other species that may avoid net tows or camera surveys.

Because animal distributions in the water column are patchy, determining where to collect eDNA samples is critical. The location of water column biomass can be informed by shipboard EK80 echosounders. However, because *Mesobot* must stay 200–1,000 m from its support vessel (to stay within communication range and avoid collisions due to an unexpected ascent), there is uncertainty regarding whether information gathered by the shipboard EK80 sonar is the same as the environment that *Mesobot* is surveying. We were able to solve this major issue during the multi-vehicle expedition for the first time by using the EK80 sounder mounted on *DriX* and positioning *DriX* directly above *Mesobot* to enable targeted sampling. This was a major accomplishment of the mission—it highlights the value of using complementary technologies to overcome some of the limitations of ship-based ocean exploration.

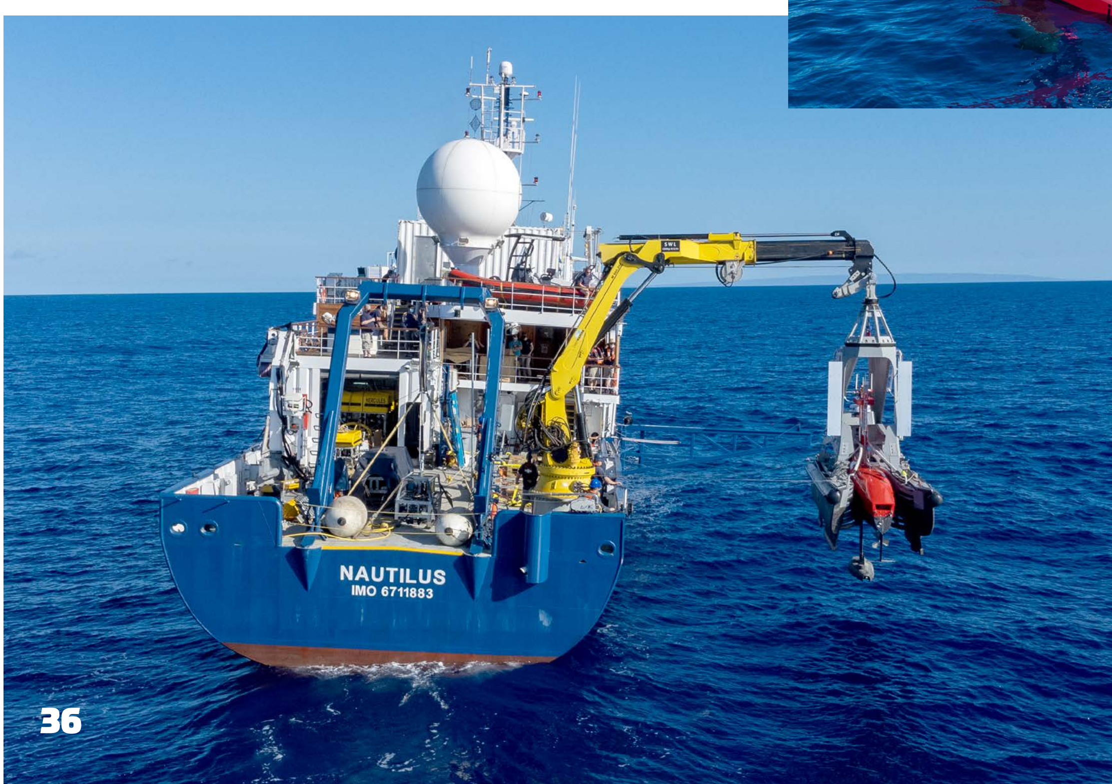
DriX Operations from E/V *Nautilus*

By Larry Mayer and Val Schmidt

The integration of the University of New Hampshire's uncrewed surface vehicle *DriX* into E/V *Nautilus* operations during the 2022 field season represents a major technological advance, heralding a new era of more efficient mapping and exploration. The 7.7 m vehicle has a slim wave-piercing composite hull, a deep keel, and a gondola that allows it to collect high-quality seafloor and water column mapping data at high speed in relatively rough seas. These characteristics led to the selection of the iXblue (now exail) *DriX* to support the Ocean Exploration Cooperative Institute's (OECI's) offshore exploration activities with specific focus on expanding the mapping and exploration footprint of the mother vessel. The field season started with a shakedown cruise during which *DriX*, its launch and recovery system (the Universal Deployment System, or UDS), and a new crane were installed on *Nautilus* and put through a series of engineering trials. Launching and recovering *DriX* and the UDS were practiced until perfected, and time was well spent on training exercises, efforts that helped assure the success of future operational expeditions (Figure 1).

DriX was once again deployed on NA139 in May 2022, an ambitious technology challenge aimed at developing new exploration approaches that use multiple autonomous vehicles in a collaborative way. Working in collaboration with the Woods Hole Oceanographic Institution AUVs *Mesobot* and *Nereid Under Ice* (*NUI*), the *DriX* team used an ultra-short baseline navigation system onboard *DriX* to precisely determine the position of the AUVs. *DriX* relayed high-resolution position information of all of the vehicles to E/V *Nautilus* in real time. Behaviors were developed that allowed *DriX* to travel at high speed and circle above the slower-moving AUVs while maintaining position directly above them. Computer displays were configured to allow operators on *Nautilus* full situational awareness of the locations of all vehicles as well as *Nautilus* (Figure 2). Once tracking and positioning issues were solved, the teams worked together to provide full two-way acoustic communications between *DriX* and the two AUVs. With this newly developed system, commands could be sent to the vehicles, directing them to change behaviors (e.g., speed or direction) and to move to particular depths. Commands could also be sent to initiate actions like opening and closing the environmental DNA (eDNA) samplers on *Mesobot* or initiating a high-resolution seafloor survey by *NUI*.

FIGURE 1. *DriX* is recovered via the E/V *Nautilus* Universal Deployment System.



