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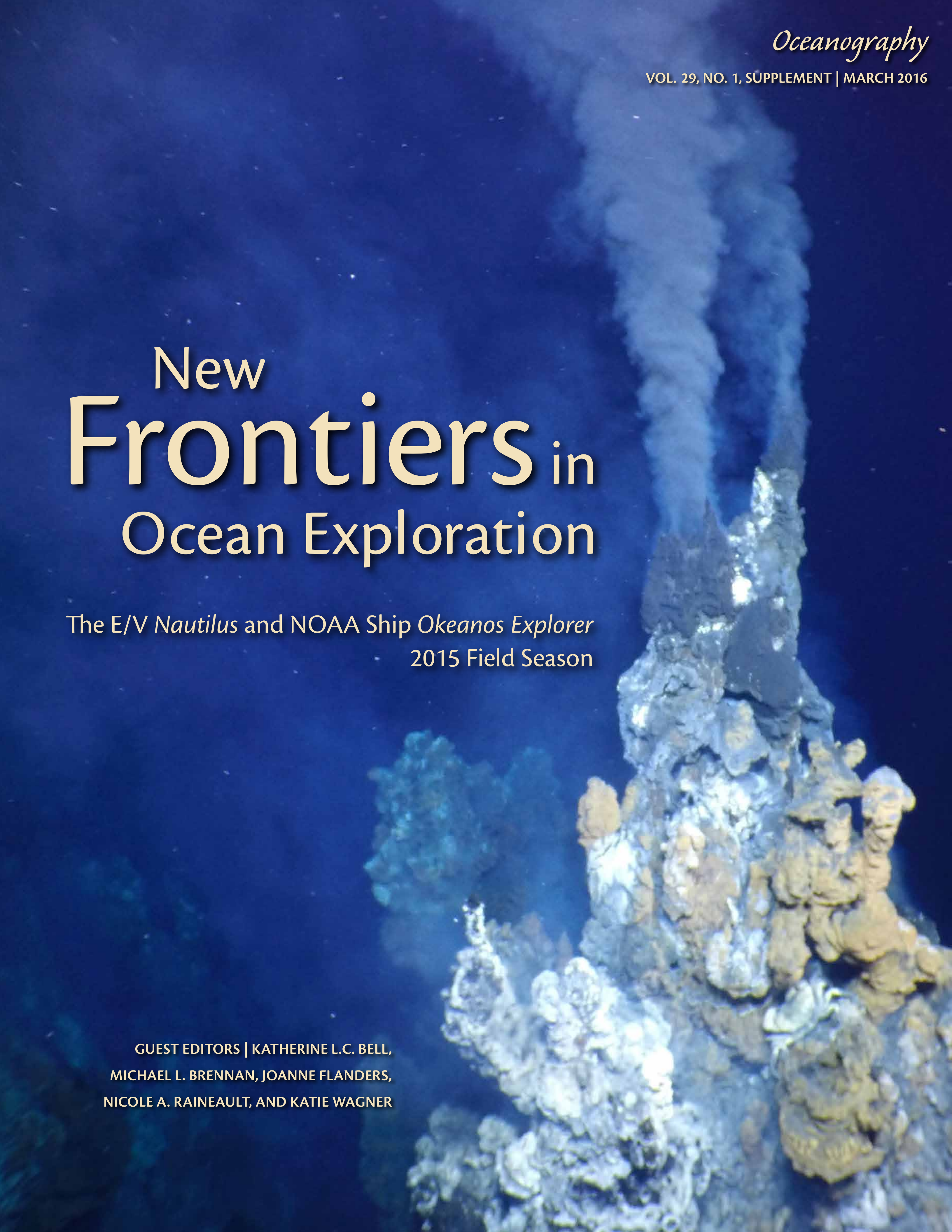

New Frontiers in Ocean Exploration

The E/V *Nautilus* and NOAA Ship *Okeanos Explorer* 2015 Field Season

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Cover photo credit: D. Fornari (Woods Hole Oceanographic Institution) and the Ocean Exploration Trust. Special thanks to C. Smart (University of Rhode Island)

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IMAGE CREDITS

Introduction

By Katherine L.C. Bell and John McDonough

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Fifteen years ago, the national ocean exploration program began with establishment of the National Oceanic and Atmospheric Administration (NOAA) Office of Ocean Exploration and Research (OER), based on recommendations from President Clinton's Panel on Ocean Exploration (2000). Since that time, two vessels have been dedicated to ocean exploration, NOAA Ship *Okeanos Explorer*, operated by OER, and Exploration Vessel (E/V) *Nautilus*, owned and operated by the Ocean Exploration Trust (OET).

These two vessels have spent time exploring in the Pacific and Atlantic Oceans, the Gulf of Mexico and Caribbean Sea, and the Mediterranean and Black Seas, making discoveries in archaeology, biology, geology, chemistry, and physical oceanography. Dozens of shipwrecks have been discovered dating from ancient times to the modern, acoustic mapping and remotely operated vehicle (ROV) dives have shed light on the flux of hydrocarbons from beneath the seafloor into the ocean, and innumerable records have been set regarding observations of organisms in new locations and new species unknown to science. And great quantities of data are now in archives awaiting scientists and students to ask new questions and make additional discoveries.

In this sixth ocean exploration supplement to *Oceanography* magazine, we present the initial results of the *Nautilus* and *Okeanos Explorer* 2015 field seasons in the Gulf of Mexico, the Caribbean Sea, and the Pacific Ocean. We include summaries of exploration and discoveries and describe new developments in technology and engineering as well as innovative outreach to stakeholders.

The results of the *Nautilus* Exploration Program are contained in the first section, beginning with a description of the technologies used on board *Nautilus* for telepresence-enabled deep submergence exploration and educational programming (**pages 8–13**). In 2015, the major addition to our technological suite was a new VSAT system graciously donated to OET by SeaTel Cobham. We also upgraded our suction sampling system, greatly increasing our capacity to collect soft, small, and fragile samples. Last year, we began including updates on sample analysis from previous cruises, and we do so again in this edition, highlighting analyses of biological and geological samples collected during the Galápagos and southern California cruise legs (**pages 14–17**). We next focus on our education and outreach programs (**pages 18–23**), which

Background photo credit: NOAA OER

Photo credit: NOAA OER

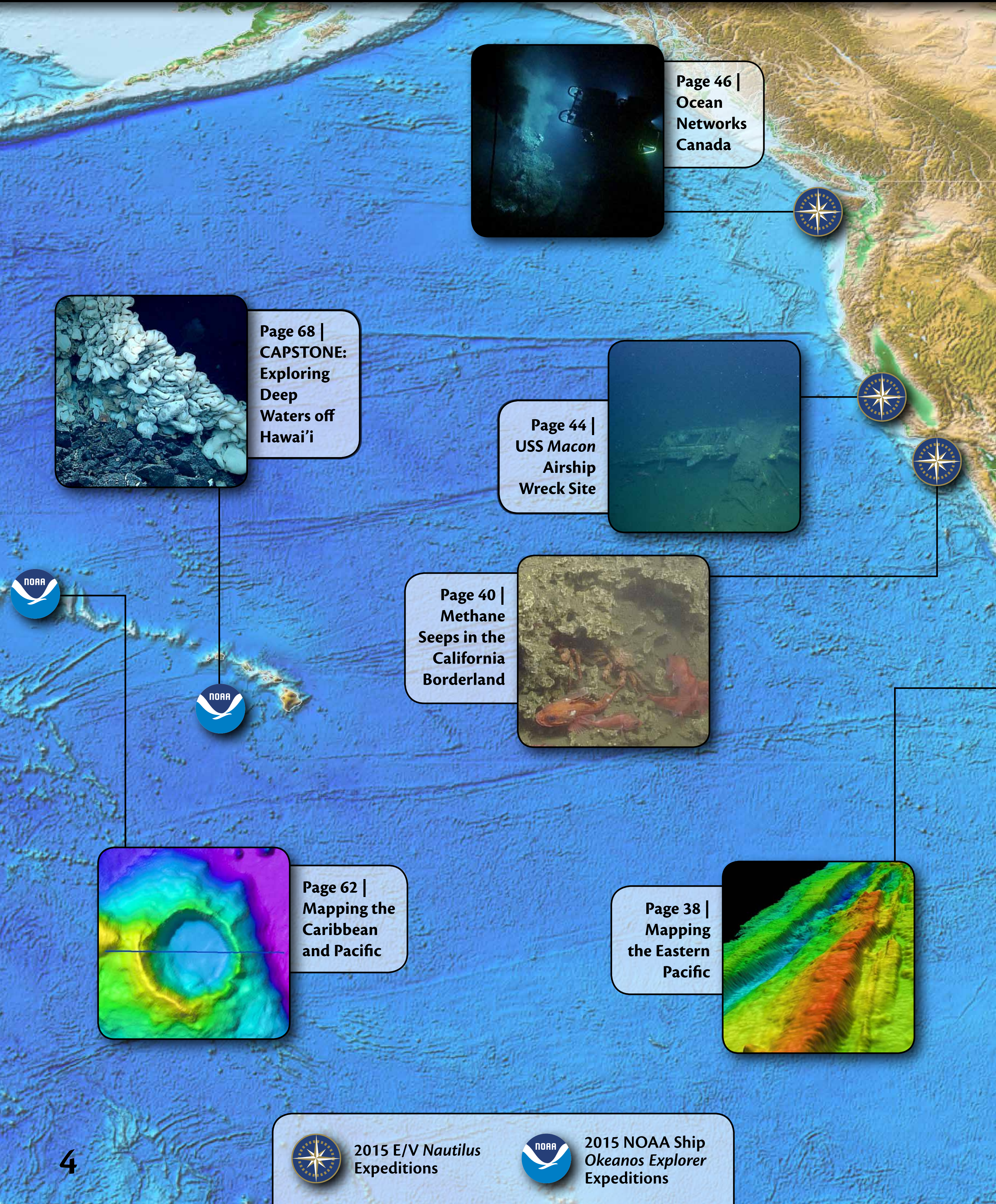
continue to reach unprecedented numbers of people, up to an estimated 80 million over the course of the 2015 field season. Not only are we engaging larger numbers of people worldwide, we are also emphasizing a community approach to our education programs, focusing our science, technology, engineering, and mathematics (STEM) efforts on a limited number of locations around the country to expose students to a deeper understanding of STEM careers and opportunities. The end of the first section focuses on the 2015 *Nautilus* expedition, which began in the Gulf of Mexico in April, transited through the Panama Canal in May, and explored from the Galápagos Islands to Canada from June through September (**pages 26–47**), focusing primarily on the geological and biological exploration of these poorly understood regions of the ocean.

The 2015 advancements and missions of NOAA Ship *Okeanos Explorer* are described in the second section. Most notably, we launched a multiyear Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE) designed to explore and characterize deepwater regions of the newly expanded system of Marine National Monuments in the central and western Pacific (**pages 68–73**). The objective is to provide authoritative, science-based information to support decision making with respect to these little-known ocean areas. On our way to the Pacific, we mapped and explored deepwater areas around Puerto Rico and the US Virgin Islands, work that included the first dive of our dual-body ROV *Deep Discoverer* and companion vehicle *Seirios* to 6,000 m in the Puerto Rico Trench (**pages 62–67**). The 2015 field season also included some significant advancements in our ability to collect and disseminate more and higher resolution data and information from the regions being explored (**pages 56–57**). We added a Kraft Predator II manipulator and sample storage box to *Deep Discoverer*, allowing for collection of biological and geological samples that are critical for understanding more about the Marine National Monuments (**pages 52–55**). We also continued our efforts to reach out to the scientific community, decision makers, and the public at large, including establishment of two new state-of-the-art Exploration Command Centers at the NOAA Inouye Regional Center in Honolulu and the University of Hawaii at Manoa (**pages 74–75**).

The new command centers join a growing list of shore-based Internet2-enabled facilities around the world that can access live video feeds and other data sets in real time from NOAA Ship *Okeanos Explorer*, E/V *Nautilus*, or any other telepresence-enabled oceanographic vessel. The ability to engage teams of scientists, educators, students, and others at Exploration Command Centers, as well as the progress being made on Internet1 and mobile access, continues to enhance the way in which we are exploring the global ocean. Using these new technologies, we can exponentially increase the number of participants contributing to the first observations of previously unknown areas, and we enable them to work with the information long after the missions are over so they can make additional discoveries.

We are excited to share the results of our 2015 discoveries with you, and we look forward to your participation in the national ocean exploration program.

Joint Program Overview Map



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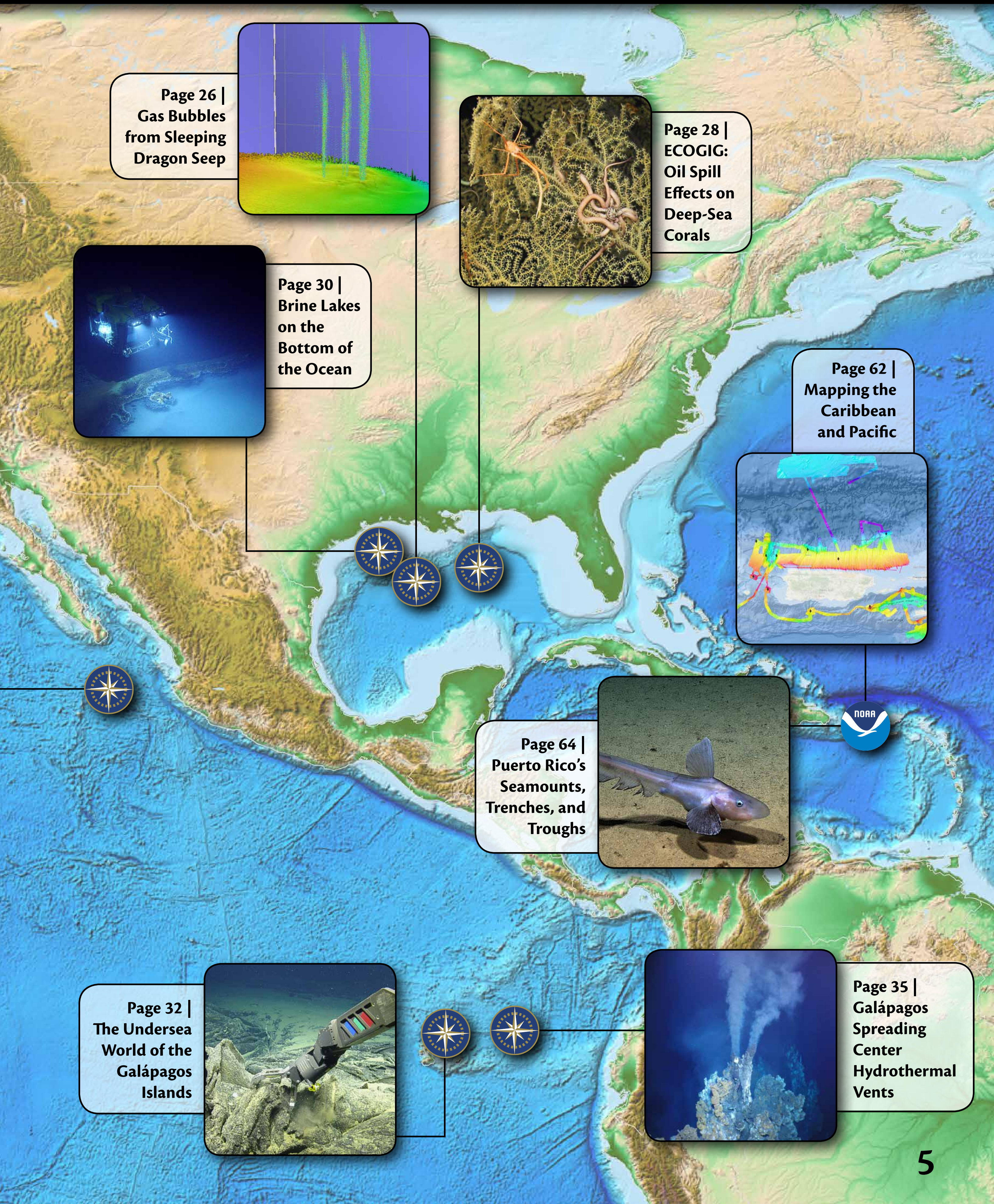
2015 E/V *Nautilus* Expeditions

2015 NOAA Ship *Okeanos Explorer* Expeditions



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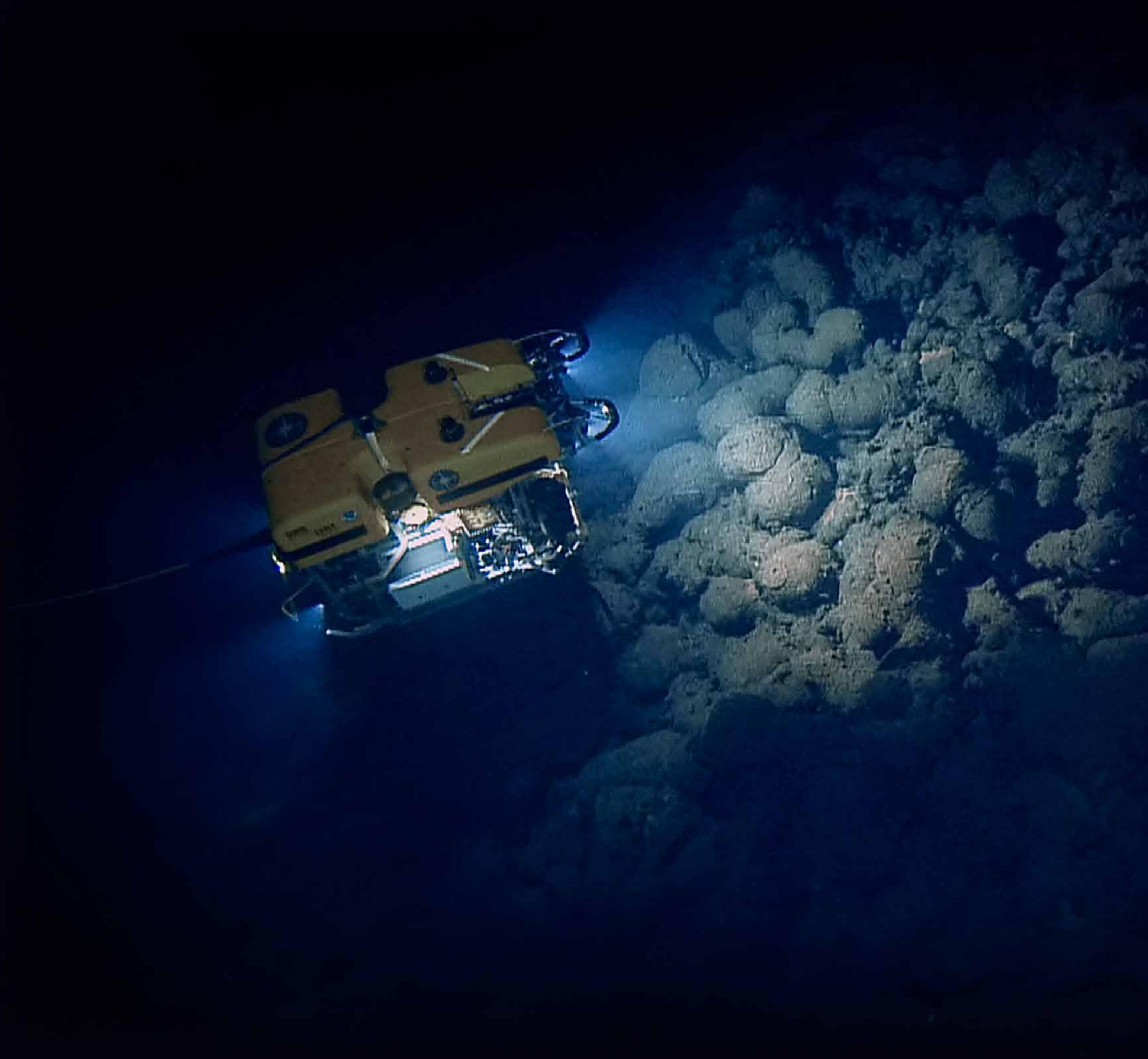


THE E/V *NAUTILUS* 2015 FIELD SEASON

Technology

E/V *Nautilus*

GENERAL

BUILT | 1967, Rostock, Germany

LENGTH | 64.23 meters (211 feet)

BEAM | 10.5 meters (34.5 feet)

DRAFT | 4.9 meters (14.75 feet)

TONNAGE | 1,249 gross, 374 net

RANGE | 24,000 kilometers (13,000 nautical miles)

ENDURANCE | 40 days at sea

SPEED | 10 knots service, 12 knots maximum

FUEL CAPACITY | 330 cubic meters

PROPULSION | Single 1,286 kilowatt (1,700 hp) controllable pitch main thruster; 250 kW bow thruster; 350 kW jet pump stern thruster

SHIP SERVICE GENERATORS | Two 500 kVa generators, one 350 kVa generator, and one 450 kVa shaft generator

PORTABLE VAN SPACE | One 20-foot van

COMPLEMENT | 17 crew; 31 science and operations

FLAG | St. Vincent and the Grenadines

HEAVY EQUIPMENT |

- Dynacon 421 ROV winch with 4,500 meter (14,764 feet) Rochester A302351 1.73 centimeter (0.68 inch) diameter cable
- DT Marine 210 winch with 1,200 m Rochester A320327 0.82 centimeter (0.322 inch) diameter wire
- Bonfiglioli knuckle-boom crane, 4.2 ton capacity, two extensions
- A-frame, 6 ton capacity

DATA PROCESSING & VISUALIZATION LAB

AREA | 44.5 square meters (480 square feet)

WORKSTATIONS | Seven workstations for data manager, data loggers, navigators, educators, data engineers, satellite engineer, video engineer; high-resolution map, multibeam, and side-scan sonar processing; flexible bench space

TELEPRESENCE TECHNOLOGY

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

REAL-TIME VIDEO STREAMING |

- Four Tandberg standard definition encoders with multiplex for encapsulating real-time video
- Harmonic Electra 7000 high definition encoder

CAMERAS | Two Sony BZR-H700 high definition pan/tilt/zoom cameras mounted to view the aft deck and port rail; one BZR-H700 in the control vans; Marshall VS-570 PTZ cameras in the wet lab (with microphone for communicate with scientists ashore) and in the ROV hanger with shore, mounted in Wet Lab and ROV hangar

COMMUNICATIONS |

- Ship-wide RTS Telex intercom system for real-time communications between ship and shore
- Handheld UHF radios are interfaced with the RTS intercom system for deck, bridge, and Control Room communications

CONTROL & IMAGING VANS

AREA | 28 square meters (301.4 square feet)

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

RACK ROOM

AREA | 17.3 square meters (185 square feet)

VIDEO STORAGE | Two Omneon Mediadecks (MDM-5321 and SMD-2200-BB) for video recording, playback, and storage

DATA STORAGE | 16 TB online storage for non-video data; 28 TB disk storage for video data

EMERGENCY COMMUNICATIONS | Iridium phone

ELECTRONICS WORKBENCH | 80 cu ft of storage

WET LAB

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

REFRIGERATION |

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

MICROSCOPE |

- Nikon SMZ800 trinocular microscope, 6.3× zoom, Vari-Mag C-mount camera adapter with additional 2.5× ocular
- Dual output cold light source
- Sony NX-5 camera
- HDMI out for sharing microscope video with shore

HAZMAT |

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

PRODUCTION STUDIO

AREA | 12 square meters (130 square feet)

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

SWITCHER | Ross CrossOver16 with ability to switch underwater, topside, or scaled computer video streaming to the Inner Space Center for live interactions

ROV HANGAR

AREA | 24 square meters (258.3 square feet)

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

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

LIFTS | 2 × 2-ton overhead manual chainfall lifts

STORAGE | Storage for spares and other equipment

ROV WORKSHOP

AREA | 18 square meters (193.8 square feet)

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

STORAGE | Storage for spares and other equipment

Acoustic Systems

KONGSBERG EM 302 MULTIBEAM ECHOSOUNDER

FREQUENCY | 30 kHz

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

SWATH WIDTH | Up to 5.5 times water depth, to approximately 8,000 meters (26,247 feet)

PULSE FORMS | CW and FM chirp

BEAMWIDTH | 1° × 1°

APPROXIMATE GRID RESOLUTION | 1% water depth (e.g., 10 m at 1,000 m depth)

KNUDSEN SUBBOTTOM PROFILER AND ECHOSOUNDER

PROFILER | Knudsen 3260 Chirp subbottom profiler and echosounder

OPERATING FREQUENCY | Dual frequency, 3.5 kHz and 15 kHz

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

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

ULTRA-SHORT BASELINE NAVIGATION SYSTEM

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

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

POSITIONING ACCURACY | 1° (better than 2% of slant range)

OPERATIONAL BEAMWIDTH | 120°

OPERATING FREQUENCY | 14.2 to 19.8 kHz

TARGETS TRACKED | Up to eight

SIDE-SCAN TOWFISH *DIANA*

SIDE-SCAN SONAR | EdgeTech 4200 MP CHIRP side-scan sonar with depressor wing

DEPTH CAPABILITY | 2,000 meters (6,561.7 feet), currently limited by 1,000 meters (3,280.8 foot) cable

TOWFISH SIZE | 125.6 centimeters × 11.4 centimeters (49.5 inches × 4.5 inches)

FREQUENCY | 300 and 600 kHz dual simultaneous

OPERATING RANGE | 230 meters (300 kHz), 120 meters (600 kHz)

HORIZONTAL BEAMWIDTH | 0.54° and 0.34° (high speed mode), 0.28° and 0.26° (high definition mode)

VERTICAL BEAMWIDTH | 50°

DEPRESSION ANGLE | Tilted down 20°

RESOLUTION ALONG TRACK (High Speed Mode) |
300 kHz: 1.9 meters @ 200 meters
600 kHz: 0.6 meters @ 100 meters

RESOLUTION ALONG TRACK (High Definition Mode) |
300 kHz: 1.0 meter @ 200 meters
600 kHz: 0.45 meters @ 100 meters

RESOLUTION ACROSS TRACK | 3 centimeters (300 kHz), 1.5 centimeters (600 kHz)

SENSORS | Heading, pitch, roll, pressure

Remotely Operated Vehicle *Argus*

GENERAL

DEPTH CAPABILITY | 6,000 meters (19,685 feet), currently limited to 4,000 meters

CABLE | 4,000 meters, 0.681 electro-optical, 3x #11 conductors, 3x SM fibers

SIZE | 3.8 meters long × 1.2 meters wide × 1.3 meters high

WEIGHT | 1,800 kilograms (4,000 pounds)

MAXIMUM TRANSIT SPEED | 2 knots

ASCENT/DESCENT RATE | 30 meters/minute (98.4 feet/minute)

PROPULSION | Two Deep Sea Systems International 404 brushless DC thrusters for heading control

IMAGING & LIGHTING

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

LIGHTING |
- Four CathX Aphos 16 LED lampheads, 28,000 lumens each
- Two Deep Sea Power & Light 250 Watt Incandescent