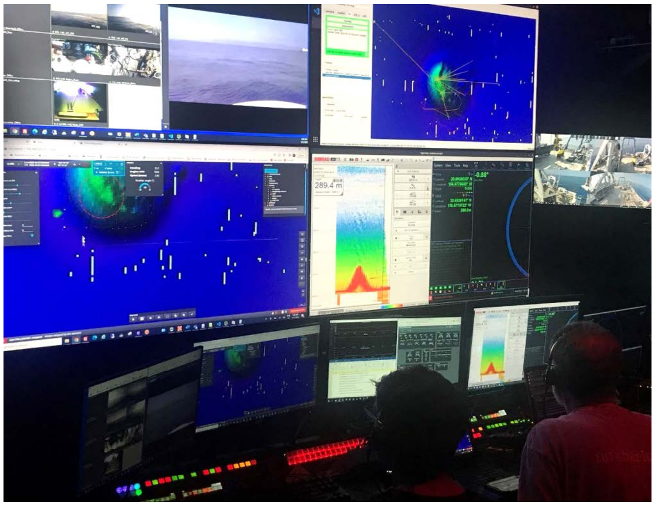
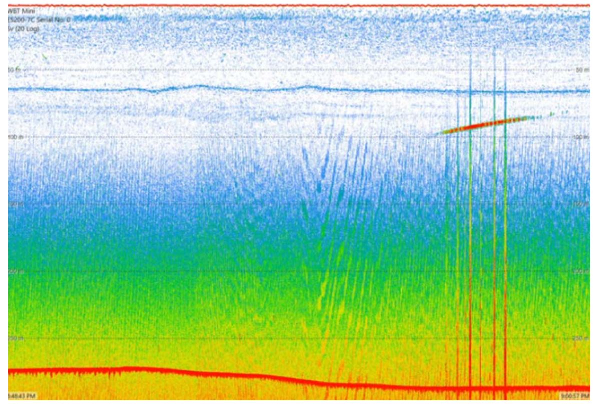


FIGURE 2. Real-time display of position and status information from USV *DriX*, E/V *Nautilus*, and AUVs *Mesobot* and *Nereid Under Ice* was available to operators onboard *Nautilus*.

FIGURE 3. As seen by operators on E/V *Nautilus*, *Mesobot* approaches a layer designated for sampling.



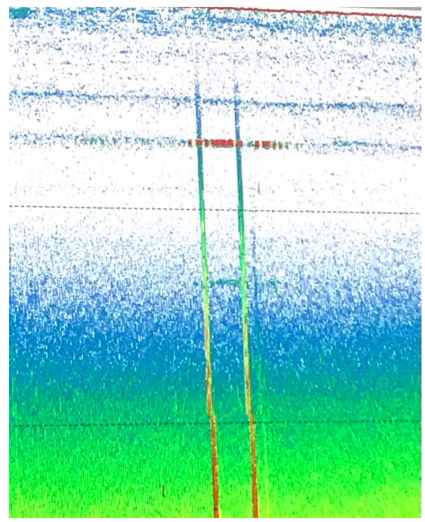


FIGURE 4. *Mesobot* is located precisely in the layer to be sampled.

The power of this sort of multi-vehicle collaboration became very clear as *Mesobot* set out on a mission to sample midwater layers for eDNA where there were high concentrations of biological organisms. Normally, *Mesobot*'s missions are pre-planned to travel and sample at set depths and times based on information derived from earlier surveys of the water column. With *DriX* circling above *Mesobot*, researchers aboard *Nautilus* were able to receive real-time imagery of the structure of the water column from a *DriX* EK80 fisheries echosounder whose data were transmitted via broadband radio to *Nautilus*. In addition, *Mesobot's* real-time profiles of water column properties were transmitted to the ship. With a clear picture of the structure of the water column below *DriX*, researchers sent commands via *DriX* directing *Mesobot* precisely to the layer to be sampled. On *Nautilus* we were able to watch in real time as Mesobot entered the layer, and verify that it sampled precisely within the desired feature (Figures 3 and 4). This capability opens a new world of directed verified sampling, removing ambiguity about whether collected samples came from the feature of interest that they intended to survey. *Mesobot*'s real-time displays also allow us to address concerns about sampling bias by avoiding disturbing organisms as *Mesobot* enters the layer.

By the end of the expedition, we were able to operate *DriX*, *Mesobot*, and *NUI* simultaneously; direct the AUVs to targets detected by *DriX*; and control their behavior via *DriX* while *Nautilus* was free to carry on its own activities within the approximately 14–20 km limit of our broadband marine radio (depending on atmospheric conditions), independent of the autonomous vehicles. With this very successful expedition, we demonstrated that we can now simultaneously conduct multiple exploration missions from a single mothership and explore the seafloor, the midwater, and the sea surface all at once—a critical step forward in advancing the efficiency of ocean exploration.

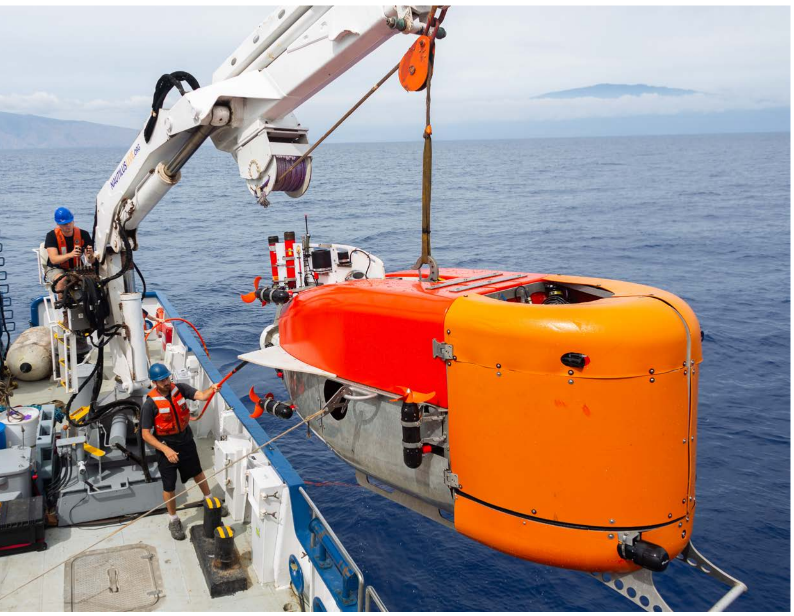
Funded by NOAA's Office of Coast Survey, NA142 in July and August brought E/V *Nautilus* and *DriX* to the waters around the remote Nihoa Island in the Northwestern Hawaiian Islands to explore the potential role of uncrewed vehicles as a force multiplier for shallow-water mapping. Rough weather conditions initially prevented the launch of *DriX* (as it would have also prevented the deployment of a manned hydrographic launch), but the long endurance and high transit speed of *DriX* allowed us to steam ~120 nm back to the protection of Kauai, launch the vehicle there, and then steam back to Nihoa with enough endurance to still carry on a sustained high-quality survey in rough weather. Independent mapping activities were conducted by the *DriX* and *Nautilus* teams, once again demonstrating the potential gained efficiencies of working with uncrewed vessels. These expeditions have clearly demonstrated the great potential of uncrewed vehicles—and we look forward to further advances and expanded capabilities in expeditions to come.

Nereid Under Ice Operations from E/V *Nautilus*

By Molly Curran and Michael Jakuba

In May 2022, Woods Hole Oceanographic Institution's hybrid submersible *Nereid Under Ice* (*NUI*) was mobilized aboard E/V *Nautilus* along with two other robotic systems, Woods Hole's autonomous underwater vehicle *Mesobot* and University of New Hampshire's uncrewed surface vehicle *DriX*. The ship set sail for a two-week expedition (NA139) on which *NUI* completed 11 dives, successfully demonstrating multi-vehicle coordination, co-exploration, remote operations, and advanced vehicle functionality.