VEHICLE SENSORS & NAVIGATION

USBL NAVIGATION | TrackLink 5000 system, acoustically triggered

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

SECONDARY HEADING | TCM2 solid state fluxgate compass

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

ALTIMETER | Benthos PSA-916

FORWARD-LOOKING SONAR | Mesotech 1071, 675 kHz, 100 meter range

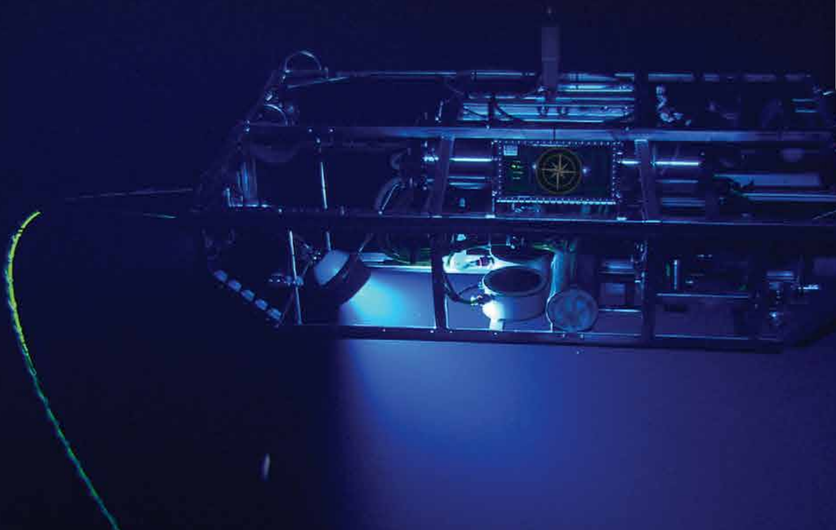
SIDE-SCAN SONAR | EdgeTech 4200 MP

SUBBOTTOM PROFILING SONAR | TriTech SeaKing Parametric Subbottom Profiler (10–30 kHz)

SCIENTIFIC INSTRUMENT SUPPORT

POWER | 110 V 60 Hz AC, 24 VDC, 12 VDC, 5 VDC power options

DIGITAL DATA CHANNELS | Three RS-232, one 100base-T Ethernet



Remotely Operated Vehicle *Hercules*

GENERAL

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

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

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

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

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

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

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

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

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

DESCENT/ASCENT RATE | 30 meters/minute (98.4 feet/minute)

PROPULSION |

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

VEHICLE SENSORS & NAVIGATION

HEADING AND ATTITUDE |

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

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

CTD | Sea-Bird FastCAT 49

OXYGEN OPTODE | Aanderaa 3830

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

USBL NAVIGATION | LINKQUEST TrackLink 5000

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

FORWARD-LOOKING SONARS |

- Kongsberg Mesotech 1071 profiling sonar, 300 kHz, 200 meter range (164 feet)
- TriTech Super SeaPrince 675 kHz, 50 meter range (164 feet)

IMAGING & LIGHTING

STANDARD IMAGING SUITE | One high definition video channel on fiber optic, four standard definition video channels on coax, generally configured as:

- Insite Pacific, 6,000 msw rated, Zeus Plus with 10× zoom lens, Ikegami HDL-45A with zoom/pan/tilt/extend –1080i SMPTE 292M output format
- Insite Pacific, 6,000 msw rated, Titan Rotate-Tilt standard definition camera (bubble camera) 480 line NTSC format
- Three Insite Pacific NOVA utility cameras, mounted to view the starboard sample box, 480 line NTSC format
- One Insite Pacific Aurora utility camera, NTSC format

LIGHTING |

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

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

HIGH-RESOLUTION MAPPING SUITE |

- Available for nonstandard mapping products
- Typical configuration is downward looking; custom configurations possible
- 1375 kHz BlueView multibeam, 90° total swath, 30 meter range, centimeter resolution capable
- Two stereo Prosilica still cameras, one black & white, one color; 1,024 × 1,360 pixels; 29° × 39° field of view; strobe lighting
- Green laser sheet with dedicated laser camera; 532 nanometers; 100 mW; 45° line generating head; inclined plane
- Raytrix R5 lightfield camera

MANIPULATORS AND SAMPLING

MANIPULATORS |

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

SUCTION SYSTEMS |

- Suction sampling system, eight 3-liter discrete samples
- Jet-suction excavation system

SAMPLING TOOLS | Mission configurable

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

SAMPLE STORAGE |

- Forward sample tray (inboard): 45 cm × 33 cm × 25 cm (17.7 inches × 13 inches × 9.8 inches)
- Forward sample tray (outboard): 68 cm × 35 cm × 30 cm (26.8 inches × 13.8 inches × 11.8 inches)
- Starboard sample drawer: 65 cm × 50 cm × 30 cm (25.5 inches × 19.7 inches × 11.8 inches)
- Payload: Up to 300 lbs depending on sensor package
- Custom configuration of boxes, crates, and containers

ELEVATORS | Mission configurable; free ascent; maximum standard payload 70 kg (150 lb)

SCIENTIFIC INSTRUMENT SUPPORT

SWITCHED POWER |

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

DIGITAL DATA CHANNELS |

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

HYDRAULIC | Proportional and solenoid hydraulic functions

- 1,150 psi at 10 GPM
- 1,850 psi at 10 GPM
- 3,000 psi at 10 GPM (advance notice needed)

EXAMPLES OF USER-INSTALLED SENSORS |

- Harvard in situ mass spectrometer
- Fluorometer
- pH sensor
- PMEL MAPR eH sensor
- Kongsberg M3 multibeam sonar
- 18 MP Ethernet connected digital still camera

Nautilus Samples Program

By Nicole A. Raineault, Laurie Bradt, Megan Lubetkin, Steven Carey, Katherine Kelley, Charles R. Fisher, Chris Castillo, Simon Klemperer, and Henry Reiswig

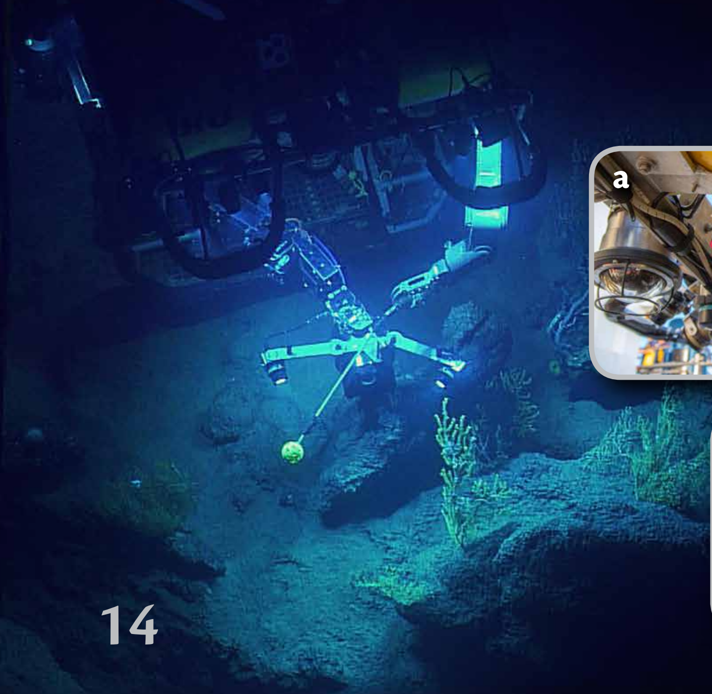
Figure 1. Science team members Megan Lubetkin, Jacob Balcanoff, Renny Kane, Steve Carey, and Suna Tüzün await the all-clear signal to retrieve samples from ROV *Hercules* after a dive.

The Ocean Exploration Trust recognizes that an interdisciplinary team is critical to running a successful sampling program, from the engineers who help improve our ability to obtain and preserve samples, to the data managers and interns who spend upward of 12 hours in the Wet Lab after a dive carefully documenting and preserving samples for scientific research (Figure 1). This year, more samples were collected and requested for research after cruises than in any previous year.

SAMPLING TECHNOLOGY UPGRADES

In 2015, the biological sample boxes were redesigned to improve the seal between the box and the lid. A watertight fit is important for keeping cold, deep-sea water in the box during the ROV's long ascent to the surface. Ensuring that the samples are not degraded by warm surface water is important for molecular identification efforts and critical for experimental studies of virtually all deep-sea organisms.

During the 2015 field season, the *Nautilus* Exploration Program collected over 2,300 subsamples from 688 individual samples, a record number. This was due, in part, to a redesigned suction or "slurp" sampler. Most mobile, fragile, and small animals are nearly impossible to sample using the ROV manipulator arm. The suction sampler is a vacuum-cleaner-like tool that has a hose connected to chambers that sit on the front of *Hercules*, above and just aft of the light bar. In the past, two discrete samples could be taken, but the new system's eight rotating chambers (Figure 2a) provide the capability to take up to seven samples, while reserving one jar as a flush chamber to clean out the hose and avoid sample contamination. The exhaust ports of each sample jar can be covered with different pore-sized Nitex mesh to optimize collection of different sizes of organisms, from bacterial mats to fish or crabs. The suction sampler can also be used to sample all fauna in a particular microhabitat and yield samples that contain many different species and dozens of subsamples (Figure 2b,c). The real work is not in taking the suction sample, but in the lab afterward, where scientists, data managers, and interns painstakingly separate out each morphotype and then take subsamples of each for preservation in a variety of fixatives for classical or molecular taxonomic analyses specific to that type of organism.



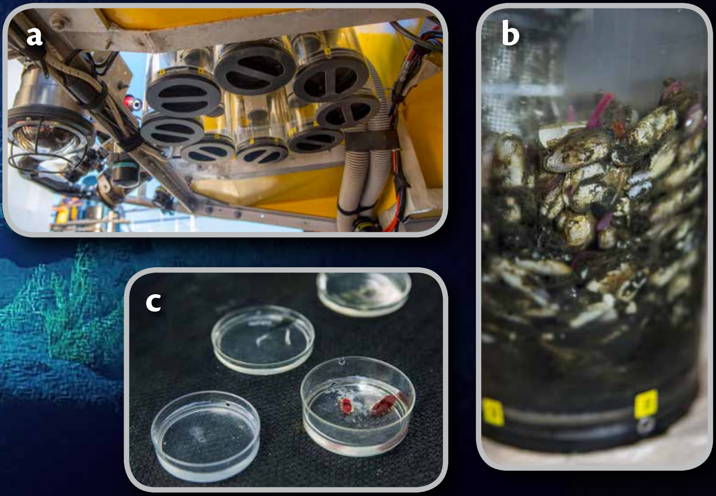


Figure 2. (a) A new suction sampler expands sampling capacity by (b) increasing the number of discrete sample chambers and thus (c) subsamples.

NEW SAMPLE PROJECTS

Work in the Galápagos Marine Reserve was a new opportunity to foster international collaboration in utilizing *Nautilus* samples for research. The 904 mostly biological subsamples were sent to over a dozen experts in countries around the world, including Ecuador, France, Australia, England, Canada, and the United States, for classical taxonomic characterization and DNA barcoding. Compared to the shallow coastal island fauna, very little is known about the deep-sea biology of the Galápagos region. These samples will help rewrite our knowledge of the biogeography of fauna living on seamounts and vents around the Galápagos. The Galápagos National Park is in the process of rezoning the Galápagos Marine Reserve to better protect the deep-sea biodiversity. Scientists at the Charles Darwin Foundation and National Geographic Pristine Seas project used our samples and data to inform rezoning of critical areas. Dives on seamounts north of Darwin and Wolf Islands, suspected spawning grounds for large fish and feeding grounds for hammerhead sharks, were primary exploration targets. Prior to this expedition, very little was known about marine life at a depth greater than 40 m in most areas of the reserve.

The Ocean Exploration Trust is beginning a program to curate and exhibit select biological and geological samples collected on *Nautilus* cruises. These samples will be curated using professional museum standards and some will become part of a series of traveling exhibits. Those samples not suitable for travel will be placed on display in the Center for Ocean Exploration at the Graduate School of Oceanography, University of Rhode Island. The nearly 3.89 m (12 feet, 9 inches) long *Riftia pachyptila* tubeworm tube is just one of the unique samples that will be displayed to the public as part of this program (Figure 3).

Figure 3. The 12'9" *Riftia pachyptila* tubeworm tube collected in 2015 is stretched out on board *Nautilus*.

Several examples of how scientists are utilizing samples collected on 2015 cruises are described below.

Geological samples are available for scientific research from the University of Rhode Island Marine Geological Samples Laboratory (http://www.gso.uri.edu/MGSLsite/mgsl_homepage.htm), and biological samples are available from the Harvard Museum of Comparative Zoology (http://www.mcz.harvard.edu).

EXAMPLE 1. Unknown Sponge Sample, Galápagos Marine Reserve

(Henry Reiswig)

A joint expedition in the Galápagos Marine Reserve was supported by the Ocean Exploration Trust, the Charles Darwin Foundation, and the Galápagos National Park Directorate. On the first dive on deep seamounts in the Reserve, our primary objective was to document the diversity of life on an unexplored underwater volcanic mountain. This unnamed seamount rises a kilometer above the seafloor from a depth of 1,300 m. From the beginning of the dive, scientists were awed by the density and diversity of life on the sides of this lava-covered undersea mountain. We collected numerous corals, fish, shrimp, crabs, sponges, and assorted other animals, some of which may turn out to be new species, but were at least similar to relatives that have been found in other places. At approximately 800 m depth, scientists stopped to collect what looked like another branched octocoral, but as the ROV settled to the seafloor to take a sample, none of the scientists, including the experts ashore, had ever seen anything like it (Figure 4). It was clearly not a coral, and the scientists hypothesized that it was some kind of hexactineliid (glass) sponge. Its spicules proved that it is a mainstream member of the class Demospongiae (Order Poecilosclerida, Suborder Myxillina) and probably belongs in the family Phellodermidae. Researchers from Canada and the UK are currently working to describe the new species using both molecular and morphological approaches.

Figure 4. A probable carnivorous sponge found in the Galápagos Marine Reserve puzzled many scientists and is now being analyzed by a team of experts.

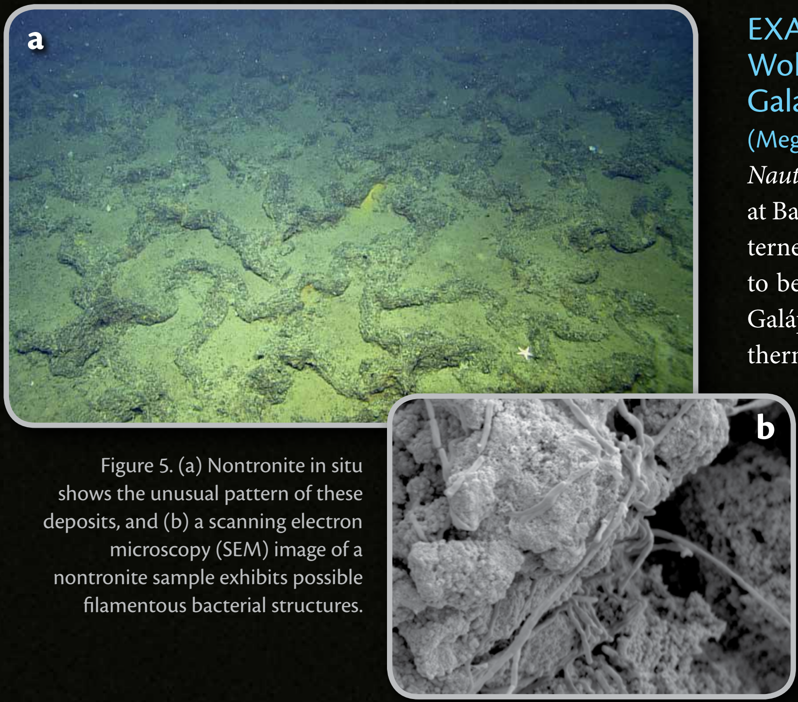


Figure 5. (a) Nontronite in situ shows the unusual pattern of these deposits, and (b) a scanning electron microscopy (SEM) image of a nontronite sample exhibits possible filamentous bacterial structures.

EXAMPLE 2. Rock Samples at Seamount No. 3, Wolf-Darwin Seamount Chain, Galápagos Marine Reserve

(Megan Lubetkin, Steven Carey, and Katherine Kelley)

Nautilus Science Intern, Megan Lubetkin, a senior geology major at Bates College, is studying an unusual occurrence of tubular patterned low-temperature hydrothermal mineral deposits, believed to be nontronite, discovered at the summit of a seamount in the Galápagos Marine Reserve (Figure 5). Although similar hydrothermal systems have been explored and sampled using coring techniques in the past, little is known about the formation of associated minerals and their exposed tubular overlapping sinuous pattern. By examining seafloor images and using a variety of techniques such as x-ray diffraction and scanning electron microscopy (SEM), among others, it may be possible to uncover how this mineral formed in such a pattern, the temperature regime in which it formed, and its connection to the associated bacteria found with it.

EXAMPLE 3. Dating Channel Islands Marine Terraces with Sediment Samples

(Chris Castillo and Simon Klemperer)

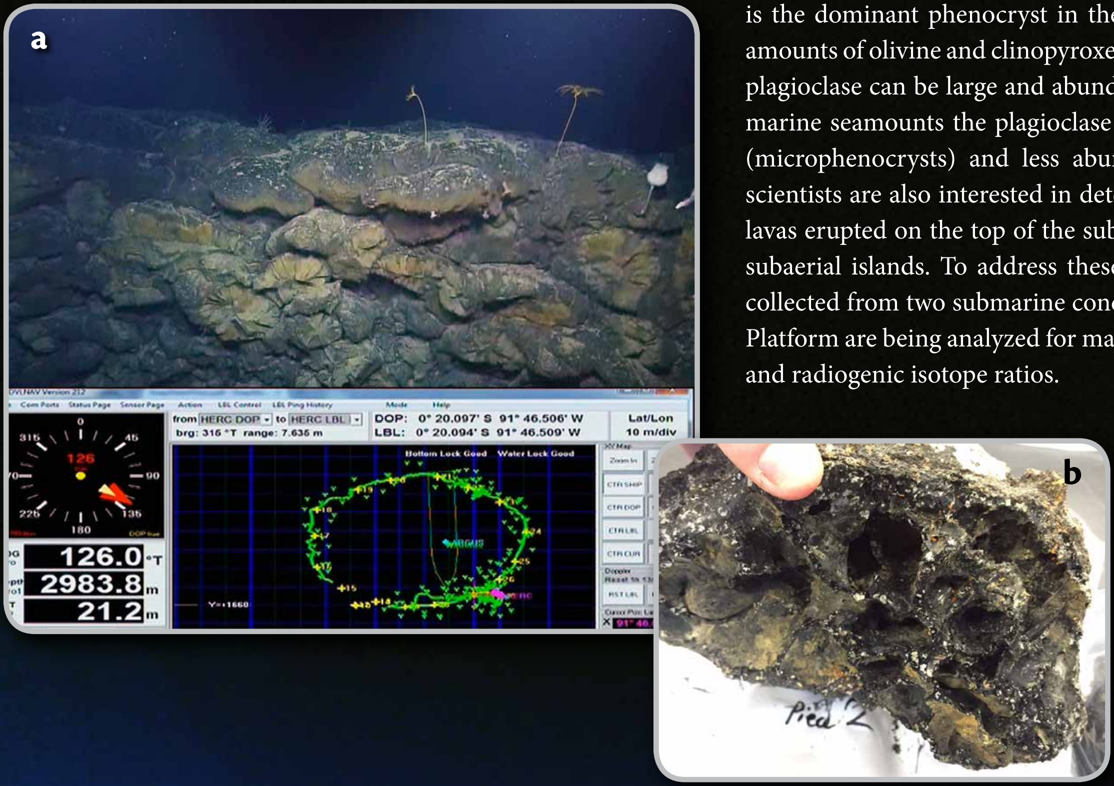
Geophysicists at Stanford University are working to understand the tectonic deformation in Southern California by dating fault offsets in marine terraces surrounding Catalina Island, and are partnering with the Southern California Earthquake Center to update community understanding of local geologic hazards. Marine terraces, which are horizontally continuous beach deposits, can be used to explore tectonic deformation because they were flat when created, and any tectonic deformation will be visible as disturbances in the terrace surfaces. In 2014, the Stanford group used high-resolution subbottom echosounding to identify vertical fault offsets in the originally flat marine terraces and to map ancient landslides large enough to generate tsunamis directed at Los Angeles. However, without physical samples from the seafloor, they were unable to date the terraces, and hence the age of faulting and landsliding. Chris Castillo and Simon Klemperer, Scientists Ashore, participated in two telepresence-guided ROV dives from *Nautilus* on the west and east sides of Catalina Island. Terrace deposits were easily identified in high-resolution video and sampled with the *Hercules* manipulator arm (Figure 6). We were able to break off in situ pieces of rock and pick up samples derived from adjacent outcrops. Samples include the shallow-water coral species *Balanophyllia elegans* as well as bivalves and brachiopods. Corals and shells contained within these sediments have been submitted for radiometric dating, for carbon and oxygen isotope analysis to determine water column temperature and chemistry during their formation, and for paleontological analysis to provide additional age controls for the marine terraces. These data will place age constraints on faulting and the tsunamogenic landslides preserved in the sedimentary record surrounding Catalina Island. In between and following the dives, *Nautilus* mapped bathymetry at high resolution to gather more detailed information on the extent and depths of the submerged terraces, and to provide geomorphologic context along the dive tracks.

Figure 6. A rock sample collected off of Catalina Island, CA, contains organisms that can be dated to help determine the ages of marine terraces found around the island.

EXAMPLE 4. Lava Samples from the Galápagos Platform

(Daniel Fornari, Adam Soule, and Dorsey Wanless)

Volcanologists, marine geologists, and geochemists from the Woods Hole Oceanographic Institution (WHOI) and Boise State University (BSU) are investigating the magmatic and submarine volcanic processes that have led to the creation of the Galápagos Platform. During the four days of diving, PhD students Meghan Jones (WHOI) and Darin Schwartz (BSU) helped direct the dives from the WHOI Exploration Command Center, while Daniel Fornari, Adam Soule, and Dorsey Wanless participated remotely via an Internet link to the ship. Samples from several deepwater lava flows (3,500–4,000 m depth) that extend nearly 20 km west from Fernandina Island, the westernmost and most active volcano in the Galápagos, were collected during two ROV dives. In addition, the morphology of the lava flow surface included numerous channels and a large collapse pit (~60 m in diameter and ~30 m deep) that was circumnavigated and explored, with samples collected along the crater rim and on its floor (Figure 7). Major element, trace element, and volatile analyses, as well as work on melt inclusions (small blobs of melt within olivine crystals in the lavas) are being carried out on the lava samples at WHOI and BSU to provide information on magmatic processes in the mantle below the Galápagos Islands. When present, plagioclase is the dominant phenocryst in the Galápagos lavas, with lesser amounts of olivine and clinopyroxene. In the deepwater flows, the plagioclase can be large and abundant, while at the shallow submarine seamounts the plagioclase crystals are generally smaller (microphenocrysts) and less abundant. The WHOI and BSU scientists are also interested in determining the heterogeneity of lavas erupted on the top of the submarine platform between the subaerial islands. To address these differences, 15 lava samples collected from two submarine cones on the top of the Galápagos Platform are being analyzed for major and trace element contents and radiogenic isotope ratios.



from HERC DOP to HERC LBL
brg: 316 °T range: 7.635 m
DOP: 0° 20.097' S 91° 46.506' W
LBL: 0° 20.094' S 91° 46.509' W
126.0 °T
2983.8 m
21.2 m

Figure 7. (a) (top) Lobate and pillow lavas along the upper rim of the crater are home to a few stalked crinoids and vase sponges. (bottom) The *Hercules* navigation screen indicates vehicle positions with green symbols as the ROV completed its circumnavigation of a large collapse pit (~ 60 m diameter, ~ 30 m deep) located in the center of a deepwater lava flow off the west coast of Fernandina Island, Galápagos. (b) This basaltic lava sample NA064-091 collected from the top of the collapse pit was found to contain abundant plagioclase phenocrysts and large (~ 2 cm) vesicles.

A Community Approach to STEM Education

By Allison Fundis, Megan Cook, Samuel Garson, Katherine Sutton, Scott Munro, and Susan Poulton

The Ocean Exploration Trust's (OET) education and outreach programs serve as models of real-world science, technology, engineering, and mathematics (STEM) content and as mechanisms for captivating student and public interest in STEM disciplines. In 2014, OET launched the Community STEM Program to concentrate its suite of educational programs within individual communities across the United States to both centralize and expand efforts to engage a broad group of students, educators, and the public, with the goal of increasing STEM literacy and proficiency. In 2015, the Community STEM Program grew significantly, and it continues to expand in 2016.

To engage a broad base of learners, OET has developed and implemented a suite of educational opportunities and programs focused on STEM disciplines and vocational skills, including: (1) seagoing programs for high school, undergraduate, and graduate students; (2) broad and far-reaching public engagement and outreach; (3) STEM and expedition-based curricula and educator training workshops; (4) opportunities for young and early career professionals; and (5) professional development opportunities and programs for educators and artists. Our approach throughout these programs is to use role models and mentorship to drive achievement, motivation, and continued interest in STEM fields.

As the Corps of Exploration sails the world aboard E/V *Nautilus*, moving forward the fields of marine biology, chemistry, geology, and archaeology, it is also engaging a new generation of STEM learners in classrooms, out-of-school programs, collegiate lecture halls, museums, science centers, and living rooms around the world.

COMMUNITY STEM PROGRAM

The Community STEM Program represents a new approach to fostering intracommunity collaborations through the lens of ocean exploration. OET's educational philosophy is centered on the principle of nurturing learners as they advance through our program offerings (Figure 1). This mentoring approach is strengthened as OET works in partnership with key community organizations already active in STEM learning, such as at public science venues, collegiate educational institutions, and out-of-school programs. The cumulative effect of layering education offerings and promoting intracommunity mentoring from STEM leaders enables the Community STEM Program to have an impact far beyond that of a single program alone. In its second year, the Community STEM Program had many successes in locations across the United States. Participating communities included Corpus Christi, TX; Lake Charles, LA; Broward County, FL; and southeastern Connecticut. Communities implementing partial components of the Community STEM Program included Washington, DC; Houston, TX; Dallas, TX; San Francisco, CA; and Lemont, IL. The network of STEM exploration mentors grew significantly, with 21 community representatives participating in at-sea programs, including eight Science & Engineering Internship Program students, four Honors Research Program students, three Science Communication Fellowship educators, and six Nautilus Ambassadors.

Figure 1. The Community STEM Program's four tiers:

INSPIRE. Individuals are introduced to the *Nautilus* Corps of Exploration through the Web and social media, or by watching television specials and documentaries.

ENGAGE. Audiences engage with the Corps through live and interactive broadcasts at museums, science centers, and public venues, and in classrooms.

EDUCATE. Community members make use of educational and professional development opportunities such as using STEM Learning Modules, attending training workshops, or participating in a *Nautilus* expedition.

COLLABORATE. Students and early career scientists and engineers continue to develop alongside STEM professionals they met through the *Nautilus* Exploration Program and actively support the planning and operations of *Nautilus* expeditions.

(above) A student in San Pedro, CA, gets a tour of the ROV controls from pilot Buzz Scott while *Nautilus* is in port. (right) Students tour *Nautilus* with members of the Corps of Exploration while the ship is docked at AltaSea at the Port of Los Angeles.

(above) Winning entry of the annual *Nautilus* expedition patch design contest submitted by Won Lok Yiu from China.

PUBLIC OUTREACH

Nautilus Live and Digital Media

The 2015 season broke outreach records for OET, bringing ocean exploration to the largest national and international audiences since the program's inception in 2009. Our total media reach—including televised specials, press, digital media, and the Nautilus Live website—exceeded 80 million during the six-month field season. OET's digital reach alone—including the Nautilus Live website and social media platforms—exceeded 23 million views. There was a 40% increase over 2014 in traffic to the Nautilus Live website, with over 3.6 million page views. The continual expansion of our public outreach efforts brings new audiences aboard to the INSPIRE tier.

Social media continued to grow as a platform for reaching audiences worldwide in 2015. We had a 100% increase in Facebook views over the previous field season, reaching 12 million people, and Nautilus Live received more than 11,600 Facebook comments, almost double the number received in 2014. Our Twitter audience increased 80% to 1.2 million total impressions, and our Instagram audience rose by 300%. The ability of quality content to spur imagination and scientific curiosity attracted a diverse and active conversation across these platforms and increased audience participation.