NUI was interoperated with *DriX* and *Mesobot* separately and with both vehicles simultaneously. We used *DriX* as a tender vehicle and relay between *NUI* and *Nautilus* in order to provide acoustic navigational aid for the vehicle. We also communicated vehicle integrated command downlink as well as vehicle state, scalar data, multibeam, and imagery uplink. We utilized *NUI*'s unique capability of being able to operate as either an ROV or AUV. After operating *NUI* as an ROV, we switched to AUV mode, with *DriX* serving as tender when the ship needed to maneuver to recover *Mesobot*.



Nereid Under Ice (*NUI*) is shown being deployed from E/V *Nautilus* during the 2022 technology integration expedition (NA139).

NUI is in the water and *Mesobot* (yellow top) and *DriX* (red vehicle at left) are secured aboard ship, all prepared for collaborative operation during the 2022 E/V *Nautilus* technology integration expedition.

NUI next to E/V *Nautilus* during the 2022 technology integration expedition.

Another accomplishment of the mission was successful co-exploration, which combined human and robotic exploration in a tightly coupled system to achieve results neither could accomplish alone. In this expedition, co-exploration enabled live operator oversight of the mission and real-time access to survey data to efficiently request data over low-throughput acoustic links in areas of interest. The team used co-exploration bathymetric data transfer to locate targets and complete a camera survey with progressive imagery—a nested search in a single dive that would traditionally take a vehicle multiple dives to accomplish. Additionally, we demonstrated we could control and monitor *NUI* via a robot operating system (ROS) package that transports messages across an acoustic link (ros_acomms). We used this approach in parallel with co-exploration, enabling co-exploration to be run using the same acoustic pathway.

The *NUI* team also successfully demonstrated remote operations that involved remote diagnostics with an augmented reality headset, hardware and software creation and implementation of a virtual private network suitable for vehicle interaction, and network latency measurements. Lastly, we made progressive steps in vehicle functionality that involved long-range acoustic communications and long-range teleoperation. For our long-range dive, *DriX* tended *NUI*, demonstrating the potential for carrying out operations at distances dramatically farther from the ship than is possible with a conventional ROV. These important accomplishments of the mission highlight the value of using multiple complementary exploration technologies to enable the force-multiplier of autonomy.

From Shore to the Abyss

Exploration of Marine Mammal Communication, Shark Communities, Maritime Heritage, and Microplastic Pollution in the Main Hawaiian Islands

By Daniel Wagner, Matthias Hoffman-Kuhnt, Ariana Agustines, Rachael Z. Miller, Justin Dunnavant, Jason T. Raupp, Allison Fundis, Ian Miller, and Teresa Leonardo

In 2022, the National Geographic Society and the Ocean Exploration Trust initiated a partnership focused on the scientific exploration of shallow-water habitats. Between September 1 and October 24, E/V *Nautilus* conducted three back-to-back expeditions as part of the From Shore to the Abyss program (Figure 1). These expeditions focused on nearshore surveys around the islands of Maui, Lānaʻi, and Hawaiʻi to study marine mammal communication and soundscapes, shark communities, microplastic pollution, and maritime heritage. During 35 combined days at sea, these expeditions successfully completed 116 scuba and 40 small boat surveys to support these field studies.

MAMMAL COMMUNICATION AND SOUNDSCAPES

The marine mammal team conducted two field research projects while onboard *Nautilus*. One project executed targeted surveys of marine mammal communication using a hand-held array that simultaneously collected video and multichannel audio data (Figure 2a), while the second project conducted general soundscape surveys via hydrophone arrays that were mounted on the seafloor for up to 36 hours. The team covered a total distance of 600 km using the *Nautilus* small boat to conduct 12 targeted mammal communication surveys and collect a total 342 gigabytes of data using the hand-held array. Communication behaviors of schools of Hawaiian spinner dolphins (*Stenella longirostris*; (Figure 2b) and bottlenose dolphins (*Tursiops truncatus*) were documented during these surveys, which marked the first time these species were recorded with this hand-held device in Hawaiian waters. Additionally, the team deployed bottom-mounted hydrophones at five locations to depths of 25 m and recorded a total of 315 gigabytes of acoustic data across 115 hours. One of the key successes of these projects was fine-tuning the methodologies for using both of these devices, which will allow for future studies on the location and movement of vocalizing marine animals.

SHARK COMMUNITIES

During 74 successful deployments of baited remote underwater video (BRUV) cameras to depths of 2–200 m, the shark project team surveyed shark communities for a total of 89 hours at 21 sites across the islands of Maui and Hawaiʻi (Figure 3a). BRUVs documented three different shark species, including grey reef shark (*Carcharhinus amblyrhynchos*), sandbar shark (*Carcharhinus plumbeus*), and Galápagos shark (*Carcharhinus galapagensis*; Figure 3b), all exclusively documented at depths greater than 80 m on *Halimeda*

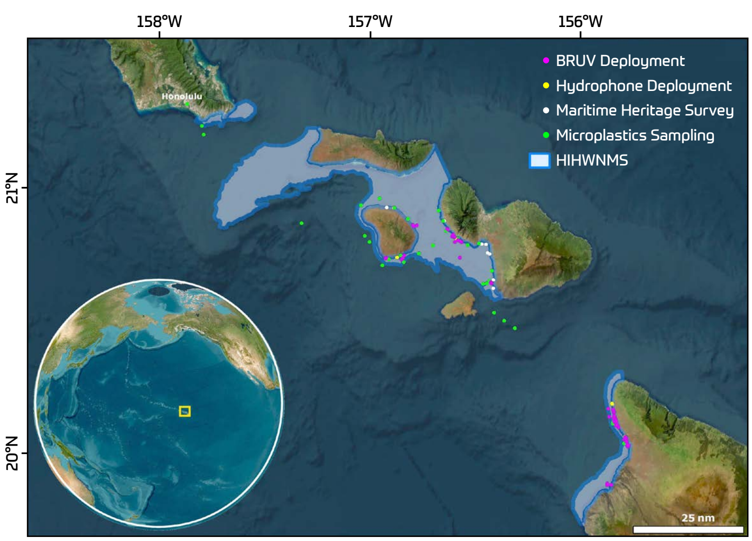


FIGURE 1. Map showing the locations of field operations conducted during the three E/V *Nautilus* expeditions funded by the National Geographic Society in support of the new From Shore to the Abyss program. The majority of these field surveys occurred within the Hawaiian Islands Humpback Whales National Marine Sanctuary (HIHWNMS).

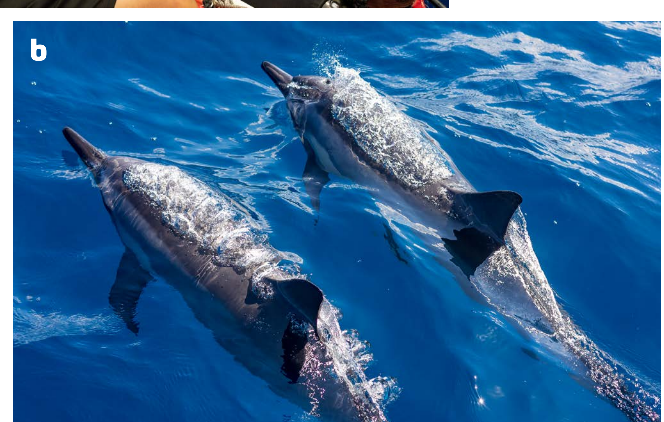


FIGURE 2. (a) A snorkeler receives a hand-held device to use in a survey of marine mammal communications. (b) Spinner dolphins were surveyed as part of this study.

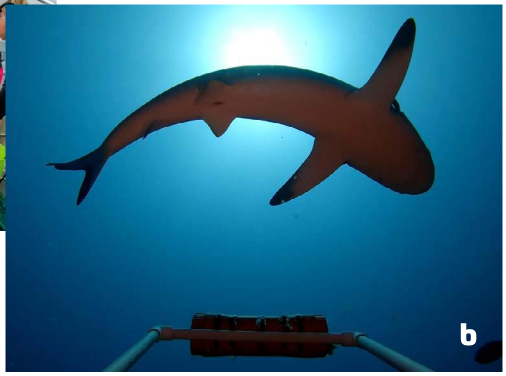


FIGURE 3. (a) A baited remote underwater video (BRUV) is deployed from a small boat. (b) This Galápagos shark was recorded using a BRUV.

FIGURE 4. A researcher analyzes a slide of microplastics collected from surface water.

algal beds, rubble, or sand habitats. Video recordings with imaged sharks were processed using a new artificial intelligence tool to assess its machine learning capabilities for identifying shark species. In addition to video data, the team collected 82 eDNA seawater samples at BRUV deployment sites to cross-reference video records.

MICROPLASTICS

While the Hawaiian Archipelago, the northwest in particular, is a known sink for marine debris and derelict fishing gear, less is known about the smallest marine debris, microplastics. While onboard *Nautilus*, the microplastics project team investigated the presence of microplastics and anthropogenic microfibers suspended in the air and in surface water. A total of 35 sites were surveyed, primarily around Maui and Lānaʻi, with a few additional surveys off the Big Island and Oʻahu. At each location, the team collected 3 × 1 liter surface seawater samples and ran an air pump for 30 minutes at 10 liters per minute. In addition, atmospheric deposition buckets were placed on the bow and on an elevated observation deck aboard *Nautilus*. Samples were vacuum filtered, transferred to glass slides using Easy Lift tape, and analyzed under polarized light microscopy (Figure 4). Preliminary results indicate the presence of synthetic and anthropogenic particles, primarily fibers, in low numbers in all collected samples.

MARITIME HERITAGE

The maritime heritage project team surveyed 11 archaeological sites during the last of the From Shore to the Abyss expeditions. These included the remains of aircraft, amphibious assault vehicles, and moorings associated with World War II on the west shore of Maui; lost cargo and tanker ships along the north shore of Lānaʻi; and a historically significant whaleboat housed at the old Lahaina Prison on Maui. Maritime heritage sites were each filmed with GoPro 4K video cameras, and nearly 50,000 still images were extracted from this film at two-second intervals. The still images were processed using Agisoft Metashape software to create high-resolution, three-dimensional photogrammetric models that document the state of preservation of each site (Figure 5), enabling future studies to assess changes over time. These models are not only invaluable to archaeologists and resource managers for assessing site conditions and potential impacts, but also constitute vital education and outreach tools that connect public audiences to our past.

CONCLUSION

The From Shore to the Abyss expeditions marked the inaugural year of what will hopefully become a long-standing collaboration to conduct at-sea expeditions that bring together the complementary capabilities of the National Geographic Society and the Ocean Exploration Trust, particularly the ability to engage a broad spectrum of the exploration community—including early career and highly accomplished explorers, local community collaborators, storytellers, and educators. In addition to the science accomplishments, the 2022 From Shore to the Abyss expeditions provided numerous education and outreach activities, including 169 live ship-to-shore interactions, 60 social media posts, 16 website stories, seven live panel events, five original video productions, and four Explorer Classroom events. Over the course of the three expeditions, live stream video feeds received over 63,000 views, highlight videos garnered 44,000 views, and live events reached another 40,000 learners in 27 US states and six other countries.

FIGURE 5. This three-dimensional photogrammetric model images the F6F Hellcat site located in Maalaea Bay, Maui.

Data System Upgrades on E/V *Nautilus*

By Matt Koskela, Timothy Burbank, and Julian Race

A major goal of E/V *Nautilus* expeditions is to provide a rich foundation of publicly accessible data to catalyze follow-on investigations. Post-expedition, collected data are submitted to Rolling Deck to Repository and the Marine Geoscience Data System, which provide gateways through which data are also cataloged in NOAA's National Centers for Environmental Information. ROV video is uploaded to the Nautilus Live YouTube channel and made available to the world. To make all of this happen, *Nautilus* is equipped with an intricate data system, which was upgraded substantially during the last year.

The *Nautilus* data systems facilitate real-time science operations, perform post-processing, and archive data products. Real-time navigation and sensor data must be passed to the ROVs and mapping systems, as well as any guest vehicles. Those data are transmitted alongside live video to participants on shore and to public audiences. Automated processes convert the raw sensor output to analysis-ready products, while the team on board manually processes and reports on the data using the onboard computing infrastructure. All raw and processed products are collected to centralized storage, and identical copies are written to a redundant set of hard drives that are archived and delivered to the lead scientists at the end of each expedition.

Over the past two years, the Ocean Exploration Trust has made substantial infrastructure and process upgrades to keep our data services robust and aligned with modern standards. In concert with the commissioning of our new control vans, we installed an all new fiber-optic backbone connecting *Nautilus*'s rack room with the control vans and other key areas of the ship (Figure 1). We migrated the multiple physical networks to virtual local area networks (VLANs), consolidated a number of legacy computers by virtualizing the onboard server infrastructure, and added a next generation firewall to manage bandwidth for the entire ship to our satellite uplink (Figure 2).

VLANs allow each port of a network access switch to be configured for a specific network. Traffic over the trunk connection between switches is tagged with a VLAN ID for each network and then separated out by the receiving switch. Physical devices connected to the switches still appear as if they were on separate networks, but the virtualized networking reduces the amount of cabling and the quantity of physical switches required.

This new architecture has been implemented to improve security and reliability by separating devices with specific requirements onto their own networks. Virtualized networking allows new networks to be added for guest vehicles—isolating the vehicles to their own VLANs (and

FIGURE 1. An all new fiberoptic backbone connects E/V *Nautilus*'s rack room with the control vans and other key areas of the ship.