Additionally, 2015 was a successful year for traditional media coverage, with over 650 media hits in every major US market and attention in top international markets, including National Geographic, BBC, AP, Reuters, The Weather Channel, CNN, FOX, ABC, NBC, CBS, BBC, CBS, Fox News, Buzzfeed, Mashable, Upworthy, Jezebel, IFLS, *The Dodo*, *Houston Chronicle*, *Popular Mechanics*, Yahoo News, and NPR Science Friday. Each expedition received additional local and national media coverage highlighting participating educators, students, and scientists as hometown ambassadors of ocean science and exploration.

Live Broadcasts

Telepresence technology installed on *Nautilus* allows onboard team members to ENGAGE with onshore audiences through special programming at venues such as universities, museums, science centers, out-of-school programs, and classrooms. This shipboard broadcasting capability enables educators, scientists, engineers, and students to participate in live interactions with tens of thousands of people annually at these venues and with online audiences via the Nautilus Live website.

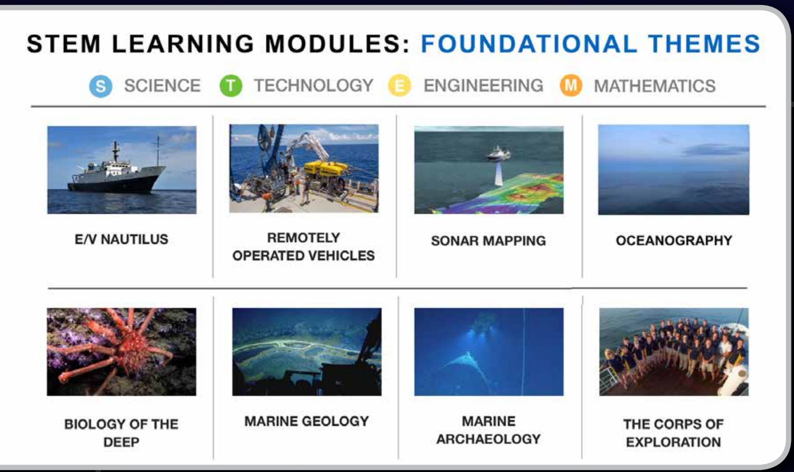
Along with extending the duration of the 2015 broadcasting season, OET significantly increased the number of interactive broadcasts and the number of sites reached to 352 live interactions into 123 venues across 28 states, five countries, and a US territory. Major venue partners during the 2015 field season included the Houston Museum of Natural History, Perot Museum in Dallas, TX, Titanic Belfast Museum in Northern Ireland, Exploratorium in San Francisco, CA, Aquarium of the Pacific in Long Beach, CA, and the Museum of Discovery and Science in Fort Lauderdale, FL. OET also continued outreach programs with a variety of schools, universities, research conferences, and out-of-school programs, including Boys Scouts of America, Girls Scouts of America, and Boys and Girls Clubs.

An important element of the ENGAGE level of programming is the opportunity for students and audience members to speak directly to our Corps of Explorers through the "Send a Question" feature of the Nautilus Live website. In 2015, our scientists, engineers, and educators received over 57,000 questions, a 30% increase over 2014. Audience questions were answered over the audio stream accompanying the live video feed. Enhancements to the website allowed basic oceanographic data such as vehicle depth and water temperature to stream alongside the video feed during remotely operated vehicle (ROV) operations, boosting the viewing experience. The interactive element of the Web experience enables audiences around the world to contribute archaeological and biological observations throughout the season, creating a crowd-sourced participatory experience that encourages the public to dive deeper into the content and research being conducted on board.

EDUCATION PROGRAMS AND PROFESSIONAL DEVELOPMENT

By establishing partnerships with schools, out-of-school programs, and curriculum developers, OET has developed and implemented a series of educational programs that expose hundred of thousands of students to the breadth of STEM disciplines used in ocean exploration and research. OET's educational resources and programs—including the STEM Learning Modules, Honors Research Program, Science & Engineering Internship Program, Science Communication Fellowship, Artist-at-Sea Program, and Nautilus Ambassador Program—are constructed in a way that a young child could begin using the resources and continue through the program as they mature (Box 1).


(above) The Honors Research Program class of 2015 in front of decorated sails that adorned the ocean current drifters they designed and built.



Box 1. STEM Learning Modules

By Katherine Sutton, Samuel Garson, Megan Cook, Stella Barth, Lloyd Godson, Nell Herrmann, Lindsay Knippenberg, Tiffany Risch, Karen Romano Young, Stephanie Stoeffler, Leah Walzer, and Allison Fundis

The STEM Learning Modules serve as a concept companion to ocean exploration conducted by E/V *Nautilus* and the Corps of Exploration. They are intended to supplement educators' current curricula and foster student engagement in STEM disciplines. The modules are guided by performance expectations of the Next Generation Science Standards, Common Core State Standards, and Ocean Literacy Principles. Developed in part by professional educators who are alumni of the *Nautilus* Exploration Program, the first edition of the STEM Learning Modules was published in June 2015.

Each module explores a facet of the *Nautilus* Exploration Program and falls under one of the eight foundational themes found within all *Nautilus* expeditions. Modules lead students through the myriad STEM components involved in deep-sea exploration, including real-world challenges the Corps of Exploration face and concepts used to address them. Lessons are paired with guiding questions, themes, standards addressed, educator and learner instructions, and universal assessment rubrics. STEM Learning Module lessons are designed for sixth grade audiences, with extensions and differentiation for a variety of grade levels, student needs, and learning environments. Separate versions of each module are available for students and educators. They guide learners, who have a basic to advanced understanding of oceanography, through the lessons.

In August 2015, formal and informal educators were given online access to the modules for the first time. A permanent online platform for the modules and associated digital content will be further developed in 2016. Module content will continue to expand in the next year, including adding expedition-specific lessons for the upcoming exploration season.

The debut of STEM Learning Modules across Community STEM Program sites also contains an evaluation component. Initial evaluation focused on program design, implementation, and module ease of use. Expanded evaluation will include efficacy metrics and summative influence of STEM Learning Modules as a classroom resource.

Professional Development for Educators

In parallel with the release of STEM Learning Modules, OET launched STEM Academies, training workshops for formal and informal educators in communities participating in the Community STEM Program. Attending educators received the full suite of STEM Learning Modules, hands-on training with the module activities, and training in best practices for incorporating live deep-sea exploration into the classroom. They also participated in a live broadcast event with the Corps of Exploration and had the opportunity to network with local educators and STEM professionals. Professional development focused on highlighting the STEM foundations of ocean exploration and opportunities within the community to connect young learners to role models within the Corps of Exploration. The *Nautilus* Exploration Program STEM Academies were taught as a one- or two-day event within each community. Some Academies included training sections led by local STEM industry partners and universities to further connect classroom STEM learning to local workforce development.

In 2015, OET hosted STEM Academies in Lake Charles, LA; Corpus Christi, TX; Broward County, FL; Groton, CT; and Lemont, IL. STEM Academies trained 99 classroom educators and informal education staff with a combined reach of over 100,000 students.

Nautilus Ambassador Program

Nautilus Ambassadors are leaders at Community STEM Program locations who sail for a short cruise aboard *Nautilus* as an introductory experience to ocean exploration and sea-going research. Ambassadors are united by their passion for learning and dedication to STEM education as classroom teachers, informal educators, STEM professionals, or community leaders. During their time on board, Nautilus Ambassadors are exposed to science, technology, engineering, communications, and education outreach platforms as they shadow professionals in each field. After their offshore experience, Ambassadors return home as a representative of the *Nautilus* Exploration Program to share the excitement of ocean exploration and research with their peers, schools, and communities.

Honors Research Program

Since 2010, the Honors Research Program has provided the opportunity for a small cohort of rising high school seniors to participate in a five-week summer program at the University of Rhode Island Graduate School of Oceanography (URI GSO) followed by a culminating experience serving as part of the science team on board *Nautilus*. While at GSO, students are exposed to the interdisciplinary nature of oceanography by experts in geology, biology, archaeology, engineering, science communication, and computer science. Students collaborate on capstone STEM projects aimed at preparing them for their time at sea and contribute research data to the scientific community.

In its sixth year, eight students participated from public and private high schools in Connecticut, Florida, Idaho, Puerto Rico, Rhode Island, Texas, and Virginia. While at GSO, the students were tasked with two main projects to complete. The first project centered on the curation of deep-sea coral data from sites explored during the 2014 and 2015 field seasons' ECOGIG expeditions (**see pages 28–29**). ECOGIG scientists analyze coral communities for colony growth and change, but lack an easy way to visualize metadata context from each dive. Student teams collected, correlated, and mapped relevant site details and water characteristics associated with each deep-sea coral studied. Students then compiled the data and began looking for patterns within the data sets. In the second project, students collaborated on the design, construction, and deployment of four GPS-enabled ocean drifters—two surface drifters and two deepwater drifters—to study the complexities of global ocean currents. Students were tasked with researching previous successes and challenges of the Student Drifters Program (http://studentdrifters.org) and then developing their own drifters that would make them more reliable for long-term data collection at sea. In collaboration with local scientists and by using global data models, the students selected launch points for their drifters within the planned operational areas for the 2015 *Nautilus* expeditions off the California coast. The students' drifters gathered valuable information, returning position locations for 58 consecutive days. The students' data were shared with Remote Sensing Inc., an industry partner that used these findings to refine computer models of the California coastal currents. The students' data were also featured on the NOAA National Marine Fisheries Service (New England) website.

(left) Honors Research Program students ready their surface current drifter for deployment on the aft deck of *Nautilus*.

Science & Engineering Internship Program

Since its inception, the *Nautilus* Science & Engineering Internship Program has provided hundreds of talented undergraduates, recent graduates, and graduate students with hands-on exposure to the fields of ROV and video engineering, ocean science, and seafloor mapping while being mentored by STEM professionals. Interns, who are selected by a competitive process, sail on *Nautilus* for three to five weeks as part of the expedition team. ROV engineering interns learn about vehicle systems, maintenance, and operations in addition to co-piloting *Argus* during ROV dives. Video engineering interns operate all video equipment during ROV dives and learn about the complexities that allow shipboard broadcast systems to stream live video and data to shore. Ocean science and seafloor mapping interns work in critical roles as members of the science team, processing data and managing samples during ROV exploration and multibeam mapping surveys. Interns also serve as role models to their peers, the public, and students around the world through the Nautilus Live website and live broadcasts from sea. In 2015, 19 students participated in the Science & Engineering Internship Program from 13 US states and Israel, including student representatives of the Boy Scouts of America and NOAA's Education Partnership Program.

The Science & Engineering Internship Program highlights the talent of many partner universities within Community STEM locations. In 2015, an internship in navigation was officially incorporated into the program and offered as workforce development to US Naval Academy midshipmen and US Coast Guard Academy cadets. This internship focuses on the logistics and operational navigation skills required to work with a cross-cultural team and remotely controlled robotic vehicles.

The progressive nature of our education programs was highlighted this season by Navigation Intern Julia Arthur, an alumna of the 2012 Honors Research Program (HRP). Through her participation in the HRP, Julia solidified her decision to pursue a career in oceanography, confirmed the US Naval Academy was her top choice for college, and passionately wanted to stay involved with the *Nautilus* Exploration Program. Julia was our first alumnus to return to another OET program, and she continues to serve as an ambassador for exploration within the US Naval Academy and her community.

Science Communication Fellowship

The Science Communication Fellowship (SCF) trains formal and informal educators to professionally communicate the science and operations of the *Nautilus* Exploration Program to onshore audiences. This professional development fellowship trains educators in the leading practices of science communication and digital storytelling, and introduces each participant to cutting-edge research and the STEM professionals conducting these studies. Shortly after acceptance into the SCF program, Fellows attend OET's annual Science Communication Workshop at GSO to: (1) learn effective science communication strategies and hands-on technical skills to enable them to translate their at-sea experience to shoreside audiences; (2) gain fundamental science and engineering knowledge to underscore the mission and objectives of the 2015 expedition season; (3) learn best practices for incorporating the *Nautilus* Exploration Program into formal and informal education spaces; and (4) bring personal experience and resources to network with other Fellows and develop local outreach and education plans for the upcoming field season.

(below) ROV Engineering Intern Jessica Sandoval pilots ROV *Argus* during one of the 2015 Galápagos Islands expeditions. Jessica is an undergraduate studying biological engineering at MIT.

(above) Science Communication Fellows Ariel Zych, Education Manager at the Science Friday Initiative, and Rachel Rayner, Education Coordinator at the Discovery Science and Technology Centre, with ROV *Argus*.

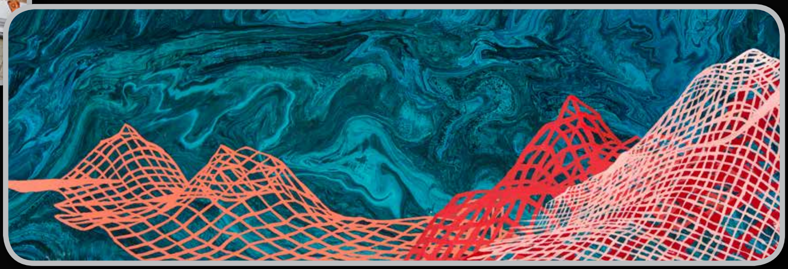
While at sea, SCFs moderate the audio broadcast of live exploration, translating complex science for classroom and public audiences as well as weaving shore-based audience questions into the conversation. SCFs also lead the broadcast outreach of ship-to-shore interactions. Within their communities, SCFs become roles models of exploration and STEM outreach. The deliverable of the fellowship is an original STEM-focused lesson or outreach effort to translate their experience to a broad audience of learners. These deliverables contribute to the growth and expansion of the STEM Learning Modules.

The 2015 cohort, selected from a competitive process, included 22 educators from 15 states including: Arkansas, Connecticut, California, Florida, Georgia, Maine, Massachusetts, New York, North Carolina, Ohio, Oregon, Rhode Island, Tennessee, Texas, and Washington, as well as Australia. Fellows represented formal education institutions from the elementary to college level, encompassing homeschool, special needs education, and public, private, and charter schools. Informal educators came from backgrounds as diverse as National Public Radio, outdoor education and leadership, municipal and national museums, science centers, and arts education.

Artist-at-Sea Program

The Corps of Exploration embraces the way artistic expression and creativity complement the curiosity-based process of exploration. OET was proud to host its second year of the Artist-at-Sea Program and brought two artists on board in 2015. Having artists on board allowed OET to integrate the arts into our outreach programs to effectively transform the focus on STEM into STE[A]M education. Artists are powerful role models for young followers of the expedition who, through these creative outlets, may have seen themselves in a scientific endeavor for the first time.

Rebecca Rutstein, an award-winning visual artist based in Philadelphia, sailed during the seafloor mapping expedition from the Galápagos Islands to California as *Nautilus* revealed hidden seafloor features along the transit route. Using mesh-grid digital elevation models of data gathered only hours before, Rutstein projected and painted landscapes on canvas, incorporating scientific data and ship movement in her work. These painted canvases created studies for her large-format paintings she would work on once she returned home. Karen Romano Young, a children's book author and illustrator, returned this season as a Lead Science Communication Fellow. While aboard, she was keen to learn about the different perspectives and resolutions mapping technologies provide. Romano Young is in the process of writing and illustrating a book for upper elementary and middle school students that will show how mapping, plate tectonics, and submersible technology have come together to make revolutionary deep-sea discoveries. The book features the *Nautilus* Exploration Program mapping efforts and members of the Corps of Exploration.



(above) Artist-at-Sea Rebecca Rutstein works in the lab aboard *Nautilus* painting seafloor bathymetry data as they are acquired with the ship's multibeam echosounder. (right) Rutstein's painting of seafloor features seen in bathymetric data off of the Galápagos Islands. Galápagos Seamounts II, 10" x 30", acrylic on canvas.

The excitement and interdisciplinary nature of ocean exploration provides a window to the great opportunities available for future scientists and engineers. By igniting interest in ocean exploration through the Community STEM Program, we hope to motivate more students to be lifelong learners and pursue careers in STEM disciplines. It is our goal to use all of our education programs and outreach efforts to inspire the next generation of explorers and to ensure any child can find a STEM role model within the *Nautilus* Corps of Exploration and from within their own community.

E/V *Nautilus* Field Season Overview

By Katherine L.C. Bell

The 2015 field season charted new waters for Exploration Vessel *Nautilus*, as we entered the Pacific Ocean for the first time. From May to September, the Ocean Exploration Trust and our 217 participants from 94 organizations in 18 countries undertook nine remotely operated vehicle (ROV) and four mapping cruises beginning in the Gulf of Mexico, transiting through the Panama Canal, then up the west coast of Central and North America. The expedition was composed of a combination of Basic Exploration and Applied Exploration cruises. Basic Exploration locations and objectives are chosen based on community-driven workshops and are funded by the NOAA Office of Ocean Exploration and Research through a grant under our Memorandum of Agreement. Applied Exploration cruises are directed by scientists who fund shiptime aboard *Nautilus* and take advantage of our telepresence capabilities and extensive education and outreach network to reach broad audiences during expeditions.

The season began with a shakedown cruise from St. Petersburg, Florida, to Gulfport, Mississippi, to perform patch tests on our multibeam echosounder and test the *Hercules*/*Argus* ROV system. With all systems ready, we began our final projects in the Gulf of Mexico with Applied Exploration collaborators with whom we have worked for the past three years. The Gulf Integrated Spill Research (GISR) Consortium continued measuring the natural gas budget for bubbles released at the Sleeping Dragon seep in the northern Gulf of Mexico (**pages 26–27**), and the Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) Consortium continued studies of the effects of oil and dispersant on corals and closely related communities affected by the 2010 Deepwater Horizon oil spill (**pages 28–29**). The final two cruises in the Gulf of Mexico were a combination of Applied Exploration, funded by the Max Planck Institute for Marine Microbiology, and Basic Exploration. These projects were a complementary effort to characterize cold seep features of the deep Gulf of Mexico through experimental laser spectrometry, high-resolution mapping of a brine pool, and biological sampling and experimentation (**pages 30–31**).

At the end of May, we began the long transit through the Gulf, Caribbean Sea, and Panama Canal, and on to the Galápagos Islands, where we began a series of Basic Exploration cruises in regions identified as high priority target areas during the 2014 Eastern Pacific Workshop (Bell et al., 2015). On the Galápagos Platform, we explored several seamounts and submarine flanks of the larger islands in order to characterize their deepwater biological communities and also examined the geological formations that make up the foundation of the Galápagos archipelago (**pages 32–34**). Our work on the Galápagos Rift involved returning to some known hydrothermal sites as well as exploring the area for unknown sites (**pages 35–37**). Both of these campaigns resulted in incredible biological and geological discoveries, which are currently being analyzed.

Given that a very small fraction of the world's seafloor has been mapped, we took advantage of the long transits between Galveston, Texas, and the Galápagos Islands, and the Galápagos and California to collect multibeam echosounder data and train new seafloor mappers on *Nautilus* systems. These mapping transits resulted in the identification of previously unknown seafloor features, and the resulting maps are being made available to interested stakeholders (**pages 38–39**).

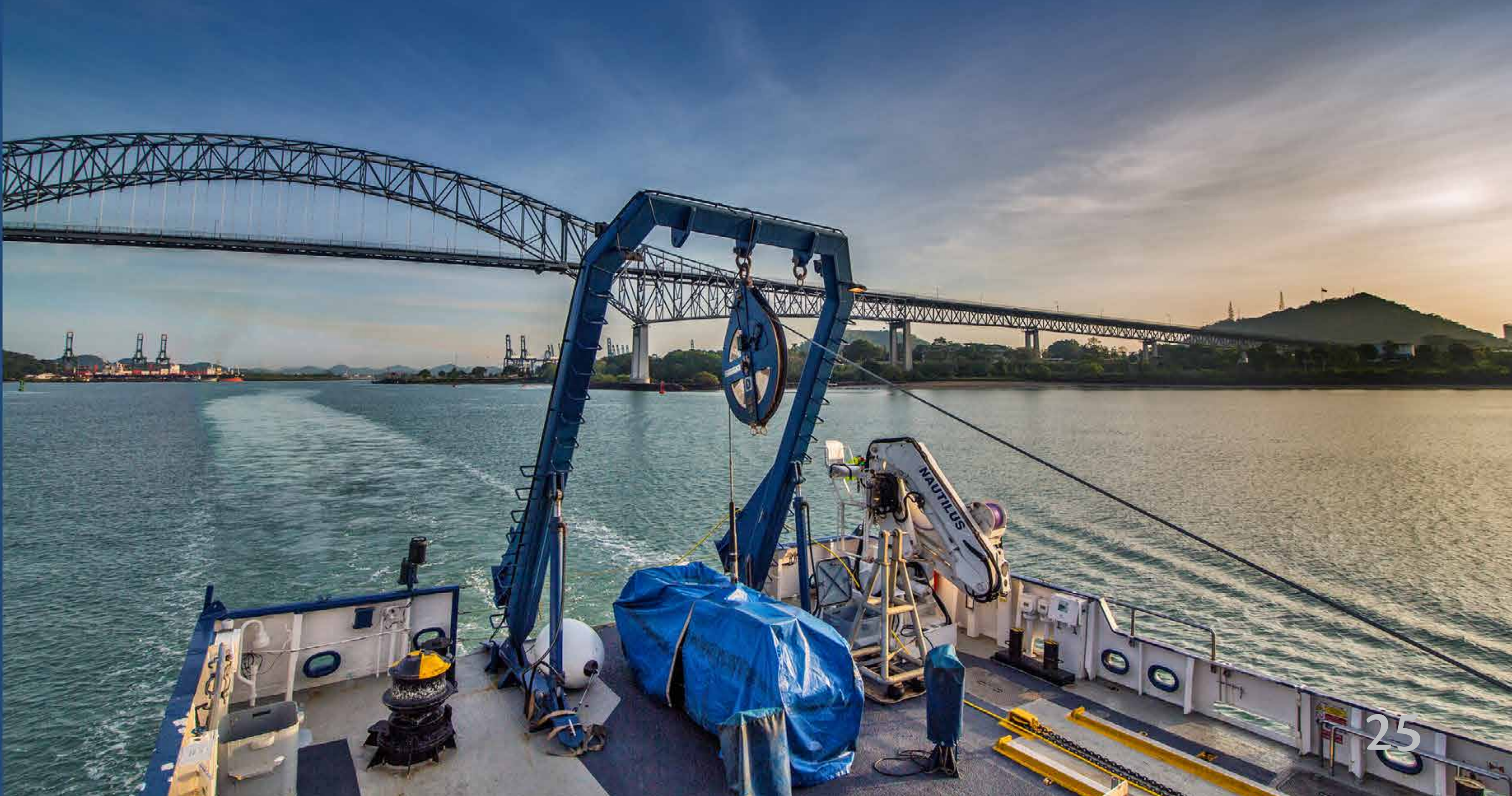
Following the long transit from the Galápagos, we worked our way up the California coast, where we discovered extensive areas of hydrocarbon seeps. Some of these areas spanned oxygen minimum zones where we observed biological systems living close to one another but in very different environmental conditions (**pages 40–43**). Within the Monterey Bay National Marine Sanctuary, we also dove on and mapped at high-resolution the wreck site of USS *Macon*, the only surviving remains of a US Navy Akron-class rigid airship (**pages 44–45**).

We completed the season in September, working with Ocean Networks Canada on a final Applied Exploration project in an effort to service the VENUS and NEPTUNE cabled observatories, as well as to conduct additional scientific exploration in nearshore areas off the coast of British Columbia (**pages 46–47**). *Nautilus* is wintering over in Victoria, British Columbia, and we are planning to begin our next field season off the Pacific Northwest in May 2016.

It is our intention to have *Nautilus* remain in the Pacific for the foreseeable future, working in the eastern Pacific in 2016 and 2017, in the central Pacific in 2018 and 2019, and the western Pacific in 2020 and beyond. The specific locations and objectives of our Basic Exploration projects will be determined by active participation of the oceanographic community in our biannual workshops and Scientists Ashore program, and we look forward to expanding our network of scientists involved in these programs. Similarly, as we expand to new operating areas, we are also open to new Applied Exploration opportunities in the Pacific Ocean. Should you be interested in using *Nautilus* to conduct either seafloor mapping projects or ROV operations, please contact charters@oceanexplorationtrust.org. We look forward to working with you.

2015 *Nautilus* Season at a Glance

15	Cruises
143	Days
98	ROV dives
1,028.5	Hours in the water (42.85 days)
688	Samples collected (2,339 subsamples)
86,924.36	Square kilometers mapped



Fate and Transport of Gas Bubbles from Sleeping Dragon Seep in the Northern Gulf of Mexico

By Scott A. Socolofsky, Andone Lavery, John Kessler, Binbin Wang, John A. Breier, Mihai Leonte, Eric Chan, and Nicole A. Raineault

Knowledge of the fate of hydrocarbon bubbles and droplets in the ocean is important for understanding the behavior of accidental subsea oil well blowouts and for quantifying the global geochemical cycles of hydrocarbons released at natural seeps. The purpose of the G08 (NA056) cruise on E/V *Nautilus* was to measure a complete natural gas budget for bubbles released at the Sleeping Dragon seep in the northern Gulf of Mexico (28°51.1421'N, 88°29.5109'W). This cruise was part of the Gulf Integrated Spill Research (GISR) Consortium, funded by the BP/Gulf of Mexico Research Initiative (GoMRI). The GISR Consortium objective is to understand and predict the behavior of petroleum fluids in the ocean environment to help prevent or mitigate the effects of future subsea oil spills.

A comprehensive mass budget for free and dissolved natural gas at the Sleeping Dragon seep was obtained using several measurement systems mounted on ROV *Hercules* and E/V *Nautilus*, as follows:

SUPR SAMPLER. This instrument uses a 14-valve pump system to collect precision, high-throughput samples of discrete geochemical features in the water column. It was used to obtain samples of water exiting the seafloor at seeps, water column profiles of seep plumes at different heights above the seafloor, and background samples in and around the plumes (Figure 1). For this cruise, some samples were collected in 2 L bottles for chemical analysis and others were collected into 15 L impermeable bags for biodegradation experiments.

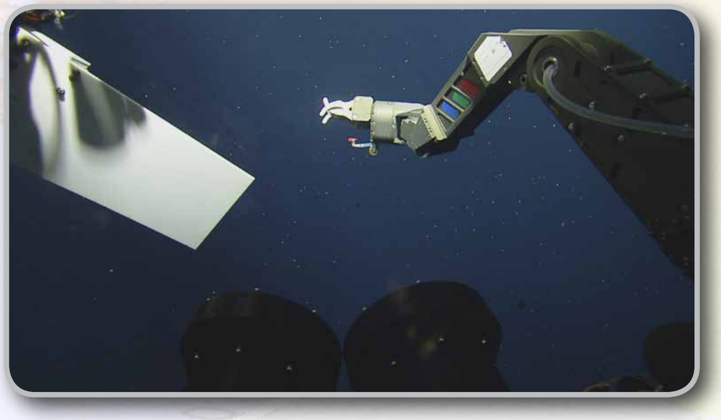


Figure 1. The SUPR sampler collecting a water sample high above the main flare of the Sleeping Dragon seep at about 100 m altitude. Intake is through the tube attached to the starboard manipulator arm of ROV *Hercules*. The back plate for the TAMU-CAM system is attached to the port manipulator arm, and the camera pressure housings are partially visible at the bottom of the image.

ROCHESTER BIODEGRADATION BAGS. The SUPR sampler 15 L bags with a gas-impermeable membrane were used to collect samples at the seep source and also high in the water column. These samples were then incubated on the ship in a constant-temperature refrigerator set to conditions at the sample location. Incubation continued at Stennis Space Center following the cruise. The incubated samples were periodically tested for methane, oxygen, and a host of complementary attributes, including microbial DNA. These experiments help to quantify the biodegradation rate for these seeps and to identify type and abundances of microbes responsible for the consumption of dissolved natural gas.