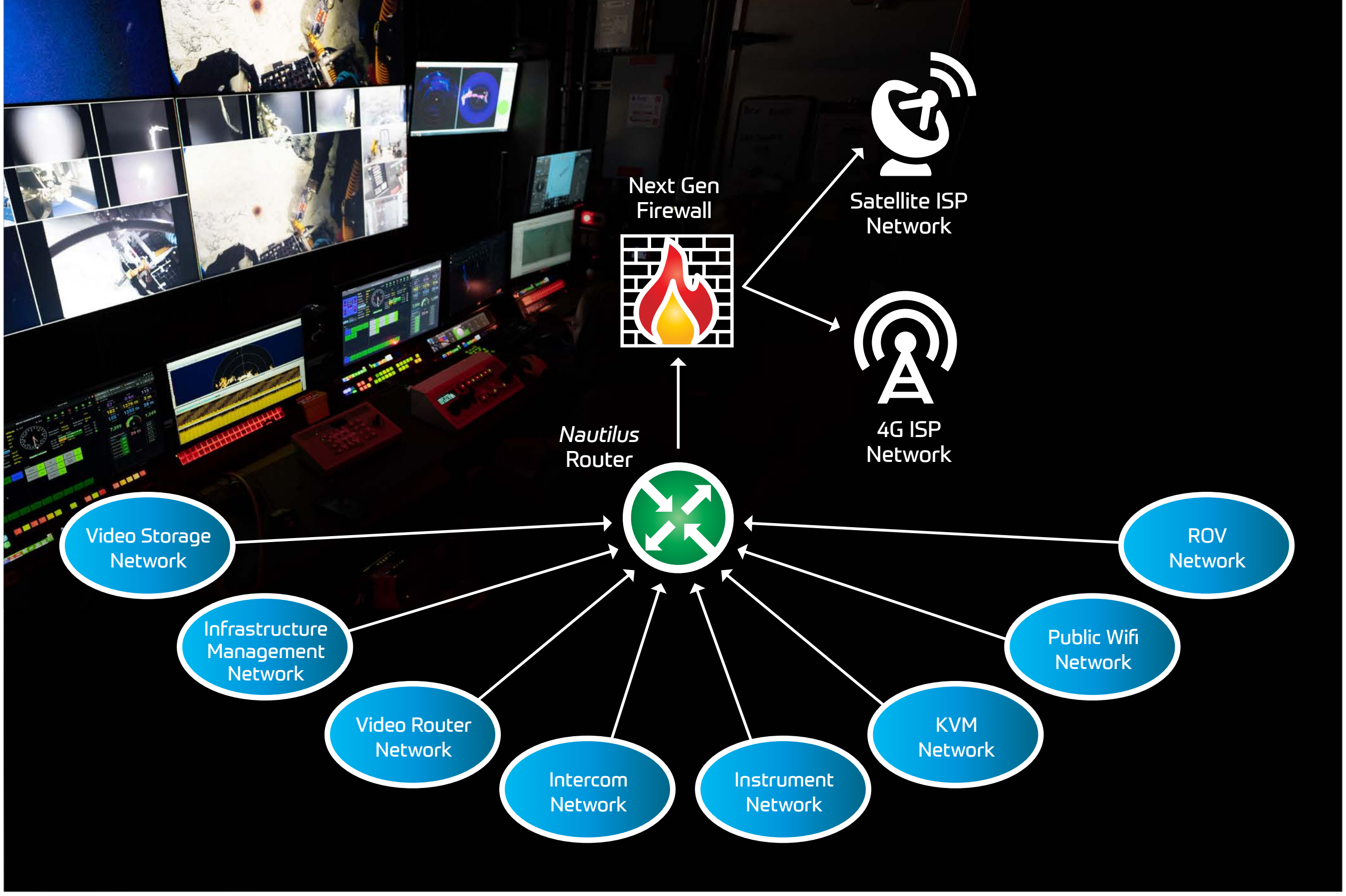


FIGURE 2. Diagram of the new data system architecture implemented to improve security and reliability.

subsequently their own IP address range), while enabling routing within the aggregation infrastructure so that navigation data can be shared to the vehicles and mission-generated vehicle data can be ingested into file servers for a more comprehensive data package delivery.

With this higher level of network agility, the *Nautilus* team is able to support multiple varying pieces of instrumentation in addition to multiple guest vehicles at any given time, often simultaneously. The approach further allows *Nautilus* to be operated alone, without the control vans should they be removed and installed on a vessel of opportunity in the future. Without needing to employ more or different network switches, existing access switches may be reconfigured through software to assign specific ports to the desired VLAN, and equipment can be connected to switches of convenience rather than unique stand-alone switches.

Another significant transition has been the widespread adoption of virtual machines. We have migrated many of our legacy aggregation processes into their own purpose-specific virtual environments, managed by a hypervisor running on a robust server. This architecture is redundant, employing two identical so-called "core servers" that each have the ability to run any or all required processes on board. They also have the ability to load balance by running some processes on one server with the remainder on the other. Doing so allows us to migrate the individual virtual machines from one core server to the other as needed, maximizing up time for mission-critical processes and allowing for necessary routine maintenance without interfering with operations.

To optimize use of our limited connectivity bandwidth at sea, we have added a redundant pair of Fortigate next generation firewall appliances as the gateway between the internal *Nautilus* networks and the public internet. Where previous systems could limit connections per device or network, and route to a single outgoing connection, the next generation devices can allocate bandwidth per application and dynamically route to multiple outgoing connections. This configuration ensures optimal performance of mission-critical services (i.e., live video, teleconferencing, science data transfers) without limiting other processes that run in the background, and it can be expanded to use remaining available bandwidth. It also allows multiple internet connections to be combined—VSAT when offshore, 4G nearshore, hardwired in port—and lays the groundwork for integrating higher bandwidth, lower latency, near-Earth orbit systems when they become available.

Through strategic system hardware upgrades and network architecture changes, network management on *Nautilus* has been simplified while providing more capable and more flexible resources to our users. As our operations continue to evolve and diversify, we are well positioned to continue providing excellent data products for years to come.

Recent Upgrades to E/V *Nautilus*'s Video Products

By Ed McNichol and Dave Robertson

The *Nautilus* Exploration Program is perhaps best known for the spectacular imagery that is collected on every ROV dive. This high-resolution imagery provides not only a powerful tool for connecting the public with remote locations in the deep sea, but it is also an invaluable asset for scientists in their quest to learn more about the largest and least explored parts of our planet (Figure 1). During the 2022 field season, the Ocean Exploration Trust completed a series of upgrades to its standard video products in order to continue improving the user experience of the many members of the scientific community who use E/V *Nautilus* video data.

As part of upgrades to the file-based workflow, media content is now recorded directly to an internal solid state drive (SSD) pool on two Cinedeck ZX85 recorders. At the conclusion of every ROV dive, the onboard video engineer performs the following steps to verify data integrity and ensure that files are accurately archived:

- An MD5 checksum is computed for each created video file and written to a sidecar file.
- Video files are then copied to network-attached storage (NAS) arrays, and an additional checksum is computed for each copied video file.
- The original and copied checksum files are compared to one another to ensure that the copy operation was 100% accurate; checksum reports are generated and saved.
- Once all files are transferred to the linear tape-open (LTO) data storage for permanent archiving, video files are deleted from the SSD pools to free up space prior to the next ROV dive.

In addition to completing the workflow upgrades described above to ensure that data are accurately transferred to permanent archives in 2022, we changed the way video files are named and organized in order to make it easier to locate files of interest. Specific changes made to the file structure schema and names include (Figure 2):

- Parent folder names are now included in the name of each subfolder.
- Each folder and subfolder name now includes the code of the expedition (e.g., NA141), dive number (e.g., H1926), vehicle (e.g., ARGUS), and video resolution (e.g., ProRes).
- Individual file names include all the information listed above, in addition to a timestamp and sequential four-digit serialized number to make it easier to sort individual files.

We hope that these recent upgrades will provide improved discoverability and usability of the large volumes of video data that are produced on every *Nautilus* expedition, but we will continue soliciting feedback from our partners to ensure that our products meet the needs of the scientific community.

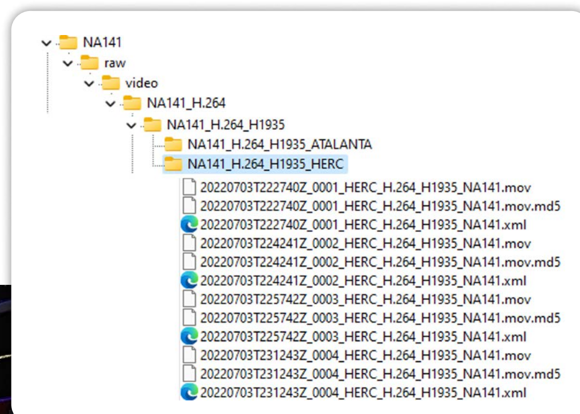


FIGURE 2. The upgraded file name structure implemented during the 2022 field season.

FIGURE 1. Video engineer Dave Robertson works in the control van aboard E/V *Nautilus*.

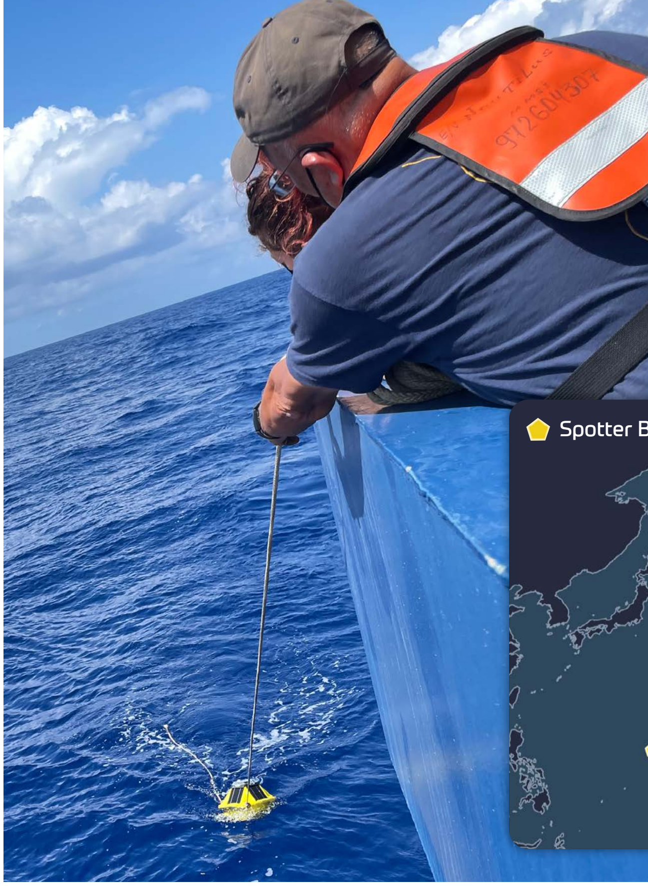


FIGURE 1. A Spotter buoy is deployed from E/V *Nautilus* during a 2022 expedition to Johnston Atoll.

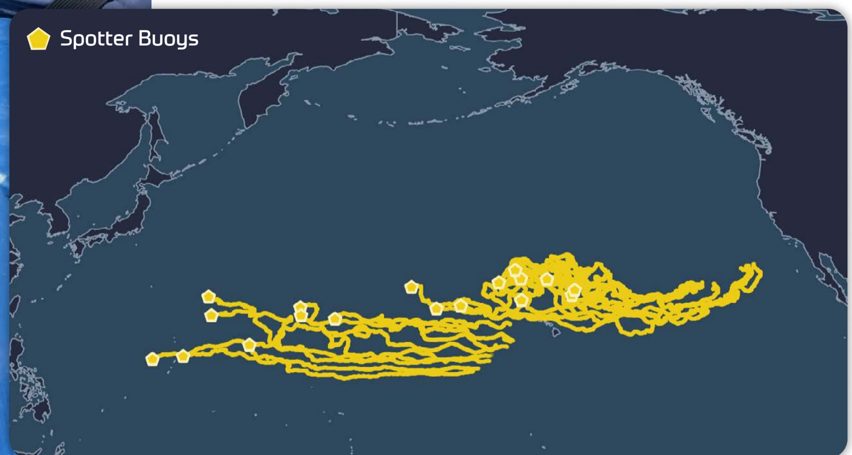


FIGURE 2. Drift tracks of Sofar Spotter buoys (yellow pentagons) deployed from E/V *Nautilus* in 2021 (the 10 easternmost buoys) and 2022 (the eight westernmost buoys).

Ocean Exploration Trust Deploys Sofar Ocean's Smart Buoys in the Pacific to Fill Gaps in Marine Weather Data

By Brendan Crowley

BUILDING A PARTNERSHIP AROUND OCEAN EXPLORATION AND PUBLICLY ACCESSIBLE DATA

The Ocean Exploration Trust (OET) and Sofar Ocean first joined forces in 2019, when E/V *Nautilus* deployed three Spotter smart buoys during a voyage to American Samoa. The basketball-sized buoys—which are solar-powered and drift freely with ocean currents—collect wave, wind, sea surface temperature, and barometric pressure data (Figure 1). In the open ocean, these data are transmitted via satellite; near the shore, data are sent via cellular connection.