GAS SAMPLER. Gas bubbles were collected using an atmospheric pressure sampler borrowed from David Valentine (University of California, Santa Barbara) and a custom device rigged from a Niskin bottle. The principle of this instrument is to trap gas in a sample chamber that is isolated from atmospheric contamination. Gas samples were collected by *Hercules* at the seep source and analyzed by gas chromatograph to obtain the composition of the emitted natural gas.

TEXAS A&M UNIVERSITY (TAMU) HIGH-SPEED CAMERAS. Two high-speed Phantom cameras from Vision Research (Miro cameras) were used in a stereoscopic configuration to make high-speed, high-resolution image sequences of bubbles and droplets within the seep plumes. A white back plate was used to enhance the image quality of the bubbles (Figure 1). The gas bubbles dissolve and shrink with increased altitude, results that are quantified for selected images at the seafloor, at 200 m, and at 300 m altitude above the seafloor (Figure 2).

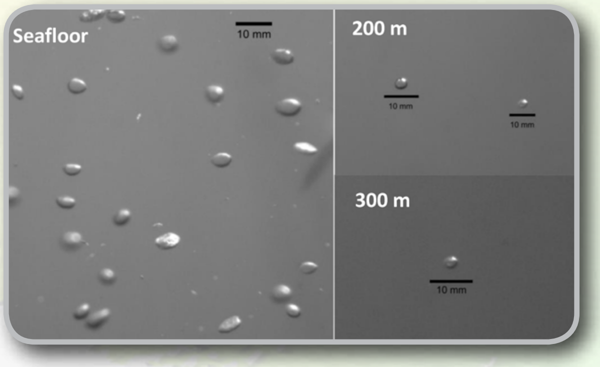


Figure 2. Images of seep bubbles from the TAMU-CAM at altitudes of 1.5 m, 200 m, and 300 m. A 10 mm scale is shown in each camera frame for reference.

Figure 3. Four down-looking, broadband acoustic transducers mounted on the back of ROV *Hercules*; the far-right instrument is a Doppler velocity log.

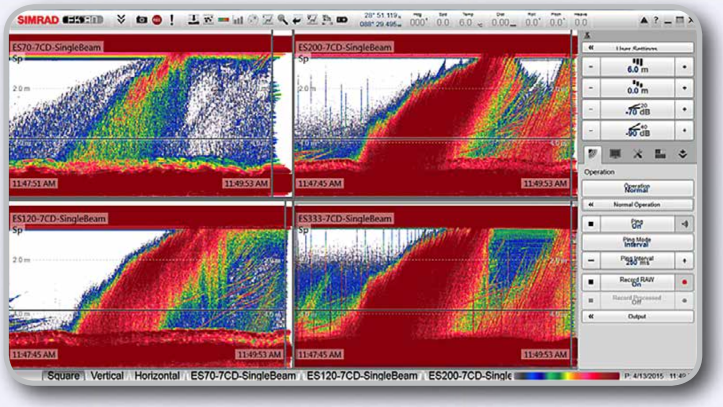


Figure 4. Broadband acoustic backscattering data collected by the Simrad system mounted on ROV *Hercules* with 70, 120, 200, and 333 kHz transducers during a transect at 5 m above the Sleeping Dragon seep on April 13, 2015.

WOODS HOLE OCEANOGRAPHIC INSTITUTION (WHOI) BROADBAND ACOUSTIC SYSTEM. An acoustic array of four approximately octave-bandwidth piston transducers with center frequencies of 70, 120, 200, and 333 kHz was mounted on the rear lower bar of ROV *Hercules* in a down-looking orientation (Figure 3). The system allows tracking and imaging of bubbles as well as quantification of their sizes and structures based on the resonant frequency of particles in the imaging path. The tracks of individual bubbles are clearly visible as thin lines in the transducer output; in regions of higher bubble concentration, the flare appears as a strong, red water-column return. Sample backscatter data from a transect 5 m above the Sleeping Dragon seep reveals the plume (Figure 4).

FORWARD-LOOKING KONGSBERG M3 SONAR. An additional acoustic system was used to track the bubble column flares and position the ROV relative to the plume for each water column measurement. M3 data were used successfully to visualize the weak bubble plumes for over 500 m of rise above the seep sources. This information allowed the shipboard crew to maneuver *Hercules* to a plume at any height and also to measure plume cross-sectional dimensions as a function of height above the bottom.

Additional measurement systems on board *Nautilus* provided a means to close the mass balance for the emitted gases. An air-sea flux system integrated several instruments to capture the mass transfer at the air-water interface, including an anemometer with co-located air sampler and a flow-through system for collecting seawater from the upper mixed layer. Both the flow-through air and seawater samples were analyzed in real time for methane and carbon dioxide concentrations using a cavity-ringdown spectrometer (CRDS) as well as a gas chromatograph with a flame ionization detector (GC-FID) installed in the wet laboratory. Spatial air-sea flux data were acquired along survey paths coordinated with the multibeam surveying.

Between ROV dives, multibeam echosounder surveys were conducted along repeated ship tracks to measure the acoustic backscatter from bubble plumes in the water column to capture the evolution of the plume trajectories as currents changed. Post-processed multibeam data show the trajectory and height of rise of bubble flares from the Sleeping Dragon seep (Figure 5). ROV observations of the gas bubbles in the water column confirm that the multibeam detects the bubbles until they are dissolved. Plumes were not observed in the multibeam data above approximately 300 m depth, which corresponds to the maximum height of detection by both the M3 and the WHOI broadband acoustic system.

Together, these measurements quantify the flux and composition of natural gas emitted at the seafloor, the evolution of bubble properties as the bubbles rise through the water column, gas concentrations in the water near the seep plume and associated biodegradation, and the spatial variability of methane flux at the air-sea interface.

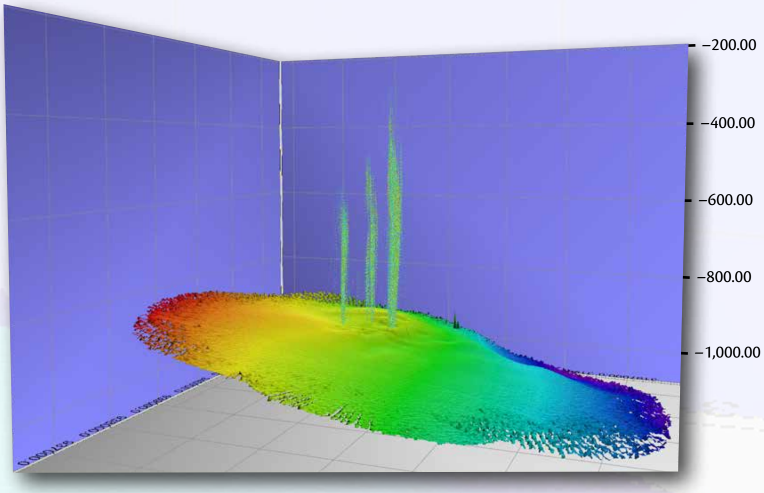


Figure 5. Visualization of the Sleeping Dragon seep flare using the *Nautilus* multibeam sonar. The visualization was created using the Fledermaus software package courtesy of Katie Hutschenreuter, a graduate student working with Scott A. Socolofsky.

ECOGIG: Oil Spill Effects on Deep-Sea Corals Through the Lenses of Natural Hydrocarbon Seeps and Long Time Series

By Erik E. Cordes, Steven Auscavitch, Iliana B. Baums, Charles R. Fisher, Fanny Girard, Carlos Gomez, Jennifer McClain-Counts, Howard P. Mendlovitz, Miles, Styles Smith, Samuel Vohsen, and Alaina Weinheimer

The 2015 Ecosystem Impacts of Oil and Gas Inputs to the Gulf (ECOGIG) expedition was a continuation of a three-year partnership between our Gulf of Mexico Research Institute-funded research consortium and the Ocean Exploration Trust to study the effects of oil and dispersant on corals and closely related communities affected by the 2010 Deepwater Horizon oil spill (White et al., 2012, 2014; Hsing et al., 2013; Fisher et al., 2014a,b; Figure 1A– C). As part of our analysis, we explored a new site to the west of the Macondo well in lease block Mississippi Canyon (MC) 462 where we examined 50 new corals for impact from the spill (Figure 1D). A total of over 250 corals were re-imaged in 2015 for this ongoing time-series study. Another goal was to initiate a study to determine how proximity to natural seeps affects corals and infauna in these communities.

On this cruise, four new study sites were established in areas that host large coral communities: Atwater Valley 357, Green Canyon 234, Mississippi Canyon 751, and Mississippi Canyon 885. In each area, we established two sets of study sites, one close to seeps and another away from any visual evidence of seepage. At some of these hydrocarbon seep sites, one coral species in particular, *Callogorgia delta* (Figure 2F), is able to survive and, in fact, thrives (Quattrini et al., 2013). Stable carbon ($\delta^{13}C$) and nitrogen ($\delta^{15}N$) isotope analyses of tissue samples revealed that some of the corals collected near signs of active seeps have incorporated seep primary production into their tissues (unpublished data of author Charles R. Fisher). Other subsamples from the corals will be used to determine whether exposure to oil and gas induces changes in gene expression either in the corals or the microbial communities associated with the corals. Metabolomic analysis of coral tissues is also in progress to determine whether the metabolomes (the complete sets of small-molecule chemicals found within biological samples) of corals collected near and far from active seeps differ. These studies will improve our understanding of observed responses documented in corals exposed to high concentrations of oil and dispersant during the Deepwater Horizon oil spill.

Also during this expedition, we collected a variety of corals at four different sites spanning a depth range from 394 m to 1,060 m for laboratory-based analyses and experiments with live specimens (Figure 2). These collections included the scleractinian coral *Lophelia pertusa*, the black coral *Leiopathes glaberrima*, and the octocorals *Paramuricea* sp., *Callogorgia delta*, *Muriceides* sp., *Chrysogorgia* sp., *Clavularia rudis*, and two colonies that represent two different species of bubblegum corals. *Lophelia pertusa*, *Callogorgia delta*, *Muriceides* sp., *Paramuricea* sp., and *Leiopathes glaberrima* were kept alive during the cruise and transported to Temple University and Pennsylvania State University, where marine aquaria in our laboratories provide their basic requirements for survival and growth. Keeping live corals enables us to conduct experiments that will help to answer questions related to the corals' responses under different anthropogenic stressors such as climate change and oil exposure. After six months, these corals remain in excellent condition (Figure 3), and some of them have grown measurably. Corals were also collected for morphological analyses to address questions related to their ecology and evolution, and to determine how the different environmental conditions

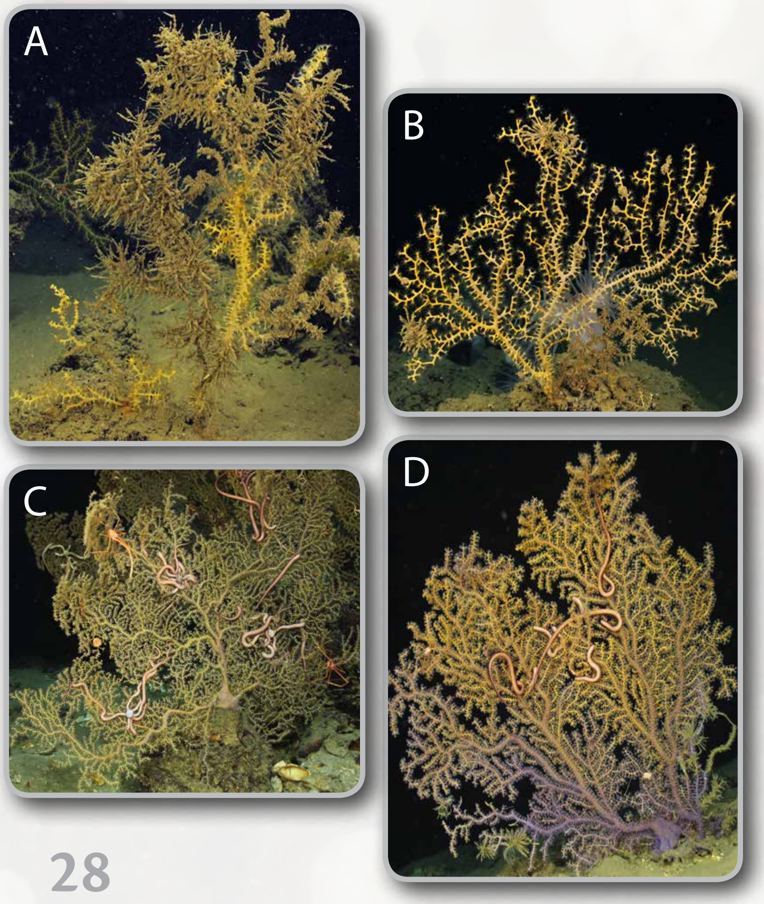


Figure 1. Images taken in 2015 for monitoring of coral impact and recovery from the 2010 Deepwater Horizon oil spill in the Gulf of Mexico. (A) *Paramuricea biscaya* at the first site observed with damaged corals in lease block Mississippi Canyon (MC) 294. Note extensive hydroid growth over most of the remaining colony branches. (B) *Paramuricea biscaya* from the site in lease block MC 297 first seen in 2011, with patchy hydroid growth on damaged portions of the colony. (C) *Paramuricea* sp. b3 from a control site in lease block Atwater Valley 357, with associated brittle stars and crabs and no apparent damage to the colony. (D) *Paramuricea* sp. b colony from a new site for this study in lease block MC 462, with attached brittle star and hydroid growth on damaged portions near the sediment surface.

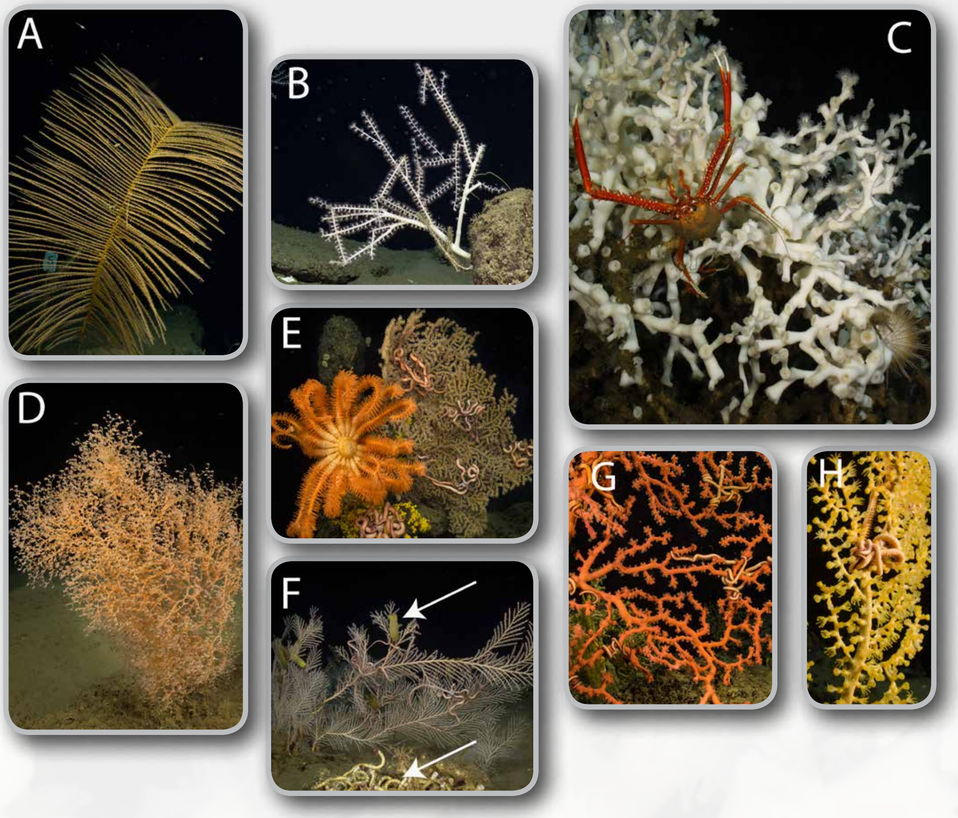


Figure 2. Representative deep-sea corals photographed and collected during *Nautilus* cruise NA057. (A) Black coral *Bathypathes* in lease block MC 344 at 1,850 m depth. (B) Bamboo coral (Subfamily Keratoisidinae) found at ~1,800 m depth in MC 344. (C) *Lophelia pertusa* from Viosca Knoll 906 photographed at 400 m depth. (D) *Chrysogorgia* sp. found at ~960 m depth in MC 462. (E) In a typical deep-sea association, octocorals of the genus *Paramuricea* and different species of brittle stars and sea stars top a small boulder in a photograph taken in MC 462 at ~1,000 m depth. (F) *Callogorgia delta* were often observed growing close to seepage activity in association with the tube worm *Lamellibrachia luymesi* (bottom arrow) and scyliorhinid catshark egg cases, which attach to branches (upper arrow). MC 885 is at ~640 m depth. (G) Bubblegum coral *Paragorgia* cf. *regalis* photographed in MC 294 at 1,370 m depth. (H) *Paramuricea* cf. *biscaya* with a brittle star associate, also in MC 294.

found at various depths affect patterns of community assembly.

Seawater samples were collected with Niskin bottles mounted on the remotely operated vehicle (ROV) *Hercules* directly above different *L. pertusa* reefs to characterize the seawater chemistry around these coral mounds. These samples will be used to continue our investigations on the effects of ocean acidification in coral habitats. *L. pertusa* has been shown to survive and grow under some of the most adverse conditions known for colonial stony corals (Lunden et al., 2013; Georgian et al., in press), and we continue to examine the processes that underlie these abilities in order to provide insight into the responses of all scleractinian corals to ocean acidification.

Sediment push cores also were collected for multiple analyses, including microbiome, macrofaunal abundance and biodiversity, isotope ($\delta^{13}C$, $\delta^{14}C$, and $\delta^{15}N$), and particle size. Sediments were collected adjacent to corals sampled in previous years in order document further changes and potential recovery of the macrofaunal community structure following the oil spill. As part of our study of the microbes associated with corals and the effects of natural seepage on the coral microbiome, we examined the microbial communities found in sediment beneath coral colonies, as well as from the water around the corals. In order to collect enough bacteria from the water near the corals for this study, we used a submersible pump (McLane Research Laboratories model WTS-LV) on loan from the Max Planck Institute for Marine Microbiology in Bremen, Germany. The pump filtered bacteria from 40 liters of water near the corals while *Hercules* was busy with other tasks on the seafloor.

Together, these studies provide a holistic view of the ecology and physiology of deep-sea corals in their habitats. By combining the expertise of investigators with diverse interests, we hope to gain a better understanding of these remarkable ecosystems. It is only through this integrative approach that we can fully understand the response of corals to anthropogenic impacts and work to preserve them from future human disturbance in deep waters.

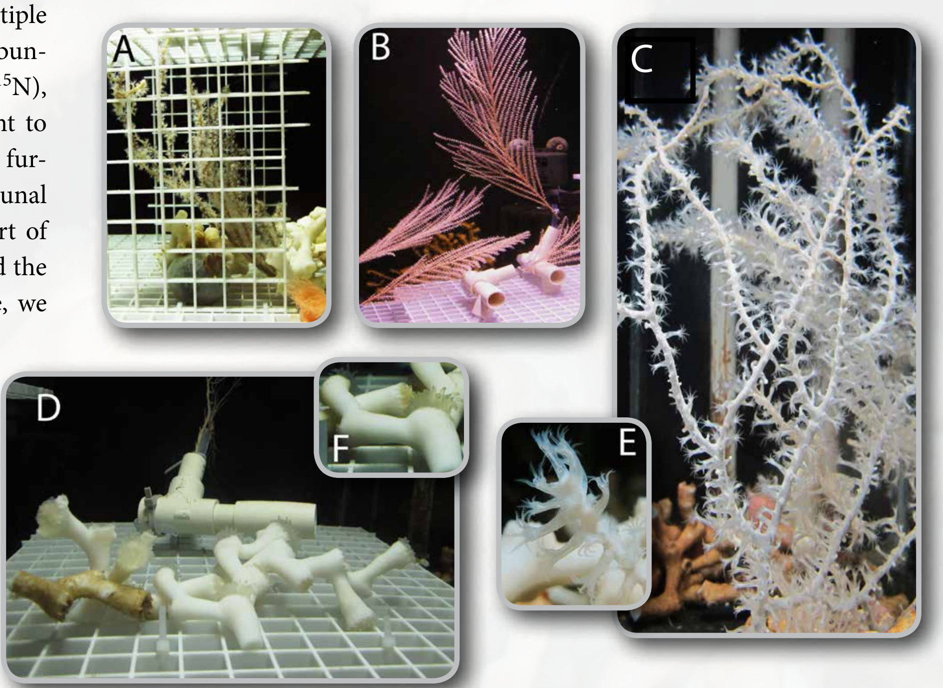


Figure 3. Octocoral colonies collected at 445 m water depth in MC 751 during *Nautilus* cruise NA057 and kept alive at Temple University. (A) *Paramuricea* sp. (B) *Callogorgia delta*. (C and E) *Muriceides* cf. *hirta*. (D and F) The scleractinian coral *Lophelia pertusa* collected at Viosca Knoll 906 at 400 m depth.

ROV *Hercules* Investigates Brine Lakes on the Bottom of the Ocean

By Erik E. Cordes, Anna P.M. Michel, Jillian M. Petersen, Scott D. Wankel, Rebecca Ansorge, Peter R. Girguis, Nikolaus Leisch, Clara Smart, Chris Roman, Silke Wetzel, and Charles Vidoudez

During two cruise legs of the 2015 E/V *Nautilus* field season, the remotely operated vehicle (ROV) *Hercules* was deployed to examine some of the cold seep features of the deep Gulf of Mexico. Cold seeps are locations where hydrocarbons that are normally trapped deep beneath the seafloor escape into the water column. The hydrocarbons are forced out from the depths by the movement of large salt bodies that developed over the course of several million years as water evaporated from an ancient shallow Gulf of Mexico (Brooks et al., 1987). Shifting of these salt layers produces cracks in the oil-bearing shale that provide pathways for upward migration of oil and gas.

At some seep sites, deep within the sediments, the interaction of porewater and salt results in a highly saline fluid (brine) that can be more than four times more saline than seawater. When this brine is expelled from the sediments, it is far denser than the overlying seawater and does not mix very easily with it. In some cases, the brine forms large pools, or even rivers, as we discovered on one of the ROV dives at a site called Garden Banks 903. The dive started at the lower end of a canyon, where large mud flows were descending the steep slope. At the entrance to the canyon, we could see small carbonate outcrops and mussel beds containing *Bathymodiolus childressi*. As *Hercules* continued into the canyon, it encountered a very steep wall with what appeared to be flows of red, white, and yellow streaming over the edge (Figure 1). When *Hercules* crested this small wall, the cameras brought a pool of brine into view. The walls of the pool were made up of barite, a barium sulfate precipitate, and the red coloration was likely from high concentrations of iron in the fluids. The fluid also contained high concentrations of both sulfide and methane. As *Hercules* continued up the brine river, there was evidence of flowing brine all along the narrow valley, with more pools at certain points where the flows were obstructed. Some were clear and white, and some had reddish walls indicative of iron precipitates. This site requires more study to understand what is happening in this environment.

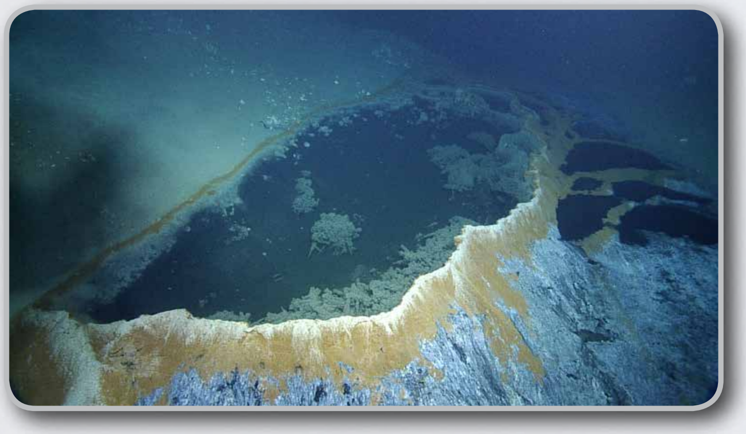


Figure 1. A brine pool, with walls made up of barite.

At active seep sites where methane and hydrogen sulfide are expelled at the sediment-water interface, large mussel beds can form (reviewed in Cordes et al., 2009). Here in the deep sea where food is generally scarce, bacterial symbionts in the mussels' gills allow them to use dissolved gases being emitted at the seafloor as a source of energy. We collected mussels at two different sites. At the first site, lease block Mississippi Canyon 853, two species of mussels co-occurred on rough topography made up of small hills and valleys. The mussels and seep areas were mostly located at the bottoms of long trenches, and we flew *Hercules* through a few of them in search of a good sampling location, observing a few well-developed mussel beds along the way. Some contained both of our target species, *B. childressi*, along with its methane-oxidizing symbionts (Fisher et al., 1987), and *Bathymodiolus brooksi*, with multiple symbiont types (Duperron et al., 2007). The second mussel sampling site was at Green Canyon 234, one of the largest and best known seeps in the Gulf of Mexico. There, a dense, football-field-size expanse of vestimentiferan tubeworms (with sulfide-oxidizing symbionts) blankets the seafloor. Beds of *B. childressi* mussels are found in some areas and carbonates with deep-sea corals (the sea fan *Callogorgia delta*) in others. In addition, areas of outcropping gas hydrates are colonized by a unique species of polychaete worm, *Hesiocaeca methanicola,* known as the ice worm (Fisher et al., 2000).

To better understand why these seep communities exist where they do—and why they are composed of different assemblages—we fitted *Hercules* with an in situ mass spectrometer (ISMS) and a laser spectrometer to provide real-time information on the chemical composition of the hydrocarbon seeps while we were exploring the sites. These types of novel sensors also collect important information on the sources of these fluids and on the energy-rich compounds contained in them that allow these types of animals to thrive.

To examine free-living and symbiotic microbial metabolisms and how they influence local carbon, nitrogen, and sulfur cycles, we employed the ISMS to analyze water samples for dissolved hydrogen, methane, sulfide, oxygen, and other volatile content. Preliminary analyses show elevated concentrations of dissolved sulfide and methane in the flowing brines, which constitute a conduit for the rapid transport of these reduced compounds across the seafloor. Finer-scale studies of the mussel communities suggest patchy availability of methane and sulfide within and among clumps. The ISMS data will also help us understand how the chemical environment dictates the activity of the symbiotic bacteria and thus the health of the mussel hosts.

On the last leg of these seafloor hydrocarbon community investigations, we focused on a larger brine pool dubbed the "Jacuzzi of Despair," in reference to its warm temperature (19°C) and high salt content—which can be fatal to many macrofauna unlucky enough to fall in (we observed large dead isopods and crabs that had been preserved along the edge of the brine pool). This crater-like, circular, brine-filled pool rose 3 m above the surrounding seafloor, and brine was spilling out on one side in a spectacular "waterfall."

One of the main purposes for visiting this brine pool was to conduct a high-resolution mapping survey (Figure 3) and to remotely detect density stratification within the pool using the 1.35 MHz multibeam sonar. The instrument registered two distinct returns, one from the surface of the brine pool and an additional return 3 m below. A conductivity-temperature-depth (CTD) sensor coupled to a hose reel was used to verify the multibeam results and provide a way to sample pool fluids (Figure 4). The top layer of the brine pool (surface down to 3 m depth) had very high salinity (80–110 psu) and a temperature of 7.8°C. Below this layer, we found dense, hydrocarbon-charged, fluidized mud at a temperature of 19°C. The sampling line and CTD were lowered ~19 m into the pool but never reached a hard bottom—shedding new light on the nature of these "bottomless" brine pools. At two locations within the brine pool, methane bubbles were observed rising toward the surface.