OET and Sofar's partnership formed around two common goals: to increase understanding of unexplored areas of ocean and to expand access to ocean data. OET's mission is to explore unknown portions of our ocean and to make the data and discoveries publicly available in order to stimulate further exploration, research, and management activities. Similarly, Sofar seeks to fill the large knowledge gaps that exist in ocean research and to make its data available to enable better decisions about our environment.

EXPANDING THE SCOPE OF SPOTTER BUOY DEPLOYMENTS IN THE PACIFIC OCEAN

OET and Sofar grew their partnership in 2021 and 2022. In October 2021, E/V *Nautilus* deployed several Spotters during a seafloor mapping expedition from San Pedro, California, to Honolulu, Hawaiʻi. The buoys have now drifted across the Pacific Ocean for over a year (Figure 2). In spring and summer 2022, additional Spotters were deployed from *Nautilus* during two voyages to Johnston Atoll. The goal of the expeditions was to explore unknown deep-water areas in the region and establish a baseline of subsurface insights. The deployment of buoys on these expeditions added important sea surface environmental data to the mission.

The single biggest challenge for ocean weather and climate forecasting is the great sparsity of observations. Sofar welcomes the opportunity to work with partners like the OET to help the company expand its global network of ocean sensors, rapidly increase real-time data density across the ocean basins, and contribute to a more sustainable future.

Providing a Foundation for Follow-On Investigations

Sample Archives at the Museum of Comparative Zoology and the Marine Geological Samples Laboratory

By Adam J. Baldinger, Katherine A. Kelley, and Daniel Wagner

A major goal of E/V *Nautilus* expeditions is to explore the ocean in order to provide a rich foundation of publicly accessible data to stimulate follow-on exploration, research, and management activities. To this end, the Ocean Exploration Trust has been partnering with the Museum of Comparative Zoology at Harvard University and the Marine Geological Samples Laboratory at the University of Rhode Island to permanently curate biological and geological samples, respectively, that are collected on *Nautilus* expeditions, as well as to make these samples available to qualified researchers around the world.

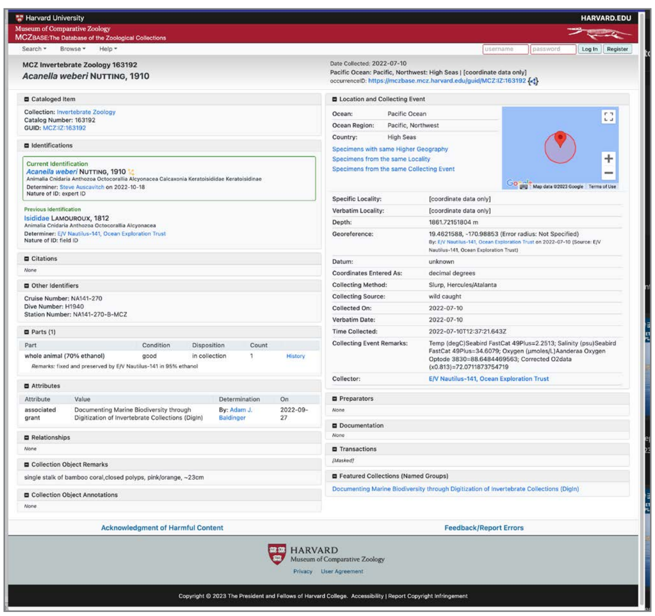


FIGURE 1. MCZ 163192 *Acanella weberi* Nutting, 1910 in MCZbase. Specimen collected from station NA141-270, dive H1940.

BIOLOGICAL SAMPLE COLLECTIONS AT THE MUSEUM OF COMPARATIVE ZOOLOGY

In 2022, metadata for 450 specimen lots from five expeditions were accessioned into the Invertebrate Zoology collections at the Museum of Comparative Zoology (MCZ). These specimen records are captured in the MCZ's museum-wide database (MCZbase) and are accessible to anyone with an internet connection (Figure 1). Records in MCZbase are also accessible through several data aggregators such as iDigBio, GBIF, and GenBank. A "Named Group" page associated with MCZbase was established this year to enable public access to information about specimens collected from E/V *Nautilus*. This Named Group site lists specimen records, including searchable links by taxa, geography, ocean regions, expedition numbers, images, videos, collectors, and specimens cited in scientific publications. Of specific interest this year was the arrival to the museum of a sea pen in the genus *Solumbellula* (MCZ IZ 163196; Figure 2). Not only is this specimen the first record in the Pacific, it is also the only representative specimen sample in the museum.

FIGURE 2. (a) *Solumbellula* specimen photographed in situ from E/V *Nautilus* at station NA141-241, dive H1938. (b) *Solumbellula* (MCZ IZ 163196) specimen on shelf within the Department of Invertebrate Zoology at the Museum of Comparative Zoology, Harvard University (©President and Fellows of Harvard College).

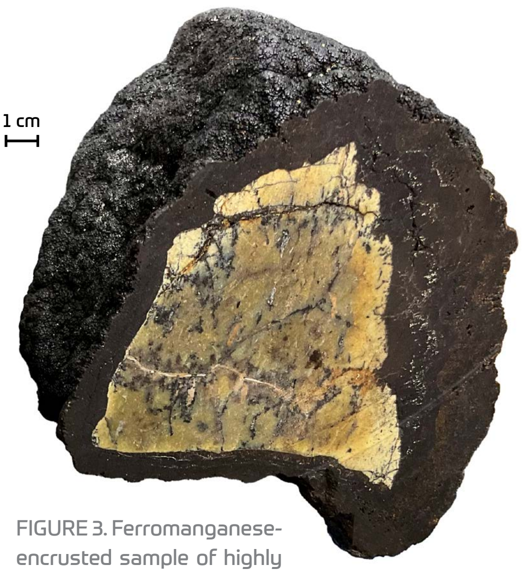


FIGURE 3. Ferromanganese-encrusted sample of highly weathered submarine lava (NA141-064).

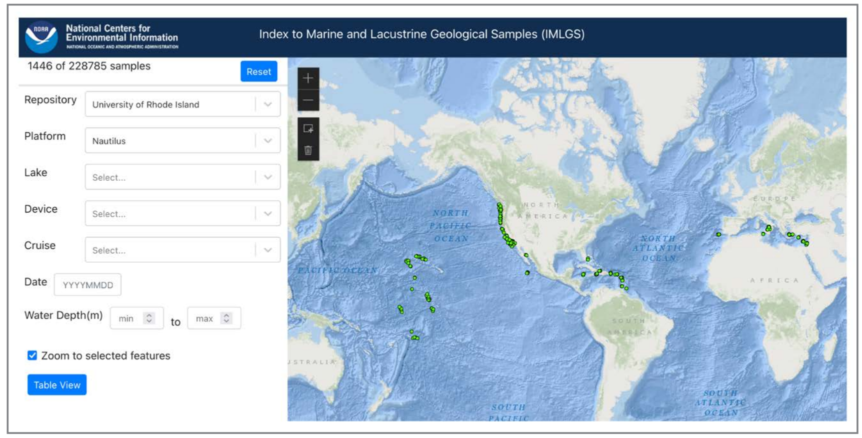


FIGURE 4. Screenshot of NOAA IMLGS web app map interface, filtered to show current *Nautilus* sample listings at the Marine Geological Samples Laboratory.