Throughout the exploration and sampling, we continuously pumped sample fluids past the inlet of the deep-sea laser spectrometer (Wankel et al., 2013) on *Hercules*, which was being used to measure carbon isotopes of the methane and carbon dioxide within the fluids. The carbon isotopes of methane can be used to "fingerprint" and understand its geologic source, while the carbon isotopes of the carbon dioxide were analyzed to assess how much methane was being microbially converted into carbon dioxide. Our preliminary analyses confirmed that this brine pool was saturated with methane. Ongoing analysis of this experimental spectral data, together with high-resolution three-dimensional mapping, will provide a more detailed picture of the physical and biogeochemical processes at work in these extreme environments. This information helps us to estimate the amount and extent of microbial processes occurring in such environments and to better understand how these ecosystems are initially formed, how they change over time, and what controls the differences among them that we observed on these and other expeditions.

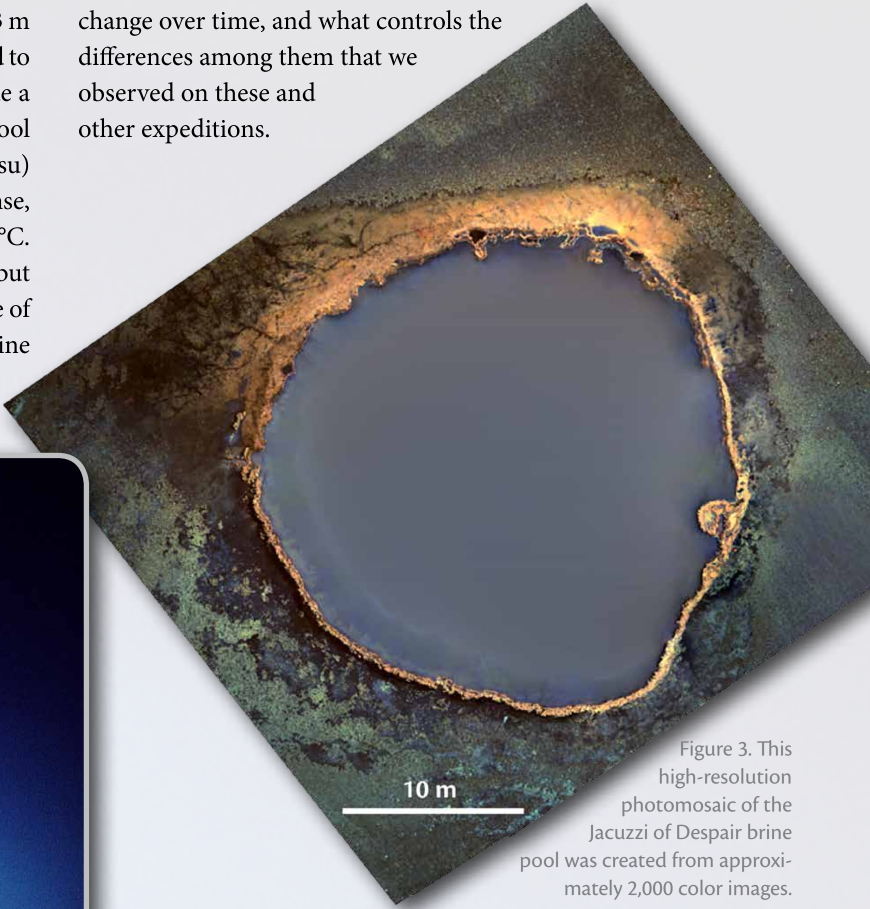


Figure 3. This high-resolution photomosaic of the Jacuzzi of Despair brine pool was created from approximately 2,000 color images.

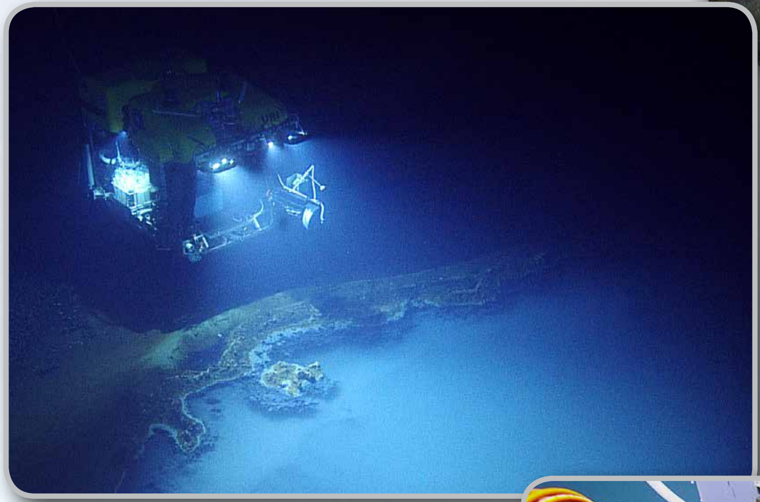


Figure 2. ROV *Hercules* explores the large brine pool called "Jacuzzi of Despair."

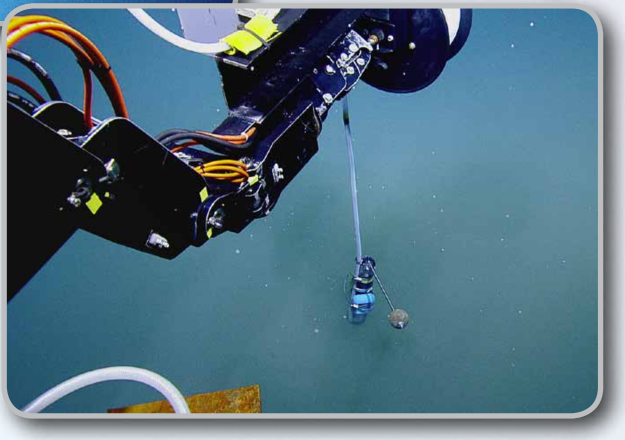


Figure 4. A conductivity-temperature-depth (CTD) sensor was used to measure the temperature and salinity deep within the brine pool. A sampling line attached to the CTD allowed brine fluids to be analyzed using a laser spectrometer located on ROV *Hercules*.

Exploring the Undersea World of the Galápagos Islands

By Steven Carey, Charles R. Fisher, Pelayo Salinas de Leon, Chris Roman, Nicole A. Raineault, Jennifer Suarez, Clara Smart, Renato Kane, Suna Tüzün, Jacob Balcanoff, Megan Lubetkin, Meghan Jones, Darin Schwartz, Daniel Fornari, Adam Soule, Dorsey Wanless, Les Watling, and Robert D. Ballard

The Galápagos Islands have been the focus of intense scientific study since Charles Darwin visited them in 1832 aboard HMS *Beagle*. His studies led to a revolution in the biological sciences and the formulation of the theory of evolution. Significant progress has been made toward understanding the biodiversity and geological formation of the islands, although much of this has centered on the subaerial, coastal, and shallow subtidal portions of the region. In contrast, most of the deep undersea environment surrounding the Galápagos Islands remains unexplored. E/V *Nautilus* cruise NA064 in June/July 2015 conducted operations on several seamounts and submarine flanks of the larger islands in order to characterize the deepwater biological communities and explore the geological formations that make up the foundation of the Galápagos archipelago. The areas explored all lie within the Galápagos Marine Reserve (GMR), a sensitive area that is targeted for preservation and management by the Galápagos National Park Directorate (Figure 1). Data and samples collected on the cruise are expected to make a significant contribution to the current rezoning of the GMR to minimize human impacts on its ecosystems.

The area to the northwest of the main Galápagos Islands, near Wolf and Darwin Islands, contains numerous seamounts, some arranged linearly, that extend to the Galápagos Spreading Center. Seamounts are of particular interest because they occur at a variety of depths and provide hard surfaces for the development of deepwater coral and sponge communities. They also lead to local upwelling of nutrients that foster enhanced fish populations, and can be the sites of hydrothermal mineralization and concentrations of economically important resources. During the first part of the cruise, three seamounts to the east and north of the Wolf-Darwin chain were explored with the *Hercules* remotely operated vehicle (ROV) in a series of transects that began in deep water on the southeast sides of the seamounts and ended in shallower water at the summits (Figure 1, area A). All the seamounts are conical with relatively flat tops and small summit craters. Each is quite distinct, with different substrates and slopes, and different fauna observed at various depths. The shallowest seamount studied extends from 1,100 m depth to approximately 300 m at its rim. This seamount harbored the highest faunal biomass, including a rich diversity of both sessile and mobile animals (Figure 2). Several of the corals collected are likely to be new species, but the

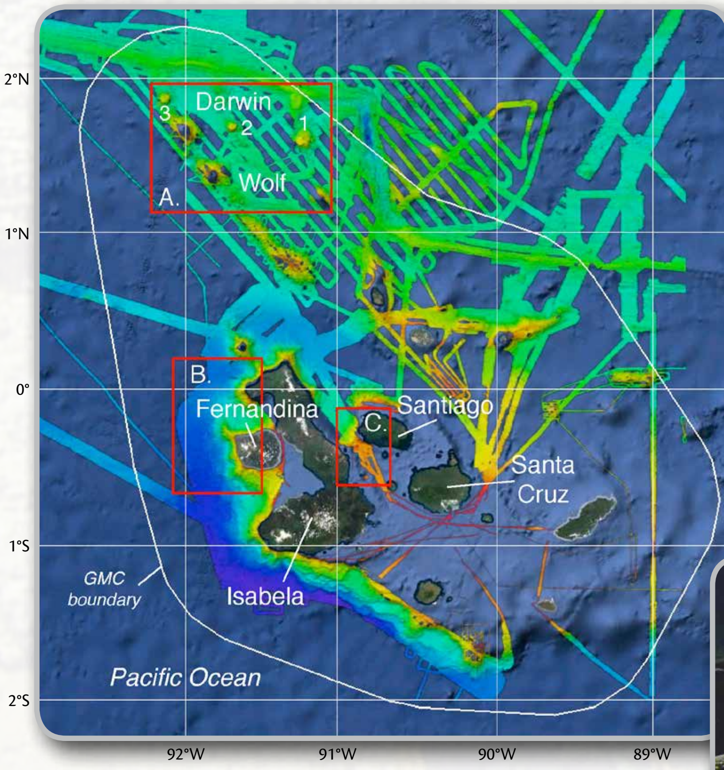


Figure 1. Operational areas for E/V *Nautilus* cruise NA064 on the Galápagos island platform. The white line circles the boundary of the Galápagos Marine Reserve (GMC). Area A: Seamounts 1, 2, and 3 to the northeast of the main Galápagos islands in the vicinity of the Wolf-Darwin seamount chain. Area B: Deepwater lava flows west of Fernandina Island. Area C: Shallow submarine cones between Isabela and Santiago Islands. Multibeam bathymetry courtesy of NOAA's National Centers for Environmental Information, S. White, A. Soule, D. Fornari, E. Mittelstaedt, K. Harpp, M. Kurz, and J. Sinton.

Figure 2. Coral and sponge colonization on the surface of a relatively recent basaltic lava flow on the slopes of a Galápagos seamount. Water depth is ~850 m.

Figure 3. Pancake batfish on the slope of Galápagos seamount 1. Water depth is 1,181 m.

Figure 4. Hydrothermal tube deposits near the summit of Galápagos seamount 3 (see Figure 1 for location). Broken crust at lower left-hand side reveals bright green nontronite and reddish-orange iron oxide precipitates. Water depth is 1,228 m.

Figure 5. Giant solitary octocoral colonizing a hydrothermal tube deposit near the summit of Galápagos seamount 2. No giant solitary octocorals have previously been known from this region.

highlights were arguably some of the non-coral fauna. Very early in the dive, we collected a pancake batfish that has never before been documented in the region and that may prove to be new to science (Figure 3). In the middle of this dive, what appeared from a distance to be a branching coral was suspected to be a glass sponge upon closer examination. Shore-based scientists agree this is a completely unknown species, with perhaps a new type of sponge growth morphology. The dive was topped off at the summit when *Hercules* encountered hammerhead sharks. These sightings confirmed data from acoustically tagged individuals that suggest sharks might visit these seamounts from their well-known habitats off the shores of Darwin and Wolf Islands to the west.

The other two seamounts were in deeper water, with their bases at about 2,000 m depth and summits just near 1,000 m. Both had generally lower density and diversity of megafauna than the shallower seamount and were more heavily sedimented than expected from the relatively steep slopes apparent in the multibeam bathymetry data acquired before each dive. Glass sponges were abundant on exposed outcrops as well as occasional octocorals, black corals, and hard corals.

None of the seamounts showed evidence of recent volcanism in the form of glassy lava flows devoid of a sediment coating. Pillow lava outcrops were common on all the slopes but were normally lightly coated with sediment that accumulates with age. At the summit of the third seamount, just north of Darwin Island (Figure 1, area A), we discovered an unusual sinuous network of tube-like deposits covering the seafloor. The tubes were several tens of centimeters in diameter and quite friable, consisting of a several centimeter thick, harder crust and a more porous interior. In areas where the tubes were cracked, the openings were colonized by mats of bright yellow bacteria. Inside the tubes, a bright green mineral was present as a soft aggregate (Figure 4). This mineral is likely to be nontronite, an iron-rich clay that forms from hydrothermal alteration of volcanic rocks at temperatures of about ~50°C. One of the tubes was occupied by a large solitary hydrocoral, a species that has never been reported in this region (Figure 5). The presence of bacteria around the tubes and the occurrence of nontronite indicate that there is an active low temperature hydrothermal system at the summit of this seamount likely driven by shallow-level magma.

On the west side of Fernandina Island, the ROV explored a series of large underwater lava flows in depths to 3,000 m (Figure 1, Area B). Several are up to 15 km long and are some of the largest submarine lava flows known. They had previously been mapped using surface-towed side-scan sonar but had never been visually observed. The objectives of the dives on these deepwater flows were to define individual flow units, collect lava samples for geochemical analyses, and make morphological observations in order to interpret flow formation processes. The Galápagos Islands are volcanic in origin and sit atop an elevated submarine platform whose formation is related to a hotspot that, in addition to building the archipelago, supplies magma to the nearby Galápagos Spreading Center. Little is known about the voluminous submarine eruptions that are associated with hotspot

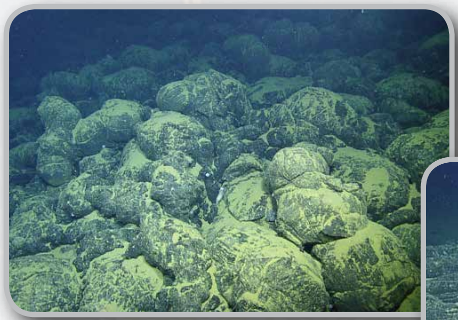


Figure 6. Pillow lavas with minor sediment accumulation on the west side of Fernandina. Water depth is 2,986 m.

Figure 8. Collapse pit on the surface of a lobate lava flow off the west coast of Fernandina. Lava drainage levels are exposed in the wall of the collapse pit. Water depth is 2,947 m.

Figure 7. Sample collection of basaltic sheet flow off the west coast of Fernandina. Water depth is 2,922 m.

Figure 9. Corals and sponges colonizing an outcrop on a shallow volcanic cone between the islands of Isabela and Santiago. Water depth is 465 m.

volcanism, and these flows west of Fernandina provide a unique window into these processes. A single flow was targeted for an ROV transect from ~3,300 m depth to shallower water up the west side of Fernandina. Despite some covering with sediment, the margins of the flow could be identified and sampled. At the distal end in water depths of ~3,000 m, the flows consisted largely of pillow lava outcrops (Figure 6). Further upslope, the flow character changed to areas of spectacular sheet flow outcrops, indicating higher magma discharge rates (Figure 7). There were numerous examples of collapse pits where magma drained away below a quenched crust. The draining produced still-stand levels of glassy lava crust apparent in the sides of the collapse pits (Figure 8). One particularly large, circular collapse pit was ~60 m in diameter and 20–30 m deep. *Hercules* descended into the pit to examine the walls and floor of the structure.

The final dive focused on two shallow-water volcanic cones between Santiago and Isabela Islands (Figure 1, Area C), which lie in a transitional area between large, highly active shield volcanoes with calderas to the west on Fernandina and Isabela Islands, and less active, caldera-lacking volcanoes to the east on Santiago, Santa Cruz, and Floreana Islands. Both cones have horseshoe-shaped craters with central domes, suggesting that minor slope failures have occurred in the past. The dive was designed primarily to sample lavas for analyses that will lead to a better understanding of the genesis of the surrounding islands and to document the biodiversity on the cones. A transect up the first cone began at about 600 m depth and ascended toward the crater. Most of the volcanic outcrops were covered by carbonate crust, but it was possible to collect samples of small lava tubes and pillow shells. A trough in the crater area was covered with well-sorted black volcaniclastic sand, which suggests that there may have been explosive submarine activity on these cones at one time. Pillow lavas along a ridge that extended from the crater to the southeast were spectacularly colonized by octocorals, black corals, and hard corals (Figure 9). To the southwest, a second cone exhibited lower biodiversity and abundance of fauna along a transect up its east side. The base of this cone was heavily sedimented with only occasional outcrops of pillow lava. The peak was very narrow and contained a linear ridge of structures up to 2 m high that resembled a picket fence heavily covered with corals, sponges, and associates. The dive ended with collection of the largest volcanic rock ever retrieved by *Hercules*, a ~45 kg single pillow basalt sample.

With new discoveries on every seamount, submarine volcanic cone, and lava flow visited, it is clear that we have only scratched the surface of the amazing subsea world of the Galápagos Island chain. When our geological collaborators ashore complete their studies of the 41 lava samples collected, we will better understand the genesis and ongoing formation of these iconic islands. In addition, the biological collections currently being examined by specialists all over the world will not only significantly increase our appreciation of the diversity of the deep-sea fauna of this region, but also result in description of many species never before seen and add to our understanding of the diversity of life in the ocean.

Exploration of Hydrothermal Vents Along the Galápagos Spreading Center

By Nicole A. Raineault, Robert D. Ballard, Larry Mayer, Charles R. Fisher, Steven Carey, Leigh Marsh, Renato Kane, Suna Tüzün, Timothy M. Shank, and Clara Smart

Scientists aboard E/V *Nautilus* explored the Galápagos Spreading Center (GSC) to revisit known, and discover unknown, hydrothermal vents on cruises NA062 and NA063. The history of these seminal sites spans nearly 40 years and includes the location where hydrothermal vents and chemosynthetic ecosystems were first discovered in 1977 (Corliss et al., 1979). The cruise objectives were to conduct visual reconnaissance transects on a segment of the GSC between the westernmost known vent site, Rosebud (Shank et al., 2003), and the easternmost known vent site, Tempus Fugit (Shank et al., 2012); to determine geological and apparent biological changes at these sites; to explore the area for unknown sites of active venting; and to collect fauna not previously reported from this region (Figure 1). Another goal was to visit the Iguanas black smoker vents, located on a fault offset from the 86°W sites, to compare initial observations from 2006 (Haymon et al., 2008) with current conditions and to collect the first samples of the chimneys and vent macrofauna if any were found (Figure 1).

The Galápagos Rift is an east-west trending spreading center in the eastern equatorial Pacific. Here, the Cocos and Nazca tectonic plates are moving apart at 5–6 cm per year, an intermediate rate among the global mid-ocean ridge system (Ballard et al., 1982). The GSC's 2–4 km wide rift valley is composed of sheet flows and pillow basalt ridges, with sparse to no sediment cover indicating there has been recent volcanic activity. This rift valley was the target of *Nautilus* multibeam mapping surveys and seven ROV dives in June and July 2015.

To cover a large area, the first dive used *Argus* as a towed camera sled starting west of the East of Eden hydrothermal site. Along the 17 km westward transect, we encountered alternating expanses of fresh, glassy pillow basalts and older, sedimented pillow basalts and lava lakes. Cloudy water, clam shells, serpulid worms, and peripheral vent fauna were observed near the East of Eden 2 and 3 sites, indicating that parts of this area remained active. Miniature autonomous plume recorders (MAPRs) placed on *Argus*' frame to measure temperature, eH, and backscatter anomalies detected a spike in seawater temperature at the active sites; however, no large point-source venting or extensive vent communities were identified in this area.

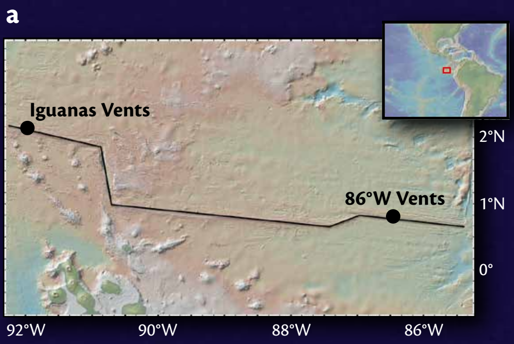
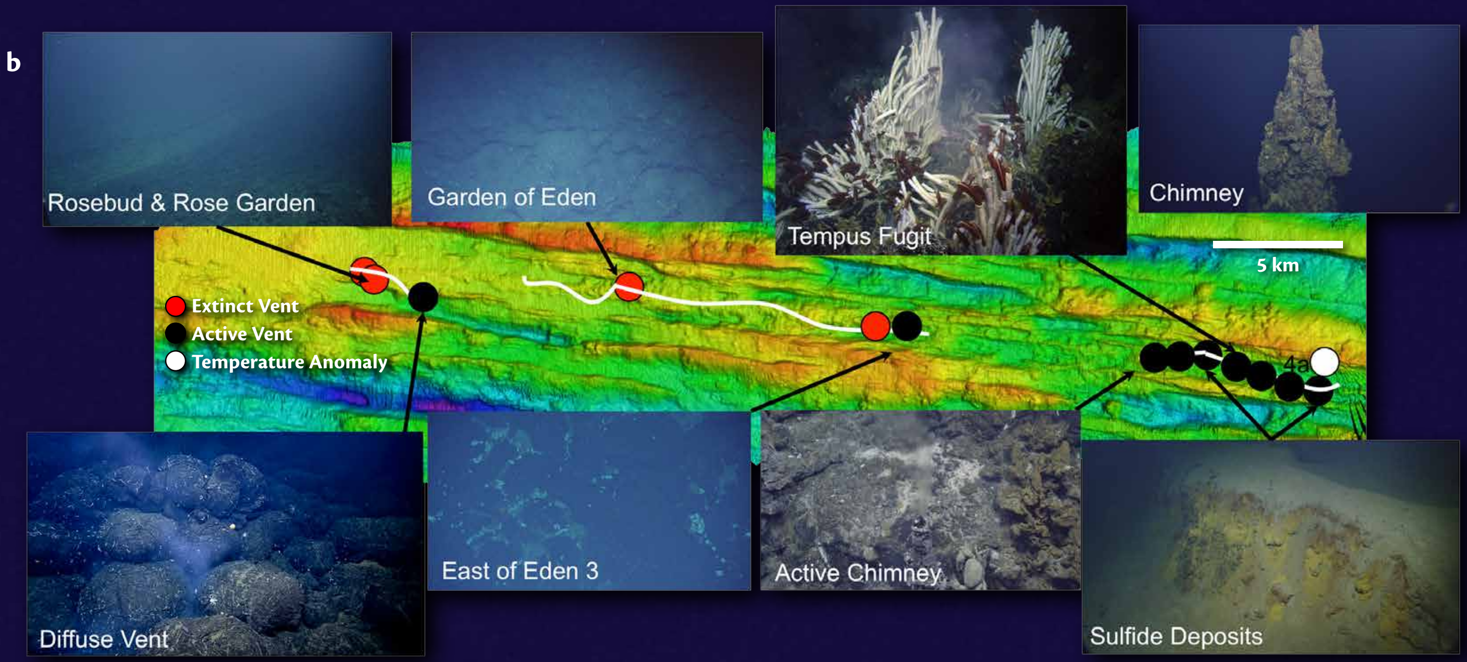


Figure 1. (a) Map of the Galápagos Rift and (b) findings at the 86°W vent sites from the 2015 *Nautilus* expedition.



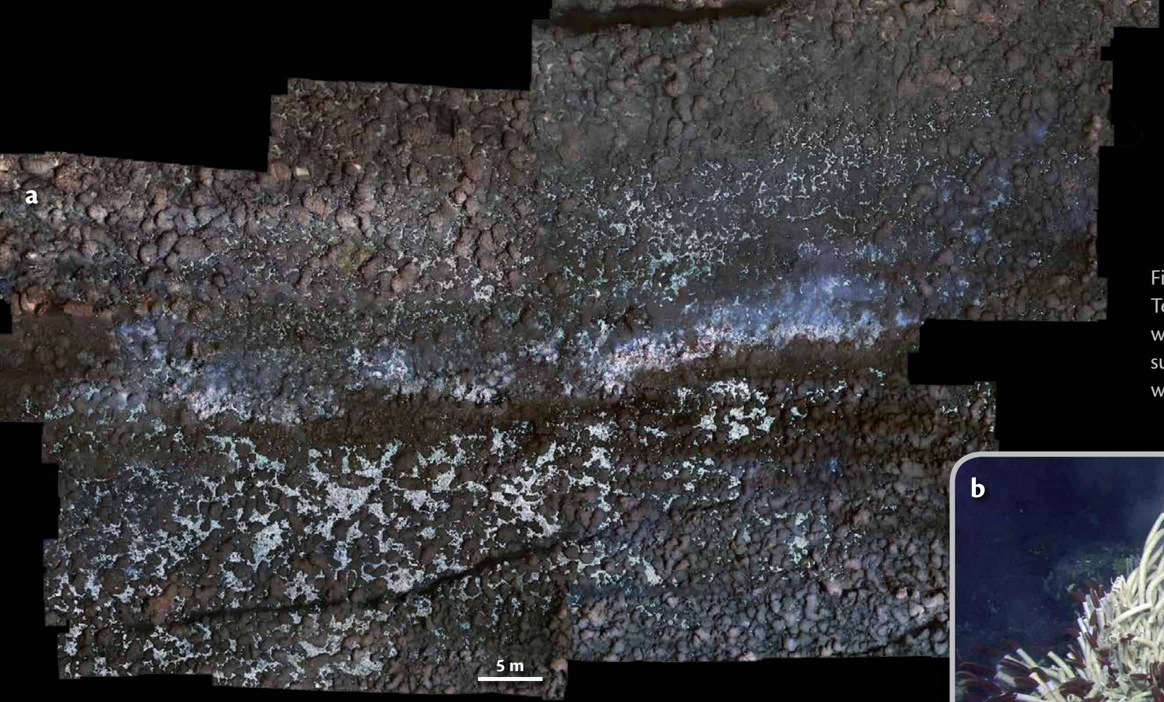


Figure 2. (a) Photomosaic of the Tempus Fugit vent site shows cloudy water in the central active region, surrounded by (b) *Riftia* tubeworms, with *C. magnifica* at the margins.

The first *Hercules-Argus* dive visited the Rosebud site, where in 2002 scientists discovered a nascent vent community containing *Riftia pachyptila* tubeworms (Shank et al., 2003). With help from scientists ashore, the shipboard scientists explored the area, looking for previously observed sheet flows or white markers left by past expeditions. Instead of active hydrothermal venting, this site appeared to be covered by fresh basalt. Several lava lakes with collapse structures and pillars were also observed in the area. Neither markers left previously nor vent fauna documented in 2001 were observed, suggesting they were buried by more recent lava flows. The Rosebud vent was in the same area as the Rose Garden site, one of the original vent sites discovered in 1977. In this same region in 2015, we observed increased sediment cover and a large lava lake. Working .5 km to the east of the Rosebud site we observed cloudy near-bottom water and serpulid worms on the seafloor. The ROVs tracked a deep, narrow fissure, but ended the dive before finding the source of the cloudy water.