All specimens are available to researchers for more detailed study by either visiting the museum or requesting that specimens be sent out on loan. Nearly all of the invertebrate specimens received from *Nautilus* complement existing projects, including the National Science Foundation (NSF)-funded grant Documenting Marine Biodiversity through Digitization of Invertebrate Collections. Since 2013, voucher specimens from 44 *Nautilus* expeditions representing 3,986 specimen lots can be found in three MCZ departments (Invertebrate Zoology, Malacology, and Ichthyology).

GEOLOGY SAMPLE COLLECTIONS AT THE MARINE GEOLOGICAL SAMPLES LABORATORY

The Marine Geological Samples Laboratory (MGSL) is an open-access sample repository funded by NSF that houses 15,000+ samples of dredged rocks, marine sediment cores, and ROV-collected materials from global ocean basins. In 2022, the MGSL accessioned 221 grab samples and push cores collected by ROV *Hercules*. Sample ingestion typically involves cutting rock samples open to facilitate accurate descriptions of their internal characteristics. This step is particularly important with the kinds of samples collected on the 2022 expeditions, many of which are coated in ferromanganese crusts that obscure the rocks' identities (Figure 3). Push cores are typically kept unsplit to aid in their preservation, but facility staff will split cores for description and sampling upon request.

E/V *Nautilus* samples at MGSL are listed publicly at NOAA's Index of Marine and Lacustrine Geological Samples (Figure 4; https://maps.ngdc.noaa.gov/viewers/imlgs/samples) and are assigned International Generic Sample Numbers (IGSNs) through the System for Earth Sample Registration (SESAR; https://www.geosamples.org/), where sample metadata are also searchable and discoverable. Notable samples accessioned into the MGSL collections from the 2022 season include several ferromanganese crusts with bulbous, botryoidal surface textures, ancient lava samples that occasionally preserve pristine glass (Figure 5), and a tooth from a *Megalodon*, the largest shark that ever lived, now extinct for millions of years.

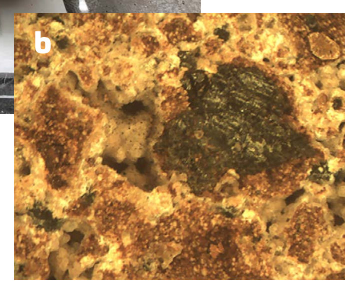


FIGURE 5. (a) Images of a lava sample (NA141-259) and a (b) microscopic view showing fresh glass (black) dispersed among highly oxidized, weathered lava (orange and yellow). Microscope close-up (field of view is ~3 mm).

Specimens at the MGSL are openly available for scientific study, and curatorial staff are available to assist with gathering the documentation and data needed for scientists to make an informed sample request. The MGSL facility welcomes visitors for sampling, education, and tours, and encourages requests for samples through the facility website (https://web.uri.edu/gso/research/marine-geological-samples-laboratory/).

2022 Science Publications from E/V *Nautilus* Expeditions

By Daniel Wagner

A major goal of E/V *Nautilus* expeditions is to provide a rich foundation of baseline information to enable follow-on exploration, research, and management activities. In addition to this annual supplement to *Oceanography*, a total of 28 science articles were published in 2022 that used data or samples collected by *Nautilus* in previous years. These publications cover a wide range of topics and scientific disciplines, thereby highlighting the highly interdisciplinary nature of OET's work.

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What is Next

By Allison Fundis, Daniel Wagner, and Robert D. Ballard

While E/V *Nautilus* expeditions in 2022 surveyed a wide range of habitats and geological features, vast areas across the US Pacific Island Region remain completely unexplored. Therefore, *Nautilus* expeditions in 2023 will return to many of these poorly surveyed regions to continue filling the large knowledge gaps that remain in US waters of the Central Pacific. This will include ROV and mapping explorations in Papahānaumokuākea Marine National Monument, as well as in the Johnston and Palmyra/Kingman Units of the Pacific Remote Islands Marine National Monument. Furthermore, in 2023 *Nautilus* will conduct dedicated seafloor mapping surveys in the US exclusive economic zone south of the Main Hawaiian Islands and also around Jarvis Island, where large seafloor areas remain unmapped.

In addition to basic exploration, 2023 expeditions will continue to support the integration of emerging exploration technologies into E/V *Nautilus* operations, particularly those from partner institutions of the Ocean Exploration Cooperative Institute. Building on the recent success of integrating USV *DriX* and AUV *Mesobot* into *Nautilus* operations, expeditions in 2023 will continue to expand the range and independence of these vehicles as they operate from *Nautilus*, and thereby seek to catalyze the force-multiplier of multi-vehicle exploration. In addition to *DriX* and *Mesobot*, 2023 expeditions will feature various other recently developed technologies, including the Deep Autonomous Profiler from the University of Rhode Island, the Hadal Water Column Profiler developed by the University of Hawaiʻi, a Raman spectrometer that will be mounted on ROV *Hercules* on select dives, and a multispectral mapping system to chart shallow-water habitats in collaboration with the University of Miami and the National Geographic Society.

In addition to these efforts aimed at advancing the goals of NOAA Ocean Exploration and the Ocean Exploration Cooperative Institute, the 2023 field season will include dedicated expeditions to support projects funded by Ocean Networks Canada and the Office of Naval Research. Building on the successful partnership with Ocean Networks Canada that started in 2015, E/V *Nautilus* will return to waters offshore British Columbia to provide maintenance and support for the Ocean Networks Canada cabled seafloor observatory that connects numerous oceanographic instruments across an 800 km loop. Tasks will include deploying various sensors and instruments, as well as conducting mapping and ROV surveys in select areas, such as the spectacular Endeavour hydrothermal vent field.

Finally, the 2023 season will also include a dedicated field survey funded by the Office of Naval Research. The expedition will bring *Nautilus* to the Main Hawaiian Islands and include the integration of a new wide-field camera array system into ROV operations, as well as the use of artificial intelligence software to quickly annotate video in near-real time.

As in previous years, partnerships will remain a centerpiece of OET's exploration efforts in 2023 and beyond. Building on long-standing collaborations with NOAA Ocean Exploration, Ocean Exploration Cooperative Institute, Office of Naval Research, Ocean Networks Canada, National Geographic Society, National Marine Sanctuary Foundation, Papahānamokuākea Marine National Monument, and many others, OET will continue exploring across the Pacific Ocean and meaningfully connect this work with audiences across the globe, particularly those from the geographies where E/V *Nautilus* will operate.

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