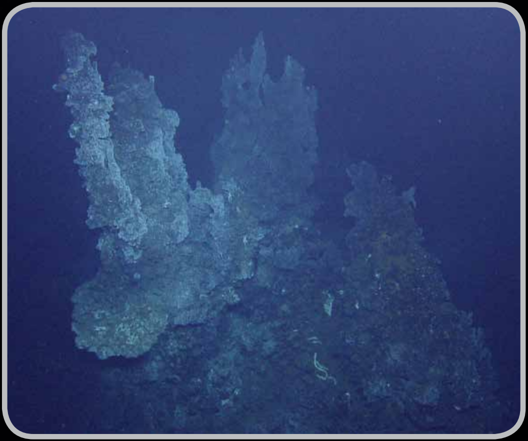


Figure 3. Chimney structures on the eastern segment of the Galápagos Rift show that high-temperature venting once occurred in this area.

The next dive was at the Tempus Fugit vent, discovered in 2010 by *Okeanos Explorer* (Shank et al., 2012). When first observed, scientists estimated that periods of venting activity and inactivity were more than 20 years old based on large dead *Calyptogena magnifica* clam assemblages present at the periphery of the vent field (Karson et al., 2015). However, small tubeworms (*Riftia pachyptila*) and mussels (*Bathymodious thermophilus*) were also found, indicating recent and active colonization (Shank et al., 2012). This dichotomy of old and new led to the vent being named Tempus Fugit or "time flies." During additional ROV dives, scientists aboard *Nautilus* found abundant live *B. thermophilus* mussels and large living *C. magnifica* clams surrounded by hundreds of square meters of disarticulated *C. magnifica* shells, confirming that this site has been active for many years, but alterations in subsurface plumbing have resulted in localized changes in the spatial patterns of diffuse venting. A photomosaic of the area is helping scientists analyze the distribution of fauna around the vent (Figure 2a). The map covered the entire venting area (100 × 150 m), which remains one of the largest low-temperature vent fields known along the GSC.

What may prove to be the most geologically significant discovery, an extinct sulfide chimney (Figure 3) was found and then sampled during a visual survey of the rift east of Tempus Fugit in the area of a water column anomaly (site 4a in Figure 1b). This area had not been visually investigated by *Okeanos Explorer* in 2010. Sediment covering the volcanic substrate suggests this area had been inactive for some time. During an 8 km transit, several chimneys and sulfide deposits ranging from .5 m to over 1.5 m tall were observed. White and blue bacterial mats were seen blanketing the seafloor over diffuse flow vents near the chimney complexes. The base of a large chimney structure venting white fluids as well as adjacent chemically stained sediments supported vent-endemic fauna, including the Pompeii worm (*Alvinella pompejana*) and other polychaete worms, along with pycnogonids, rattail fish, and galatheid crabs. Unfortunately, the ROV's manipulator arm was inoperative so we were unable to sample this fauna. However, this discovery provided the first evidence that the eastern segment of the GSC may have contained high-temperature black smoker vents. It was hypothesized that the white smokers may be black smokers in waning stages of activity.

Previously, the only known black smoker vents on the GSC were located about 660 km west of the site of our first dives and were offset from the others vents. The Iguanas vents were discovered by remote chemical sensing of the water column and photographed by camera sled in 2006. They were visited by the human-occupied *Alvin* submersible and mapped by an autonomous underwater vehicle in 2011, but had not been sampled or examined extensively using an ROV prior to our 2015 exploration. This vent field contains the tallest and largest number of active chimneys and the tallest, most vigorous smokers observed anywhere along the GSC (Haymon et al., 2008). The Iguanas chimneys produce dense black smoke and sit directly on pillow lavas, and the chimney bases are surrounded by white bacterial mats. There are at least three active chimney clusters pumping out 200°C fluids within an area extending approximately 100 m along strike. Some chimneys are up to 13 m tall and topped by multiple active spires (Figure 4). The *Hercules-Argus* ROVs surveyed several of these chimneys. Previous studies had not documented any of the classic chimney fauna found along the East Pacific Rise, but the *Nautilus* dives observed and collected communities associated with the iconic hydrothermal vent chimney polychaete *A. pompejana* near shimmering water venting from beehive-like structures. Away from hydrothermally active sources, carnivorous sponges, black corals, and serpulid worms were also observed between chimneys. These observations and collections are adding considerably to our knowledge of the biogeography of vent fauna in the East Pacific Rise-Galápagos Spreading Center region. Additional work to create a photomosaic of a black smoker, measure the black smoker flow rates, and use low-light cameras to detect bioluminescence was also conducted at this site. Structured laser light surveys over an area of diffuse flow among pillow lavas covered with gray-blue bacteria will be used to estimate flow rates.

These *Nautilus* cruises will help to better understand the history of the Galápagos hydrothermal vents and the relationship of the communities there to other vent communities around the world. There are large differences between fauna reported from the nearby East Pacific Rise and those previously known from the GSC. More than 40% of species endemic to the East Pacific Rise are absent from the Galápagos Rift (Shank et al., 2014), although scientists hypothesize that this may be partly due to our previous lack of collections from high-temperature chimneys along the GSC (Shank et al., 2014). We also obtained samples representative of a variety of different habitats, including mussel beds, mixed mussel and clam beds, and *R. pachyptila* tubeworm clumps. These collections appear to contain several additional new species, and they complement previous collections from this region. Samples from these cruises have been distributed to experts around the world to determine how many new species were found and how they are related to East Pacific Rise species. Compilation of these data will inevitably result in a new understanding of the biogeographic connectivity between the GSC and the East Pacific Rise. The geological activity of the GSC can also now be re-examined. We observed that new seafloor has been created over the last 10+ years at the western end of the rift. Newly discovered inactive chimneys on the eastern end of the rift suggest that this area once was the location of high-temperature venting, a process previously unknown on this segment of the GSC. Our results may change our understanding of rare mineral deposits in the area. Given the increased interests of mining companies in polymetallic sulfide deposits along mid-ocean ridges and the possible impact such activities might have on vent communities, it is important to point out the small amount of time it took to discover and sample major deposits associated with inactive sites. Geologists are working to determine the potential volume of sulfides deposited at now inactive areas of the GSC.

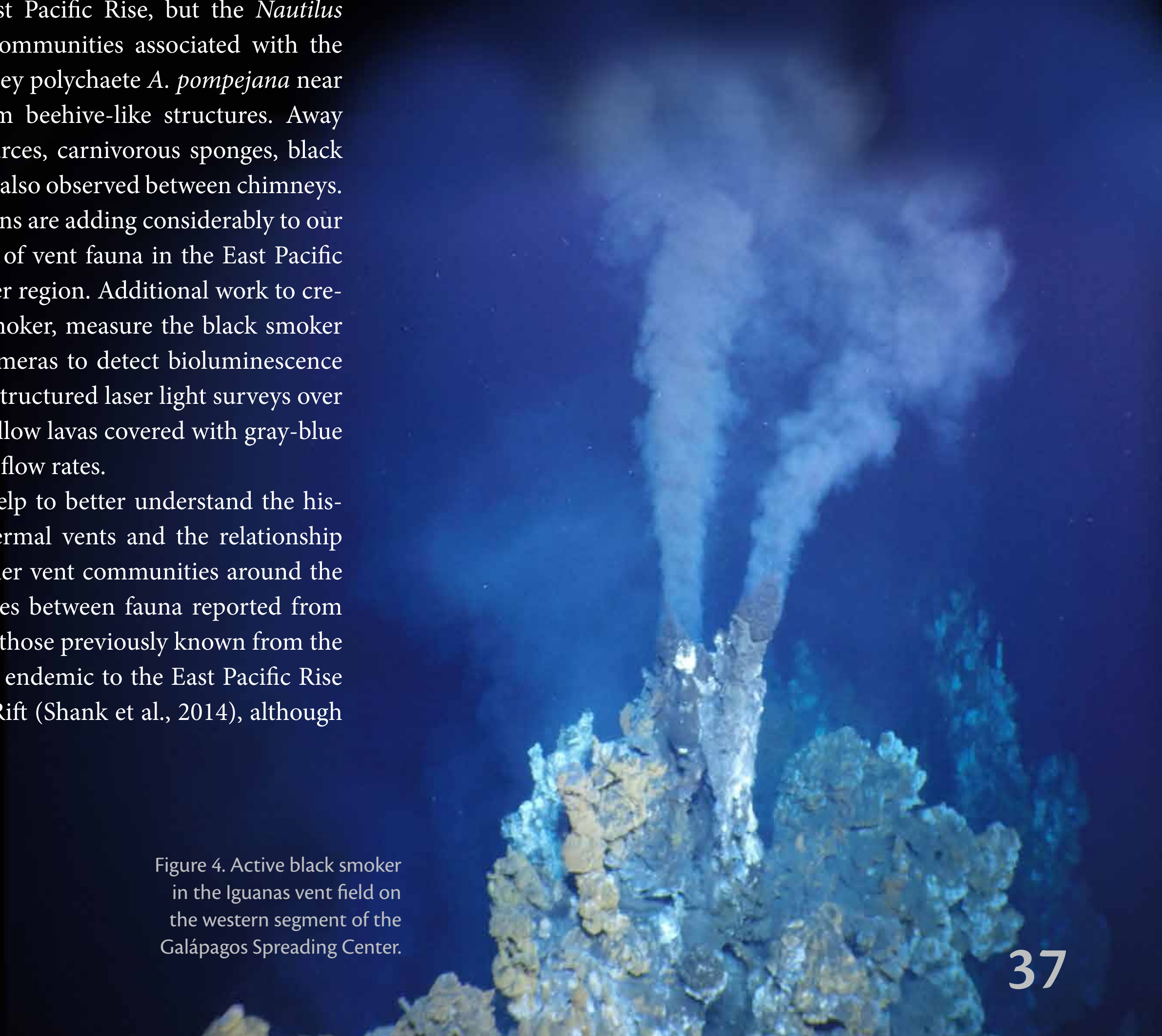
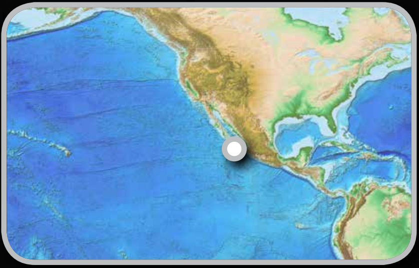


Figure 4. Active black smoker in the Iguanas vent field on the western segment of the Galápagos Spreading Center.

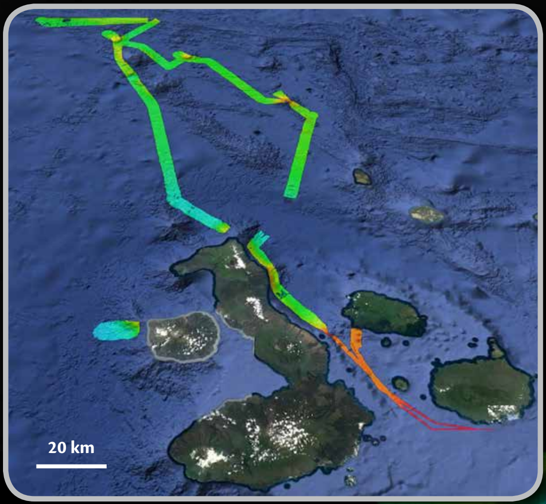


Mapping the Eastern Pacific Ocean: *Nautilus* Mapping 2015

By Nicole A. Raineault, Larry Mayer, Robert D. Ballard, and Onni Irish

E/V *Nautilus* conducts multibeam mapping surveys to create accurate bathymetric maps for science and for remotely operated vehicle (ROV) navigation. In addition, the ship collects bathymetric data during transits between ROV dive locations in previously unmapped areas that may lead to opportunities for future exploration. Between 2013 and 2015, *Nautilus* mapped over 211,355 km^2 of seafloor in the Mediterranean, Atlantic, Caribbean, Gulf of Mexico, and eastern Pacific regions. Nearly 87,000 km^2 were collected in 2015, due in large part to two long-distance transits from Galveston, TX, to the Galápagos, and from the Galápagos to San Diego, CA. The following summarizes *Nautilus* mapping during the 2015 field season, including some highlights.

Figure 2. Galápagos Marine Reserve mapping coverage by *Nautilus*.



GALÁPAGOS RIFT AND MARINE RESERVE

The US Navy first mapped the Galápagos Spreading Center in 1976 with their then-classified cutting-edge mapping technology, the Sonar Array Sounding System (SASS), on USS *Bowditch*. Their 12 kHz system produced 60 discrete depth points per swath. By comparison, the EM 302 installed on *Nautilus*, a 30 kHz system, can collect up to 864 soundings per ping. The maps made by SASS were used by scientists to plan deep-towed camera surveys that led to revolutionary scientific discoveries such as hydrothermal vents that host chemosynthetic life forms (van Andel and Ballard, 1979). Since their initial discovery, these sites have been resurveyed several times, including with the Autonomous Benthic Explorer (ABE), which collected data for making high-resolution seafloor maps (Shank et al., 2003). In 2015, *Nautilus* mapped the area from the Rosebud and Rose Garden vents to the area where a water column anomaly was detected in 2011 by *Okeanos Explorer* (Figure 1). Despite the remarkable accuracy of the SASS maps, and the fact that the seafloor is changing rapidly at this spreading center (average seafloor spreading rate of 5–6 cm yr^{-1}, resulting approximately 2.3 m of motion over 39 years), changes are not detectable at the 25 m horizontal grid resolution of the maps.

Additionally, *Nautilus* mapped over 5,600 km^2 in the Galápagos Marine Reserve to fill in gaps in existing data (Figure 2). The combined mapping products are being assembled by scientists at Woods Hole Oceanographic Institution to provide information to Ecuador to aid in their current Marine Reserve rezoning project.

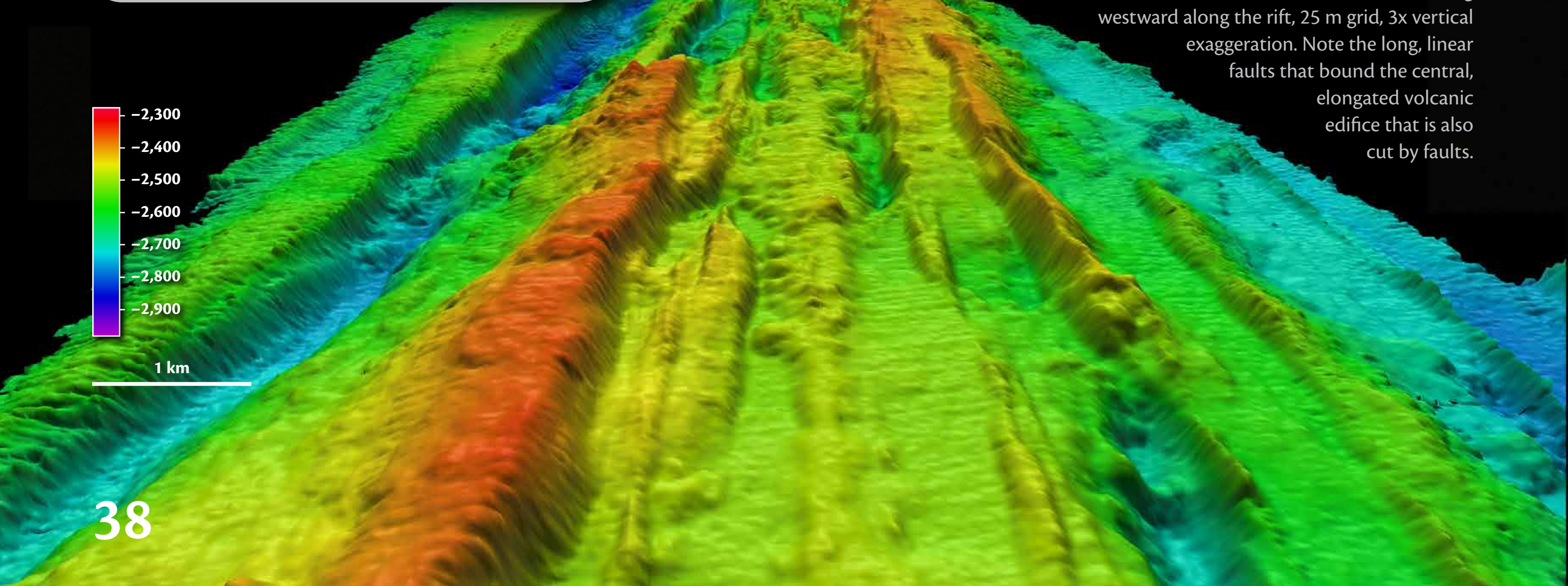


Figure 1. Galápagos Spreading Center digital elevation model from *Nautilus* EM 302 data looking westward along the rift, 25 m grid, 3x vertical exaggeration. Note the long, linear faults that bound the central, elongated volcanic edifice that is also cut by faults.

GALÁPAGOS TO SAN DIEGO

Nautilus completed its second longest mapping transit to date between the Galápagos Islands, Ecuador, and San Diego, CA. The transit provided an opportunity to survey previously unmapped areas and also to train the science team on multibeam and sub-bottom sonar mapping and processing procedures. With a limited staff to maintain 24-hour mapping watches, the small group size allowed all participants to become immersed in the seafloor mapping process. From data acquisition to processing and creating products, each watchstander gained hands-on experience on the proper execution of each step.

During the transit, *Nautilus*' multibeam echosounder was able to discern features on the seafloor that global satellite-derived altimetry had never detected. The multibeam echosounder on *Nautilus* has a horizontal resolution of ~50 m in a water depth of 3,500 m, while satellite-derived bathymetry can resolve features to only ~5 km. *Nautilus*' sonar system was able to map in detail entire seamounts and abyssal hills that do not appear in satellite-derived terrain models.

On this transit, the *Nautilus* mapped nearly 44,700 km^2 of seafloor, second only to the trans-Atlantic crossing in 2013. After creating digital elevation models from the data, watchstanders imported the maps into Google Earth and compared the echosounder maps to the mostly satellite-derived seafloor terrain to identify new features. Several were detected, including a roughly circular seamount with a crater (8 × 5 km) that rises 350 m above the abyssal depths of 3,750 m, 1,000 nm west of Colombia (Figure 3). The crater likely formed by collapse, or partial collapse, during or following a volcanic eruption.

A two-day mapping survey of areas of interest in the California Borderland helped identify and locate active methane seeps. This knowledge was then used to determine larger areas for mapping surveys and ROV dive sites on the subsequent two cruises (Figure 4).

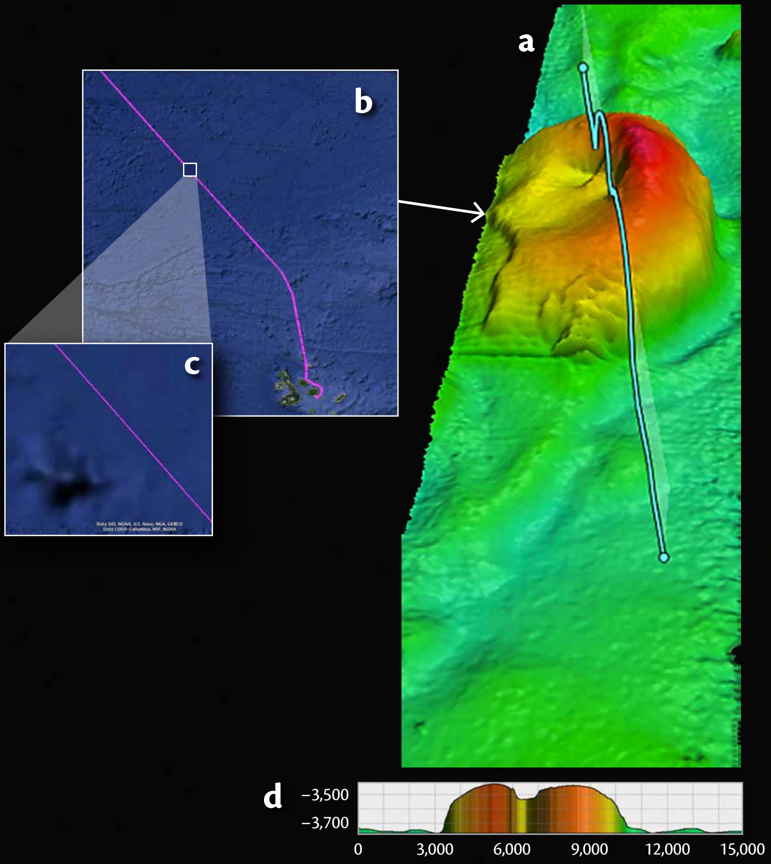


Figure 3. (a) A roughly circular seamount with a crater was discovered during the *Nautilus* mapping transit (pink line in b) between the Galápagos and San Diego. (c) An earlier, mostly satellite-derived, seafloor terrain map of the same area showed no indication of the crater. (d) NW-SE profile from across the crater at 6x vertical exaggeration.

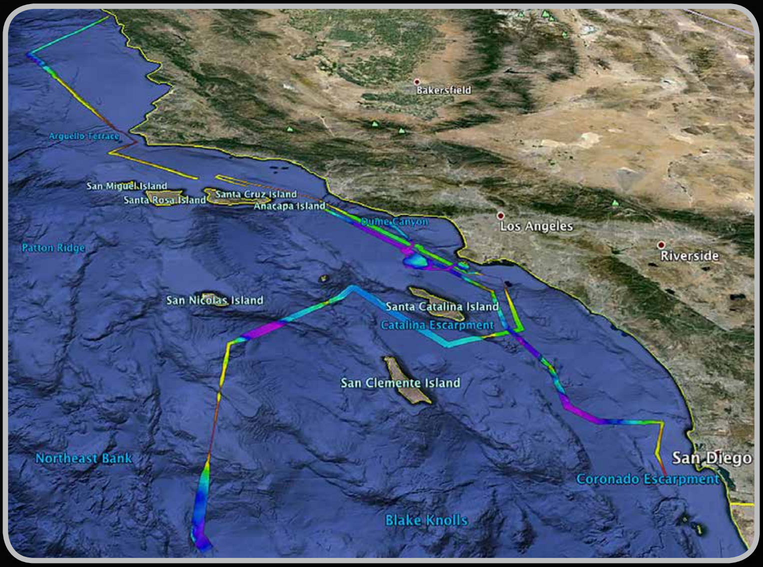


Figure 4. *Nautilus* multibeam data visualized in Google Earth shows the coverage in the California Borderland area from the 2015 cruises.

CALIFORNIA BORDERLAND

Four new seeps were discovered offshore of California between Los Angeles and San Diego. One of the seeps was located on Redondo Knoll, a feature fully mapped for the first time by *Nautilus*, while a second was located to the northwest of the knoll. Seeps were also discovered along a submarine river channel off Point Dume (**see pages 41–42**). Additional mapping off of Catalina Island helped reveal new details around Catalina Canyon. The data have been provided to the Channel Islands National Marine Sanctuary to aid in a multi-institution mapping effort. *Nautilus* will return to the region in 2016 to continue to map and discover new seafloor features and habitats in our own backyard.

Given that only about 10% of the seafloor has been mapped by multibeam echosounders, the discoveries made with *Nautilus*' 2015 mapping data clearly indicate that much is left to be discovered on the seafloor.

Exploration and Discovery of Methane Seeps and Associated Communities in the California Borderland

By Lisa Levin, Peter R. Girguis, Christopher R. German, Michael L. Brennan, Suna Tüzün, Jamie Wagner, Clara Smart, Avery Kruger, Katherine Inderbitzen, Jennifer Le, Melinda Martinez, Catalina Martinez, Ellen Kappel, Natalya Gallo, and Benjamin M. Grupe

The California Borderland off southern California is a heavily trafficked maritime corridor, yet it remains largely unexplored below the surface. The region's active tectonics create a variety of physical and chemical regimes that support a diversity of ecosystems. The objective of this expedition was to observe the distribution of species and assemblages among different ecosystems that vary in their energy sources, including methane seeps, whale falls, high-energy canyons, and across sharp oxygen gradients. As such, the first E/V *Nautilus* cruise conducted in US Pacific waters explored the area between San Diego and Santa Barbara, diving on some previously known sites to establish a baseline for the region before exploring new terrain (Figure 1).

DEL MAR METHANE SEEP

The Del Mar seep, located 48 km off the coast of Del Mar and discovered in 2012, consists of at least two elevated mounds within a strike-slip fault system in the San Diego Trough off southern California (Maloney et al., 2015). The initial discovery of this active seep revealed several distinct habitats, including colorful mats of sulfur-oxidizing bacteria and folliculinid ciliates (Figure 2a); vesicomyid clam beds; frenulate, ampharetid (polychaete), and protozoan tube beds; and carbonate rocks (Grupe et al., 2015). In addition, a number of commercially valuable fish species, including Dover sole (*Microstomus pacificus*) and thornyheads (*Sebastolobus* spp.) were present in higher numbers at the seep than in surrounding sedimented areas (Grupe et al., 2015). The scientific party explored this seep with the remotely operated vehicle (ROV) *Hercules*, focusing on constraining the full habitat heterogeneity, as well as the use of the seep by background biota, including commercially fished species. For example, sablefish (*Anoplopoma fimbria*), marketed commercially as "black cod," swam around the seep, and two king crabs, most likely *Paralomis viridis*, sat on a rock, grasping each other's claws for the entirety of one dive (Figure 2b). In addition, experiments measuring rates of colonization on a whale bone, wood (Douglas fir), and carbonate rock were collected at active and inactive seep areas in May 2013 (Figure 2c). Clear differences in colonizers were observed; for example, there was very little consumption by wood-boring clams (*Xylophaga* sp.) at the actively seeping site, whereas *Xylophaga* extensively degraded the wood at the inactive site.

PALOS VERDES MARGIN

The Palos Verdes shelf is located off Los Angeles, situated between the larger San Pedro and Santa Monica shelves. Previous geological investigations used sonar to survey this part of the shelf and found dark reflectors indicating gases trapped beneath the seafloor, possibly capped by hard material, as well as chimney-like

Figure 1. Map showing California Borderland sites explored by *Nautilus*.

Figure 2. Del Mar Seep. (a) Folliculinid ciliates form a blue mat on carbonate rock, with white and orange bacteria also present. (b) These king crabs held a long embrace during one dive. (c) Colonization substrates—wood, rock, and bone—were recovered after two years on the seafloor.

features, which mark the upward escape of sulfide-rich fluid and gas (e.g., Moore, 1960; Kleinschmidt and Tschauder, 1985; Hampton et al., 2002). These studies led the investigators to posit that these features may be evidence of shallow hydrothermal venting. If true, these vents might support taxa typically found at vents in the eastern and northeastern Pacific, or at hydrocarbon seeps and whale falls off California (Bernardino et al., 2012), and could explain some of the phylogenetic similarities among fauna found along the eastern Pacific (Stiller et al., 2013).

Two ROV dives were conducted on the Palos Verdes margin, targeting areas of putative gas seepage found during an initial *Nautilus* multibeam sonar survey. The dives explored depths ranging from ~780 m to ~200 m. Despite modest oxygen concentrations, the shelf harbored dense communities of asteroids, thornyheads, jellies (likely *Paraphyllina* and *Poralia* spp.), and catsharks (*Scyliohinidae*). Evidence for turbidite flows were found at 750 m depth, along with tubeworms, a few vesicomyid clam shells, and small patches of microbial mat. These taxa can be signs of seepage, but such chemosynthetic communities are also present upon and around organic deadfalls (Paull et al., 2008).

The most striking features on the Palos Verdes margin were the massive carbonate mounds observed throughout the dives. They ranged from 1 m to ~4 m in height and were most abundant between 350 m and 450 m depth. The mounds were heavily colonized by thornyheads, jellies, crabs, and small snails. They exhibited some degree of bubbling, presumably methane and sulfide, though the bubbling rate was highly variable. While these mounds are likely the result of microbial oxidation of methane to inorganic carbon, and though fauna typical of such seeps (e.g., clams with sulfur-oxidizing symbionts) were present at most of the mounds, thornyheads and crabs were surprisingly dense around the mounds (Figure 3).

Such carbonate mounds are clearly surficial expressions of subsurface fluid flow and microbial activity associated with methane seepage. None of the sites visited exhibited temperatures markedly above bottom seawater, suggesting they are not hydrothermally influenced systems. While hot springs are found in the shallow subtidal zone along the peninsula, further exploration is needed to establish whether there is hydrothermal flow in the deeper waters that is comparable to that seen in the better-studied eastern and northeastern Pacific. Nevertheless, the hydrocarbon seepage and the associated massive carbonate clearly represent unique and previously unrecognized habitats found less than 5 km from the Los Angeles shoreline.

Figure 3. Thornyheads, rockfish, and crabs aggregate at Palos Verdes carbonates.

POINT DUME

Three dives were conducted south of Point Dume on a suspected seep, clued in by vesicomyid clams collected during a 2013 survey by the Southern California Coastal Water Research Project and a subsequent *Nautilus* multibeam sonar survey. The dives confirmed the existence of seeps and that they host bacterial mats, clam beds, and small chimneys (Figure 4). They were initially located on a steep slope and then followed during the dives for over 1,400 m in a NE-SW direction. A more detailed multibeam survey over this area showed what appeared to be a submarine river channel continuing from a canyon further upslope and near shore (Figure 5). The seep runs along the southern/southeastern bank of this river channel, and there is a series of truncated chimneys at one location, possibly indicative of carbonate formation during past periods

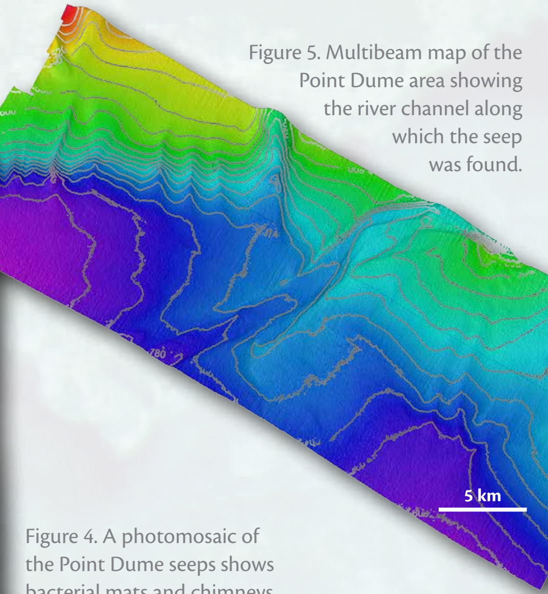


Figure 5. Multibeam map of the Point Dume area showing the river channel along which the seep was found.

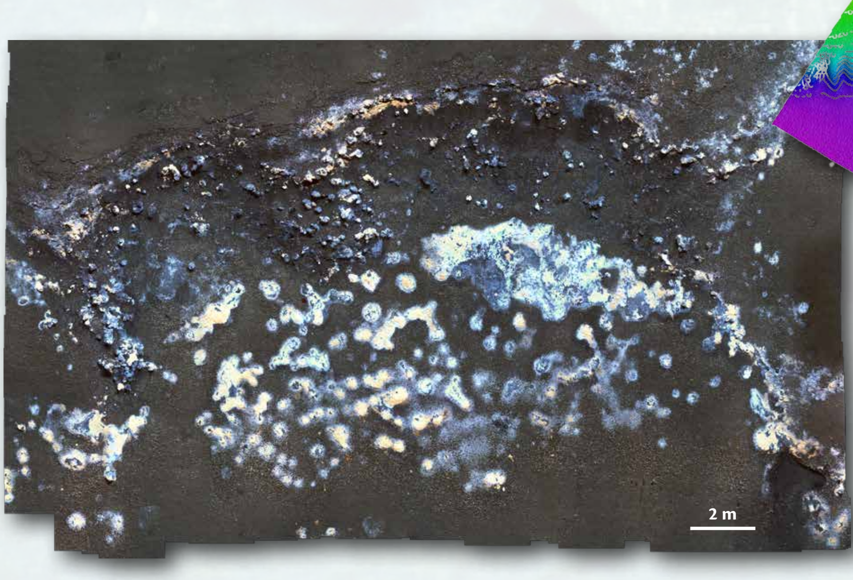


Figure 4. A photomosaic of the Point Dume seeps shows bacterial mats and chimneys.

of more active fluid flow. Interestingly, we found no evidence of seep communities or fluid flow, past or present, along the northern edge. We surmise that the pathway for fluid seepage may be a deep-penetrating, sub-vertical fault that continues subseafloor beneath the southern bank of the observed "river channel."

The Point Dume seep was dominated by a relatively small number of megabenthic taxa. Orange, white, and gray bacterial mats, presumably mainly sulfide oxidizers with possible methane oxidizers, were also present (Ding and Valentine, 2008). The mats were observed along the length of the seep, often in a narrow band only a meter wide, other times in a patchwork or overlying vesicomyid clams. Dense aggregations of small polychaetes, possibly dorvilleids, were observed on some of the bacterial mats. Several species of symbiont-bearing clams were present at high densities, including unidentified vesicomyid species and the oxygen minimum zone lucinid (*Lucinoma aequizonata*). In some cases, the clam beds were monospecific, in other cases mixed. In a distinct zone devoid of bacteria, the clams provided substrate to dense bushes of arborescent (*Pelosina*-like) agglutinating Foraminifera, which gave the sediment surface a fuzzy brown appearance. Galatheid crabs (*Munida* sp.) and an undescribed species of anemone were present at low densities across the bacterial and clam zones and at higher concentrations on the periphery of the seep. Dover sole, thornyheads, and filetail catsharks (*Parmaturus xaniurus*) were routinely present on or near the seep.

The Point Dume seep lies at 700–750 m depth within the oxygen minimum zone, where oxygen concentrations range from ~1 μM to 5 μM. Several taxa present at other regional seeps were notably absent from this seep, potentially due to low oxygen levels, including siboglinid tubeworms, folliculinid ciliates, bathymodiolin mussels, pink urchins, and California king crab.

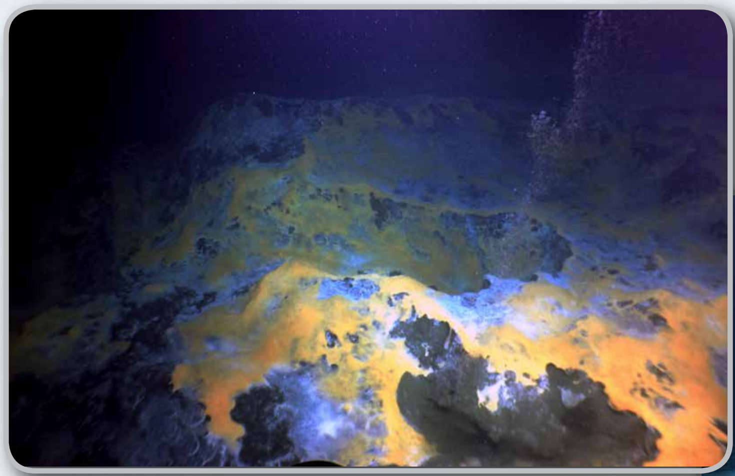


Figure 6. A bubble stream rises from a deep pit within the central crater floor of the Redondo seep. Note that the color of the microbial mat changes from predominantly yellow-orange within the confines of the crater interior to off-white on the outer flanks farther from the active vent sources. This same bimodal distribution of microbial mat coloration was also observed at other seep locations. *Photograph collected using an ROV-mounted GoPro camera provided by Daniel Fornari (WHOI)*

REDONDO SEEP

Redondo Knoll is a topographic high situated to the north and east of Catalina Island that had never been mapped systematically despite lying immediately adjacent to the main shipping lanes approaching Los Angeles harbor. During the expedition, Redondo Knoll was completely mapped. Water column sonar returns were continuously monitored to detect cold seep gas emissions from the seafloor. Although no evidence for cold seep activity was found toward the summit of the mound, strong returns from deep seafloor (~850 m) immediately to the north of the knoll indicated gas-rich cold seep activity there. Dissolved oxygen sensors on *Hercules* showed that the site is located close to the core of the regional oxygen minimum zone within a basin at a depth where oxygen concentrations were effectively zero. Consistent with this finding, the seep site was distinctive for its complete absence of any seep-endemic megafauna, unlike the Point Dume sites that were located just a few kilometers away but, importantly, under slightly more oxygen-rich conditions. Instead, a crater of dark gray mud measuring a few tens of meters across was found vigorously emitting gas bubbles, with the surrounding seafloor covered in thick mats of yellow and white bacteria (Figure 6).

WHALE FALL

Along with methane seeps, decaying whale carcasses form another major type of chemosynthetic ecosystem on the deep California margin. In November 2011, a 23 m (75 ft) fin whale (later named Rosebud) washed ashore after being killed by a ship strike. The whale was then sunk for research off Mission Bay, CA, at a depth of 800 m by marine biologist Greg Rouse of Scripps Institution of Oceanography. As at methane seeps, whale falls support species reliant on hydrogen sulfide, which is produced by the decay of lipid-rich bones. The *Nautilus* visit to Rosebud in 2015 was the fourth in four years. The decay process created many different types of microhabitats (Figure 7). The whale worm *Osedax roseus* was highly visible on the jaw bones. Cores from the

Figure 7. An experimental whale fall known as "Rosebud" is shown four years after being sunk at 800 m off Mission Bay, San Diego, CA. Note the associated white bacterial mats.

microbial mat near the whale belly and suction samples from the bone will yield information about what species are present four years into whale succession in an oxygen minimum zone. The whale fall appeared to be an aggregation site for many different kinds of fish and invertebrates, including thornyheads, hagfish (*Eptatretus deani*), Dover sole, holothurians, and ampharetid and polynoid polychaetes. The diversity of megafaunal species attracted to the whale was surprising given the low oxygen levels at 800 m.

Figure 8. Krill swarm the lights on *Hercules* at the Fish Bands site.

OXYGEN MINIMUM ZONES

Nautilus traversed major oxygen gradients during several dives. Measurements of these gradients combined with point observations of sediments surrounding the seeps created a valuable picture of the role oxygen plays in shaping the Southern California Borderland communities. The shallowest dive at 340 m occupied a site called Fish Bands, which appeared to be a seafloor interception point for the vertically migrating deep scattering layer. Dense masses of krill (Figure 8) and small fish aggregated just above the bottom, potentially providing an enormous food source for slender sole (*Lyopsetta exilis*) and other benthic fishes. This site falls within the oxygen limiting zone (22–60 µM O_2), where oxygen levels are two times higher than within the oxygen minimum zone (<22 µM O_2), allowing for the observed high densities of fish.

An ROV transect that crossed the La Jolla margin from the low-oxygen core at 700 m depth to the oxygen limiting zone at 425 m depth revealed strong megabenthos zonation. Pink urchins (*Strongylocentrotus fragilis*), burrowing urchins (likely *Brissopsis pacifica*), sablefish, and brotula (likely *Cataetyx rubrirostris*) were abundant within the oxygen minimum zone core, along with anemones and asteroids. A carbonate mound with low seepage activity was detected at ~500 m depth. The mound supported many background fauna, including nettastomatid eels, rockfish, thornyheads, the pink urchin, crabs, multiple species of sponges, the benthic siphonophore *Dromalia alexandri*, many arborescent foraminifera, and even long pelagic siphonophores. Patches of bacteria, vesicomyid clams, and the cladorhizid sponge *Abestopluma* all indicated modern methane seepage at the mound.

The San Pedro Basin, examined from 834 m to 818 m depth, was nearly anoxic, with oxygen levels <3 µM O_2 recorded at the bottom. The waters overlying the seafloor were filled with jellyfish and large numbers of benthic snails *Alia* (formerly *Astyris*) *permodesta*. A high density of these snails also covered the seafloor, often aggregated on decaying kelp or carcasses, but few other macrofauna appeared tolerant of the low-oxygen conditions.

The expedition revealed substantial physical and chemical heterogeneity on the Southern California Borderland margin. The biological assemblages reflect this heterogeneity, but also exhibit more subtle patchiness on scales of tens of meters. Overall, the diversity of fish and invertebrate megafauna that tolerate hypoxic to dysoxic conditions at <10 µM was surprisingly high, and future efforts should aim to better understand the factors governing the observed distributions. Moreover, the five seeps visited were located between 1,020 m and ~450 m depth, spanning a range of overlying oxygen conditions. The seep-endemic species appeared to exhibit depth/oxygen zonation, especially those such as tubeworms, provannid snails, folliculind cilliates, and clams bearing symbionts that carry out sulfide or methane oxidation. The seep habitats were often occupied or visited by species not recognized as seep-associated, which also changed with water depth. Finally, in addition to seeps, the slope and basin habitats with lowest oxygen, the whale fall, and frequent kelp falls added to the high incidence of chemosynthetic ecosystems on this margin.

CONCLUDING STATEMENTS

The California Borderlands expedition illustrated how much remains to be discovered in our ocean, even within just a few kilometers of land. Our new discoveries at the extensive Point Dume, Palos Verdes, and Redondo Knoll cold seep sites are excellent examples, lying on either side of the main shipping lanes for vessels heading north from Los Angeles harbor. Seafarers have been following those routes for hundreds of years, never knowing what lies just a short distance below. This work helps set the stage for a new natural laboratory for microbiological and ecological investigations. The new seep sites, whale fall, anoxic basins, and kelp falls are in close proximity, all relying to varying degrees on chemical flux from the underlying seafloor, but with different levels of oxygen available in the overlying water column. They are remarkably heterogeneous and represent different levels of complexity in terms of the chemosynthetic ecosystems that they host.

High-Resolution Imaging and Characterization of the USS *Macon* Airship Wreck Site

By Megan Lickliter-Mundon, Michael L. Brennan, Clara Smart, Bruce G. Terrell, Robert V. Schwemmer, and Alexis Catsambis

In August of 2015, scientists aboard E/V *Nautilus* took part in a joint project led by investigators from NOAA's Office of National Marine Sanctuaries, the Naval History and Heritage Command (NHHC), and the Ocean Exploration Trust to conduct an archaeological survey of the wreck site of USS *Macon*, which contains the only surviving remains of a US Navy *Akron*-class rigid airship. *Macon* lies off the coast of California in the Monterey Bay National Marine Sanctuary and, because it was owned and operated by the US Navy at the time of its sinking, is afforded protection by the Sunken Military Craft Act. This project's primary goal was to provide ongoing stewardship of this wreck site by updating site documentation to supplement previous years' surveys. The secondary goal was to study and benchmark site formation processes for an early modern-metals aviation site. The USS *Macon* site contains some of the oldest known aviation material submerged in saltwater in the United States. Despite its age and marine organism activity, the metal and organic remains of the aircraft appear to retain a high level of integrity. The survey's digital documentation methods included creating an updated photomosaic of the two areas of wreckage, on-site photography and video, and post-survey three-dimensional modeling. A detailed study and comparison of the imaging results, along with a comparison to metal sampled in 1991, will inform archaeological knowledge of the potential longevity of deepwater aviation sites.

Figure 1. USS *Macon*, the US Navy's last flying aircraft carrier, is shown in flight above two Sparrowhawk biplanes it was designed to hangar. *Credit: National Archives*

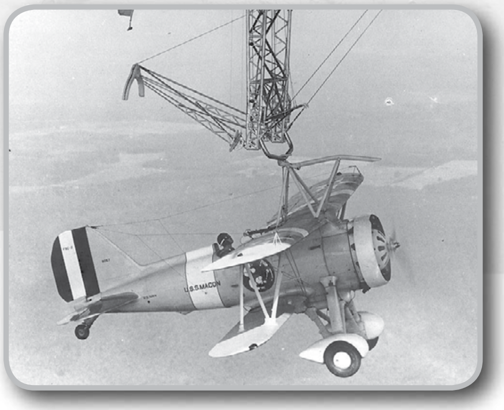


Figure 2. A Curtiss FC-9 Sparrowhawk biplane is hooked on to the trapeze that is extended below the *Macon*'s hangar for launch and retrieval of the small planes. *Credit: National Archives*

Construction on USS *Macon*, the Navy's last flying aircraft carrier, began in October 1931, and the airship was christened on March 11, 1933 (Figure 1). *Macon*'s interior midsection hangared four Curtiss F9C-2 “Sparrowhawk” biplanes, which could be released and captured via a trapeze and hook system (Figure 2). *Macon* and the biplanes participated in fleet exercises off the Pacific Coast where the Navy was developing combined aerial and nautical tactics (Smith, 1965). On February 12, 1935, *Macon* was nearing Point Sur while returning to Moffett Field following a successful exercise over the Channel Islands when a gust of wind during a storm tore the upper tail fin away, puncturing helium gas cells. The damage caused *Macon* to lose gas and eventually settle onto the ocean's surface about 4.8 km (three miles) off the coast. All but two of the crew were saved by nearby Navy vessels. The loss of *Macon* lowered the curtain on the US Navy's rigid airship program.

In 1990 and 1991, the Monterey Bay Aquarium Research Institute (MBARI) coordinated with the US Navy to locate and characterize *Macon*'s remains at a water depth of 442 m (1,450 ft). From the collected video and still photography, researchers prepared full-color photomosaics of small areas. One of these sets of photomosaics showed three of the four biplanes on site and revealed that they were extremely well preserved (Vaeth, 1992). A third survey conducted in 2005 used side-scan sonar, and in September 2006 scientists from NOAA and MBARI recorded remains of the airship and aircraft (Grech, 2007) and produced an artifact site map and a large-scale photomosaic of part of the airship. Seventy-five years after the airship went down, based on data acquired during the expedition, *Macon* was listed on the National Register of Historic Places in February 2010.

Documentation of the wreck over the past 25 years has helped researchers identify airship and aircraft components as well as trace site deterioration. Photomosaicing technology and techniques have improved since 2006, and the 2015 survey benefited from the skilled scientists and advanced equipment aboard *Nautilus*. The majority of survey hours during the 2015 expedition were dedicated to the primary goal of creating a new comprehensive site photomosaic to update the 2006 version (Figure 3). The

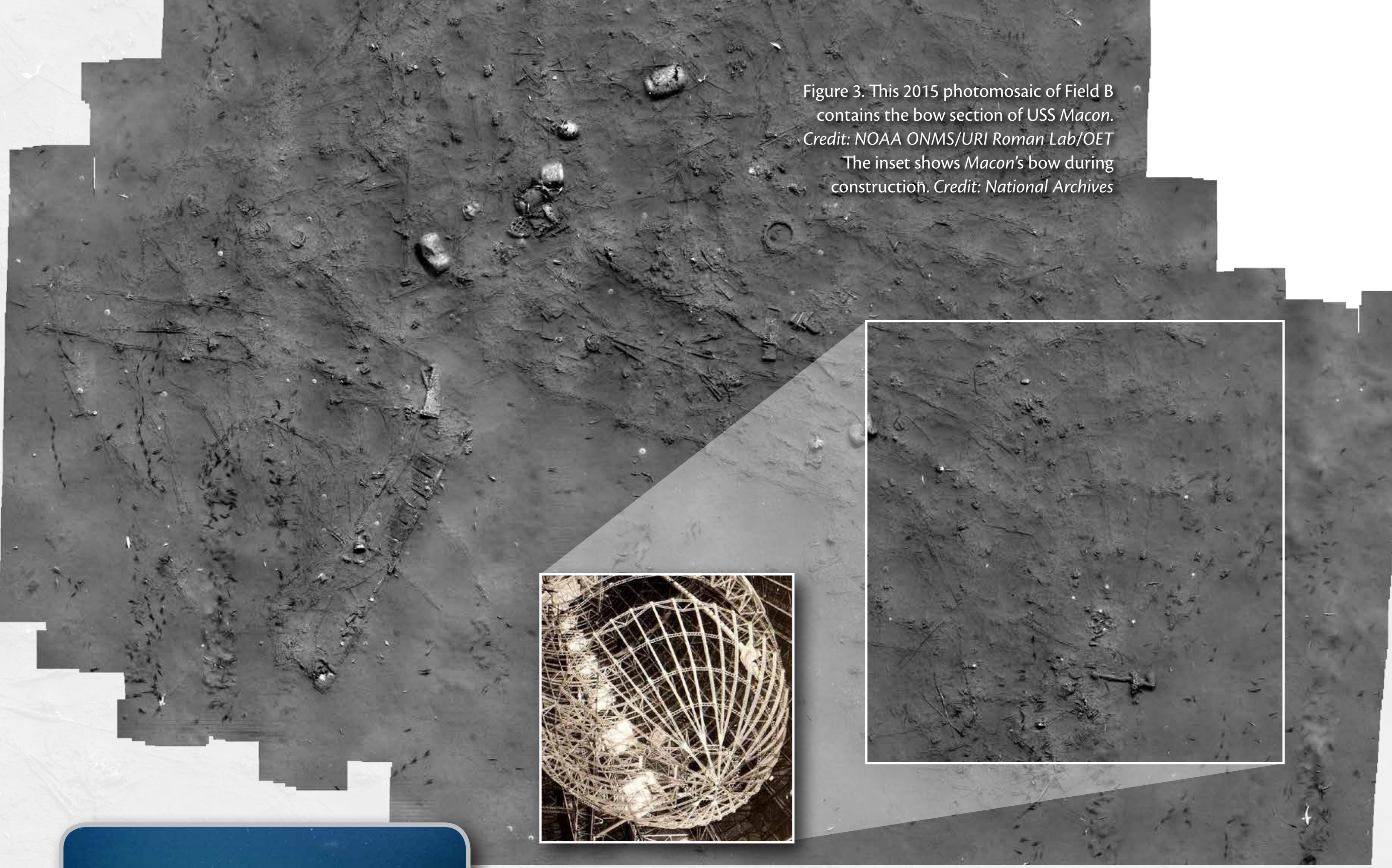


Figure 3. This 2015 photomosaic of Field B contains the bow section of USS *Macon*. *Credit: NOAA ONMS/URI Roman Lab/OET* The inset shows *Macon*'s bow during construction. *Credit: National Archives*

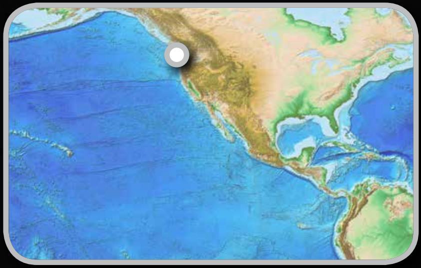
Figure 4. Collapse of the aft spar of Sparrowhawk biplane No. 4's starboard wing is evident in this image.

Figure 5. An aluminum airship structural frame piece is recovered from near biplane No. 3.

secondary goal of the imaging phase of the survey was to acquire high definition video of the fuselage, engine, and wing surfaces of the high-relief F9C-2 Sparrowhawk aircraft, particularly biplanes 1 and 2, for improved documentation and understanding of aircraft deterioration.

USS *Macon* separated into two large pieces before fully sinking and now lies in two fields, designated A and B, that are approximately 60 m × 40 m each and roughly 250 m apart. Photomosaics comprising roughly 1,500 images of each field have been constructed. Field A contains *Macon*'s aft portion and includes all four of the Sparrowhawk biplanes parked in the hangar bay, at least seven of the eight 12-cylinder Maybach engines known to be aboard, and remains of water ballast systems and the airship's galley. Field B is where the airship's bow flattened onto the seabed, and the site includes ruins of the airship's offices. One of the more exciting discoveries in the 2015 photomosaic was the ovoid, aluminum, spider web-like frame structure of *Macon*'s bow lying undisturbed and clearly visible on the seafloor (see construction photo in Figure 3 inset). Documentation of Field A biplanes reveals continuing deterioration (Figure 4), but it allows researchers to see components more clearly than ever before, and may permit identification of individual aircraft.

Following the mapping survey, we made a conservation assessment based on the aluminum's appearance, voltage readings, and a recovered sample of the onsite aluminum material. ROV *Hercules* carried temperature, pH, salinity, and dissolved oxygen sensors as well as a bathycorrometer, a voltage-reading probe that was designed for ROV use. The voltage readings taken from an FC9-2 biplane wing rib will help determine whether the aluminum is in an active or passive deterioration stage. A recovered sample of the aluminum structural frame of the airship (Figure 5) was transferred to the NHHC Underwater Archaeology Branch Conservation Laboratory and is currently undergoing chemical desalination and treatment in preparation for study and eventual museum display.



Ocean Networks Canada: Maintaining One of the World's Most Advanced Ocean Observing Systems

By Kate Moran, Adrian Round, Richard Dewey, Ian Kulin, Fabio De Leo,
Steve Mihály, and Maia Hoeberechts

In February 2006, a small team of scientists and engineers at the University of Victoria, representing what would become Ocean Networks Canada (ONC), turned on the world's first comprehensive cabled ocean observatory. The first few hours of temperature and salinity data streamed in from an instrument platform sitting in 100 m of water in the coastal fjord of Saanich Inlet, Canada, revealing surprising variations at all time scales. By 2015, ONC maintained and operated well over 300 devices on a series of cabled ocean observatories: three nodes on two cabled arrays totaling 43 km in the inshore waters of British Columbia (VENUS), an 800 km five-node loop extending 300 km off the west coast of Canada (NEPTUNE), and a coastal cabled system in the Canadian high Arctic at Cambridge Bay (Figure 1). During a month-long series of missions in August and September 2015, E/V *Nautilus,* using the remotely operated vehicle (ROV) *Hercules*, assisted ONC in maintaining the observatories. For a portion of the expedition, *Nautilus* was joined by R/V *Thomas G. Thompson* with ROV *Jason* and C/S *Wave Venture*.

Paramount in operating a cabled ocean observatory is regular maintenance of the subsea scientific instruments connected to the backbone cable at numerous nodes. These nodes are strategically placed across the deep seafloor at sites identified for their research potential (Figure 2). Node depths range from 100 m to over 2,600 m, so maintenance is accomplished with the aid of an ROV. Piloted from the command consoles on the surface vessel, the ROV manipulates large complex platforms that are lowered to the bottom (e.g., Figure 3) and connected to the network through specialized underwater wet-mate connectors. Instruments are often adjusted or moved into optimal positions, and water and sediment samples collected to support the data flowing from a variety of cameras (Figure 4), conductivity-temperature-depth (CTD) sensors, acoustic Doppler current profilers, sonars, seismometers, and hydrophones (Figure 5). During the 2015 expedition, ONC accomplished 27 *Hercules* and 16 *Jason* ROV dives to service over 275 devices, including both infrastructure systems and scientific instruments.

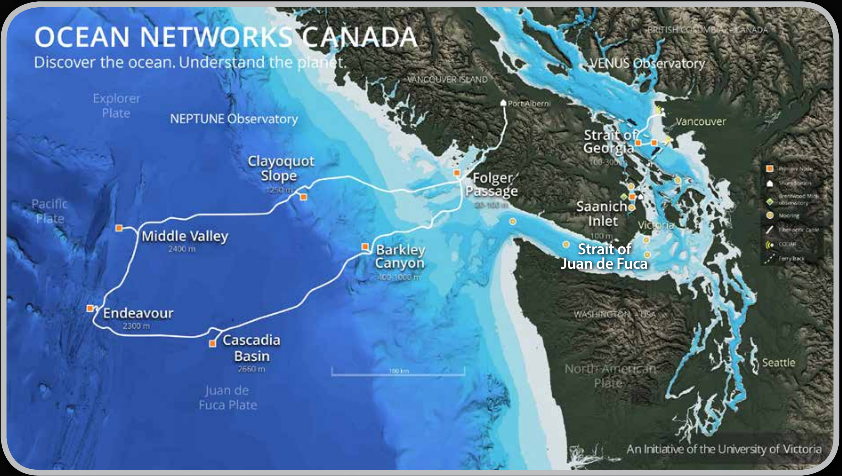


Figure 1. Locations of Ocean Networks Canada VENUS and NEPTUNE seafloor observatories. The coastal observatory in the high Arctic is not shown.

Figure 2. A ray swims by an Ocean Networks Canada node.

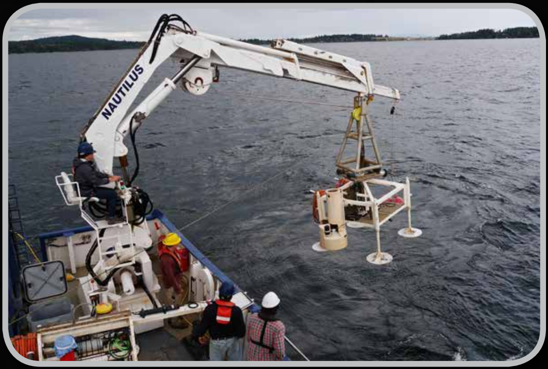


Figure 3. The deck team deploys an instrument platform in Saanich Inlet.

Figure 4. A camera observes geological and biological features on Endeavour Segment of the Juan de Fuca Ridge.

During the first set of dives from *Nautilus*, ROV *Hercules* serviced the coastal observatory VENUS. Maintenance was performed on core instrument platforms at all sites. In Saanich Inlet, this included servicing a user-controlled sediment trap, collecting sediment cores across bacterial mat boundaries, and deploying a special three-dimensional camera system designed to support computer-aided image analysis research. In the Strait of Georgia, the dives included servicing specialized instrument platforms with a suite of sonars for studying the sediment dynamics at the mouth of the Fraser River, deploying a pair of pig carcasses with a camera as part of an ongoing nine-year forensic research program, and deploying an eight-element hydrophone array to detect, classify, and track both ship noise and marine mammal vocalizations. A final dive in the strait visited the dense sponge reefs on Fraser Ridge, just north of the Fraser River mouth off the coastal city of Vancouver. The nearshore dives were characterized by challenging visibility conditions due to sediments and plankton stirred by the vigorous tidal currents.

After finishing work in the Salish Sea, a body of water that includes the Strait of Georgia, Strait of Juan de Fuca, and Puget Sound, *Nautilus* headed offshore, west of Vancouver Island, to service the NEPTUNE instrument platform located near the entrance to Barkley Sound at Folger Passage, a site located near a Rock Fish Conservation Area. At the furthest extent of the NEPTUNE network, ROV *Hercules* made a series of dives on Endeavour Segment of the Juan de Fuca Ridge (Figures 6 and 7). A suite of video surveys along the southern portion of the Endeavour vent field was directed by Thomas Kwasnitschka, ONC's visiting scientist from GEOMAR in Germany. These surveys provided the video transects necessary to reconstruct a full three-dimensional model of the Mothra Hydrothermal Vent Field.

The NEPTUNE ocean observatory has a number of complex installations, including the Endeavour and Barkley Canyon arrays. During a portion of the expedition, E/V *Nautilus* and ROV *Hercules* supported C/S *Wave Venture* to recover several cables that required replacement within the Endeavour Marine Protected Area. New and expanded cable lays are planned for 2016 to connect existing and new instrument systems along and across the ridge. Along the northern branch of the NEPTUNE cable loop, *Nautilus* laid a new cable at the Clayoquot Slope site supporting new experiments related to methane vents, plate tectonic tilt experiments, and anticipated new installations in 2016, including a planned connection to an Integrated Ocean Drilling Program borehole sensor.

While heading back to Victoria, E/V *Nautilus* and ROV *Hercules* serviced a mooring in the Strait of Juan de Fuca that monitors the exchange flows between the Pacific Ocean and the Salish Sea to assess incursions of low oxygen and low pH waters.

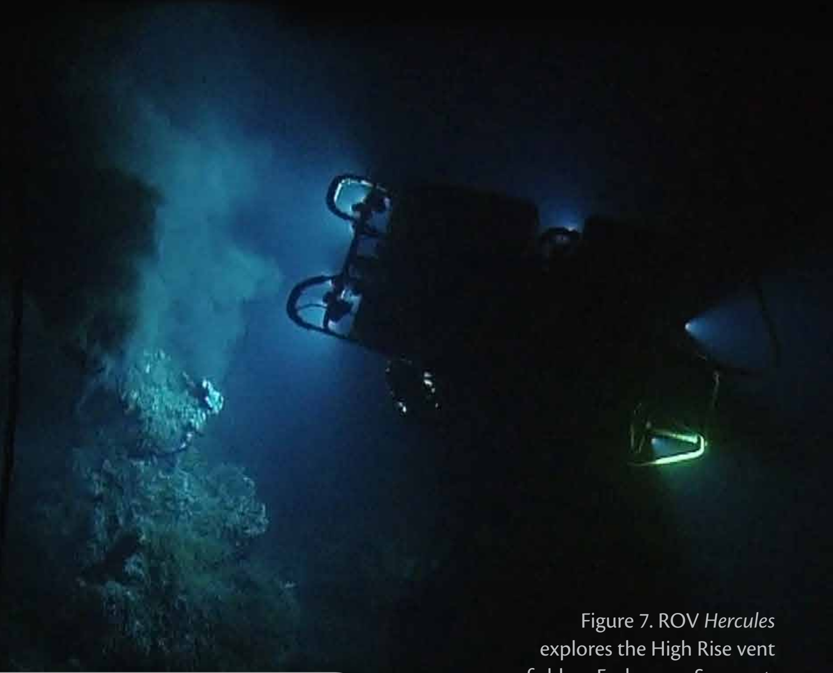


Figure 7. ROV *Hercules* explores the High Rise vent field on Endeavour Segment, Juan de Fuca Ridge.

Figure 5. A hydrophone recovered aboard *Nautilus*.

Figure 6. An underwater landscape shows hydrothermal vents along the Main Endeavour Field.

THE NOAA SHIP *OKEANOS EXPLORER* 2015 FIELD SEASON

The bow of NOAA Ship *Okeanos Explorer* from the bridge deck as sunset approaches in the main Hawaiian Islands. *Photo credit: Art Howard/ Courtesy NOAA OER*

Telepresence-Enabled Exploration with NOAA Ship *Okeanos Explorer*

By Brian R.C. Kennedy, Kelley P. Elliott, Kasey Cantwell, and Sharon Mesick

NOAA Ship *Okeanos Explorer* is the only federally funded US ship assigned to systematically explore our largely unknown ocean for the purpose of discovery and advancement of knowledge. The ship is operated through a partnership: NOAA's Office of Ocean Exploration and Research (OER) conducts all mission planning and operates the mission systems, and NOAA's Office of Marine and Aviation Operations provides and maintains ship systems and personnel. The vessel is uniquely designed to conduct telepresence-enabled systematic ocean exploration. Exploration operations are conducted in high-priority deepwater areas identified by the ocean science and management communities. The primary objective is to conduct initial site characterization, collecting baseline data about the seafloor and water column in unknown and poorly understood areas. Quality assured data are then made freely, publicly accessible as soon as possible to catalyze follow-on exploration, research, and management activities.

NOAA Ship *Okeanos Explorer*

FORMERLY | USNS *Capable*
LENGTH | 68 meters (224 feet)
BEAM | 13 meters (43 feet)
DRAFT | 5.1 meters (16 feet, 10 inches)
DISPLACEMENT | 2,312 LT
MAIN PROPULSION | Diesel electric with twin inboard turning screws (1,600 Shaft HP)
SPEED | 10 knots
ENDURANCE | 40 days at sea
RANGE | 17,780 kilometers (9,600 nautical miles)
DYNAMIC POSITIONING (DP-1) | 500 HP retractable azimuth bow thruster and two 250 HP stern thrusters
CLASSIFICATION | Stalwart-class ocean surveillance ship
BUILT | 1987, Halter Marine in Pascagoula, MS, USA
BERTHING | 46 persons (27 crew, 19 mission/science)
FLAG | United States of America
HOME PORT | North Kingstown, RI, USA

Figure 1. *Okeanos Explorer* holds station in the US Virgin Islands while the ROVs explore the seafloor. *Photo credit: Art Howard/Courtesy NOAA OER*

The first step in systematic exploration is to conduct ocean mapping using the vessel's deepwater systems to provide high-resolution bathymetric maps of the seafloor, water column acoustic reflectivity, and subbottom profiles. In situ site characterization is accomplished using OER's custom-built, two-body remotely operated vehicle (ROV) system, outfitted with powerful lighting, high definition (HD) imaging, and limited sampling capabilities. Throughout operations, telepresence is used to engage scientists and managers from many onshore locations in real time so they can collaborate on decision making during mapping, water column casts, and ROV operations. Together with the shore-based team, scientists and technicians at sea conduct preliminary site investigations, collecting enough data to provide an energized user community with justification for follow-on, hypotheses-based investigations before the ship moves on to explore more of the unknown ocean. Simultaneously, thousands of general public viewers can tune in online to watch and listen to the ongoing exploration.

BRIDGING THE SHIP-TO-SHORE GAP

Okeanos Explorer is one of the most connected ships in the world and operates in a unique way for research vessels, with most of the science team based on shore. A high-bandwidth satellite connection (up to 20 MBps of data) permits live HD video of seagoing operations and data acquisition screens to be streamed to shore in real time. On shore, the HD feeds are accessible through a multicast-enabled Internet2 connection with less than a two second delay, or via standard Internet with a delay of approximately five seconds. Access to HD video along with a suite of Internet-based tools facilitates collaboration among the science team, turning shore-based researchers into exploration stakeholders.

To take full advantage of the intellectual capital on shore, two-way communication is critical. The primary way those aboard *Okeanos Explorer* interact with the EM 302 team is through Eventlog, a persistent chat room used for operational discussion and as a proxy field journal for logging observations. Entries in

Figure 2. Data and Software Intern Dan Bolan maintains telepresence equipment. *Photo credit: Art Howard/Courtesy NOAA OER*

Figure 3. The high-bandwidth satellite connection is at the heart of telepresence operations—facilitating data transfer and ship-to-shore communications. *Credit: B. Ambrose, RTI/NCEI, R. Canfield, NOAA & NOAA OER*

Eventlog, and all data systems on board, are recorded and time stamped to Coordinated Universal Time (UTC) to facilitate post-cruise analysis. A Voice over Internet Protocol (VoIP) connection on the ship links the team via a toll-free teleconference line, allowing scientists to communicate directly with the at-sea team and to help narrate the video being streamed to shore. The teleconference is also used for daily planning meetings, outreach events, and when additional input into operations is needed.

The high-bandwidth satellite connection enables high-volume data transfers as well. The OER team conducts end-to-end data management, as defined by national and NOAA policies and international standards, of all data collected. A shipboard repository server gathers data from acquisition systems into a standardized file structure that is mirrored in a shoreside repository (accessed via FTP), providing participants with near-real-time access to data and public access to a subset of data and products through OER websites.

The combination of these tools allows any researcher with a broadband connection and a phone to participate in and help direct exploration operations on the ship. Along with traditional communications such as email, the high-bandwidth connection also enables ship-to-ship collaboration and allows the expedition team to react to emerging information. OER has also worked directly with science teams on board other vessels to share recently acquired data and quickly follow up on features of interest.

ADVANCING THE PARADIGM

Telepresence has been used as a tool to augment ROV investigations for over a decade; however, there has been little experimentation on the applicability of this technology for mapping operations. During 2015, OER investigated the use of telepresence to offset onboard staffing gaps and help train new personnel by providing additional support via a doctor-on-call model. Telepresence became a force multiplier, allowing newer personnel to lead watches while still having access to advice and assistance without burdening shipboard personnel. Real-time screen sharing permitted sonar data quality monitoring from shore, and tools developed for ROV expeditions, like Eventlog, connected EM 302 expertise with at-sea watch standers. The next step is to enable remote computer access to the sonar acquisition computers, which, in combination with direct communication to the ship's bridge, should allow watch leads to be located on shore.

OER has come a long way in pushing the boundaries of what is possible with telepresence technology since commencing operations with the majority of the science team on shore in 2010. During early years of telepresence operations, participants needed to be at a multicast-enabled Internet2 facility to view low-latency HD video, and direct communication required a specialized intercom unit. Advances in access to low-latency video and the use of teleconferencing now allow researchers based anywhere in the world to participate in an expedition. As the model continues to evolve, we look forward to leveraging new advancements as we learn from other industries and engage new partners.

Figure 4. The University of Hawaii at Manoa brought an Exploration Command Center online this year to enable scientists and students to participate in the Hohonu Moana (Deep Ocean) Expedition. *Credit: NOAA OER*

Advancing Undersea Technology

By Todd Gregory, David Lovalvo, Bobby Mohr, Karl McLetchie, and Melissa Ryan

The 2015 field season marked another year of achievements for NOAA's Office of Ocean Exploration and Research (OER) engineering group. Numerous improvements were made to OER's remotely operated vehicle (ROV) *Deep Discoverer* (*D2*) and its partner vehicle *Seirios*. Most notable was the installation of a new manipulator arm on *D2* and the addition of sample storage to the front end of *D2*. These additions allow *D2* to collect biological and geological samples from the seafloor to aid in the characterization of exploratory sites.

KRAFT PREDATOR II MANIPULATOR

The key tool that enables the ROV system to take samples from the seafloor is the manipulator arm. OER selected the Kraft Telerobotics Predator II arm (Predator), which is considered one of the industry's most capable and dexterous manipulators for specimen collecting. Currently, it is the only arm in its class with force-feedback capability. Force-feedback allows the arm's operators to sense the external forces acting on the arm, increasing pilot awareness and sensitivity.

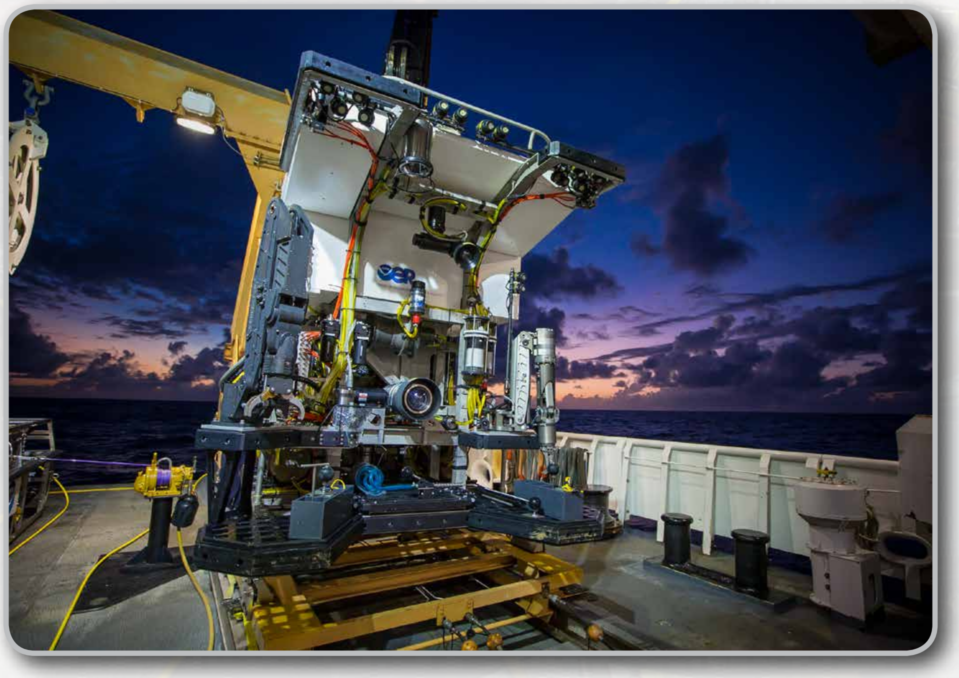


Figure 1. ROV *Deep Discoverer* (*D2*) offshore of Puerto Rico with new manipulator and frame modifications. *Photo by Art Howard/Courtesy NOAA OER*

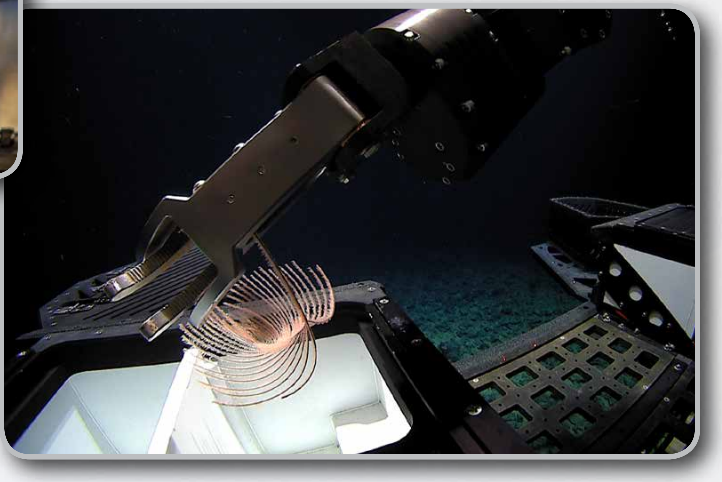
Installing the Predator arm onto *D2* was not a simple feat. Part of the challenge of installing an arm onto an existing vehicle is designing a structural foundation to tie the arm's loads into the frame. With a reach over 2 m (6.5 ft) and a lift rating of 0.9 kN (200 lb), the Predator is able to exert a tremendous bending moment into the vehicle's frame. OER engineers retrofitted a mounting system into *D2*'s frame that supports the loads and visually ties the components together in a seamless design.

One of the challenges of operating a manipulator system on an ROV is adequately imaging the working range of the arm with video cameras. A pilot who cannot see the arm from at least two perspectives at any given arm location will not have a three-dimensional sense of the arm's position with respect to its surroundings. To ensure that the pilots have adequate depth perception of the arm's working area, five high definition (HD) video cameras are distributed around the front of *D2*. One camera is the principal three-chip, broadcast quality HD camera for the best image quality, and there are also two auxiliary HD cameras positioned to either side of the vehicle. High on *D2*'s frame are two additional HD cameras with pan-tilt function that provide an orthogonal, or right angle, view of the arm's workspace. With the combination of any two of these five cameras, the pilots have a complete view of the arm's working area and can safely operate the manipulator, collect quality samples, and access *D2*'s new sample storage space (Figure 1).

On the first expedition using the Predator on *D2*, OER engineers discovered that the interfacing of the new manipulator arm resulted in seawater intrusion into the vehicle's hydraulic system. Keeping seawater out of ROV hydraulic systems is paramount, as precision valve components and electronics immersed in the hydraulic fluid should never be exposed to the corrosive and electrically conductive attributes of saltwater. OER engineers worked together with Kraft Telerobotics to diagnose and resolve a long-standing problem with the Predator II hydraulic circuit, which had

Figure 2. Coral cutter grippers installed on *D2*'s Kraft Telerobotics Predator II manipulator, offshore of Hawaii. *Photo by Art Howard/ Courtesy NOAA OER*

Figure 3. *D2's* coral cutter grippers delicately store a coral sample in the portside bio box, offshore of Hawaii. *Credit: NOAA OER*



been very difficult to detect and diagnose in a shop environment. During an exploration cruise, OER engineers carried out a series of carefully planned experiments that led to what turned out to be the correct hypothesis on what was causing the problem. In response, and prior to the next cruise, Kraft engineers designed and installed a new valve on the arm, which proved to be a successful solution to the problem. The result has been a significant increase in reliability and performance of the arm. This is a great example of OER's mission to engage in partnerships and make significant contributions to the oceanographic community.

CORAL CUTTER JAWS

One of the principal types of biological samples that OER is asked to recover from the seafloor is small pieces of deepwater corals. Images taken from the HD video cameras are helpful in documenting the coral communities and their associated organisms, but to identify an individual species of coral, scientists still need to perform DNA analysis on a physical sample.

When possible, OER chooses to only collect small voucher specimens from a coral rather than risk damage to the entire animal. To carry out this task, OER engineers further improved a prototype design for a unique set of jaws for the Predator manipulator. These multipurpose jaws have intermeshing fingers to grasp rocks, tools, and rigging, and they also have a set of scissor-like blades and urethane grippers that can snip and clamp a delicate branch of coral. The pilots are able to snip a specific branch and stow it in a sealed bio box on *D2* while causing the least possible tissue damage to the collected specimen.

Refinements to the prototype jaw design previously introduced by OER and Ocean Exploration Trust engineers included fabrication of the jaw halves using a single piece of hardened stainless steel rather than modifying Kraft's stock jaws. The resulting one-piece jaw halves are substantially shorter than the prior version, making the multipurpose grippers less cumbersome to use, especially when stowing small samples in the vehicle's storage boxes. The two jaw halves are assembled with hardened custom scissor blades, urethane grippers, and bushings (Figures 2 and 3).

FRAME EXTENSION AND SAMPLE STORAGE SPACE ON *D2*

To prepare for sampling operations in the 2015 field season, *D2*'s front end was extensively modified. An extension to the lower frame was added to provide more room for sample storage. Rather than adding a large "front end loader" type of extension to the lower frame, the engineers were careful to preserve the unimpeded field of view from the principal HD video camera.

The ROV program has, from its inception, been focused on taking the best quality HD video imagery. First, with *Little Hercules*, and more recently with *Deep Discoverer*, the ROVs have been praised for their stunning macro images. Part of the reason for both vehicles' success in collecting outstanding imagery is the proximity of their broadcast quality video cameras to the seafloor and, by extension, to the subject matter. Another key tool in collecting stunning imagery is a wide array of lighting, and *D2* pilots are able to adjust the light field by articulating the vehicle's four lighting swing arms.

The OER engineers did not want to compromise the ability to capture top-quality imagery by installing a large sample platform across the front of the vehicle frame. Instead, the frame extensions and sample storage volumes are located outboard of the main camera's field of view. During sample collections, the entire sample storage platform is extended forward into the camera's view and within easy reach of the manipulators (Figure 4a). Also, the port and starboard storage boxes can be individually articulated inboard toward the vehicle's centerline for easy access with either manipulator arm. For normal piloting and imaging, the sample drawer is retracted aft and the storage boxes are stowed outboard. The principal HD video camera's field of view is highlighted in the left image to illustrate how the frame extension and sample boxes can be located outboard of the camera's image during normal piloting/imaging (Figure 4b).

D2 is currently equipped with four storage boxes: two semi-open containers for stowing geological specimens or sampler/sensor deployments/recoveries and two sealed and insulated containers for storing biological specimens (Figure 5). Each bio box has an articulated lid that can be individually latched open/closed to ensure that valuable or low-density samples cannot escape once stowed during a dive. Upon recovery to the surface, the bio boxes' seals maintain an extremely coldwater temperature, making these storage containers suitable for collection of live specimens. The entire sampling space, particularly the gridded platforms on the forward sliders and in the center of the vehicle, can be easily modified with tools for future missions.

MILESTONES AND TECHNICAL ACCOMPLISHMENTS

The expedition to the Puerto Rico trench during spring 2015 presented the first opportunity for *D2* and *Seirios* to dive to their full 6,000 m depth rating (Figure 6). Upon successfully arriving at 6,000 m, the pilots discovered a warning in one of *D2*'s oil compensation systems. This issue forced the team to abort the dive earlier than planned. This abbreviated dive was the first and only instance of an aborted dive in the history of the vehicle system. The issue that caused the warning was identified and fixed by OER engineers, and the vehicles are ready to dive to 6,000 m during future seasons.

D2 and *Seirios* have a success rate of 99.2% for scientific dives. That rate means that only 0.8 % of planned dives were canceled or aborted due to technical malfunctions with the vehicle systems. This success rate is due to the meticulous attention to detail by OER engineers both in the design and in the maintenance of the vehicle systems.

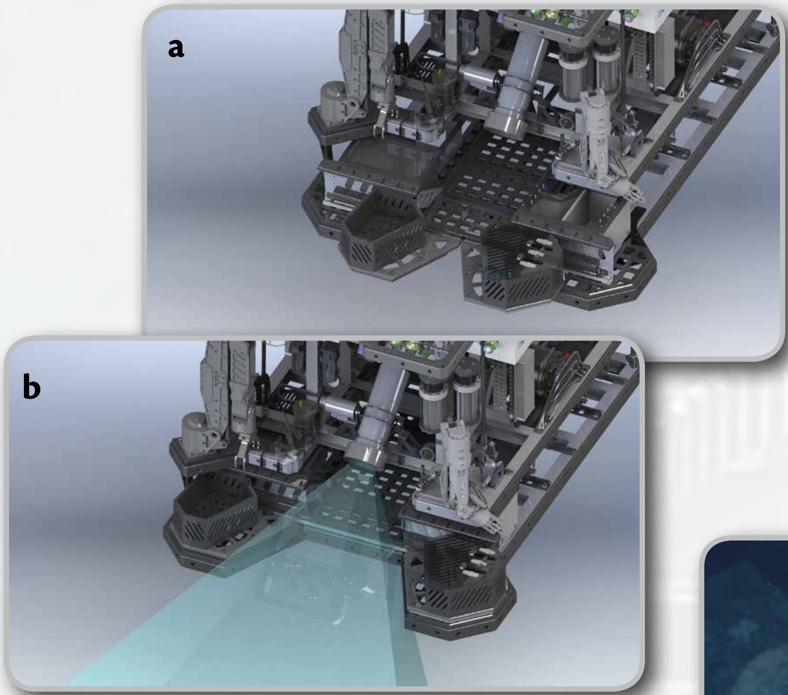


Figure 4. Three-dimensional CAD images of *D2*. (a) *D2* with the sampling drawer extended and port/starboard sliders positioned inboard. (b) *D2* with sampling drawer retracted, port and starboard sliders stowed outboard, and the unobstructed HD camera's field of view highlighted. *Image by Todd Gregory/Courtesy NOAA OER*

Figure 5. A coral sample is removed from *D2*'s portside bio box after a successful dive offshore of Hawaii. *Photo by Art Howard/Courtesy NOAA OER*

Seirios

During the winter of 2015, OER engineers upgraded about 80% of the vehicle electronics on *Seirios*. The impetus for this undertaking was the need to improve the light output, an invaluable asset to operations of a two-body system. *Seirios* was originally designed with six hydrargyrum medium-arc iodide (HMI) lights. HMIs work by producing an electrical arc between two electrodes in a volume mix of mercury vapor and metal halides, a combination that emits light when excited. These lights were chosen mainly because they burn at a color temperature very similar to sunlight, an attribute that contributes extensively to the accuracy of the colors we capture at depth. While this is an efficient means of producing light, OER's HMIs had several drawbacks. HMI lights, in addition to the lamp head, require a separate, large, heavy ballast to produce high voltages and current. Strict operation requirements limited the flexibility and use of HMIs, particularly during testing in the shop and on the *Okeanos Explorer* deck before dives. Maintaining OER's stock of aging HMIs, purchasing new units, and securing spares would also continue to prove costly, if not impossible.

The rapid development of LED technology in all industries has given the underwater community access to ever smaller, brighter, and less expensive pressure-rated LED lights. LEDs require lower voltages than HMIs and are much more efficient and easier to maintain. They also do not have the same operating restrictions as HMIs and can function safely and conveniently in air. *D2* and its 16 LEDs had performed very well during its inaugural season in 2013. During the 2014 off-season, engineers installed eight additional LEDs on *D2*. With this is mind, OER engineers replaced the *Seirios* HMI lights with 18 LEDs, increasing the lumen output by 50% at a small fraction of the cost, weight, and size of HMI lights.

In order to turn the new LEDs on and off, engineers installed three circuits and relays in the *Seirios* main telemetry bottle (the titanium housing that holds the "brain" of the vehicle). As part of this effort, the contents of the main telemetry bottle were upgraded. The entire power system (power conversion, distribution, switching, fusing, and monitoring) was redesigned. All components were rearranged to improve maintenance, accessibility, and heat dispersion. A new chassis to hold all the parts was built, and everything was rewired. Engineers also rewired the three junction boxes, including a new, improved termination junction box. All of the oil-filled, yellow PVC tubing that snakes around the vehicle and acts as a conduit for wires (Figure 7) was replaced and rewired. In the main transformer, one leg was also modified to accommodate the three-phase AC voltage required for the LEDs. Every electrical aspect of *Seirios* was reviewed and modified where necessary.

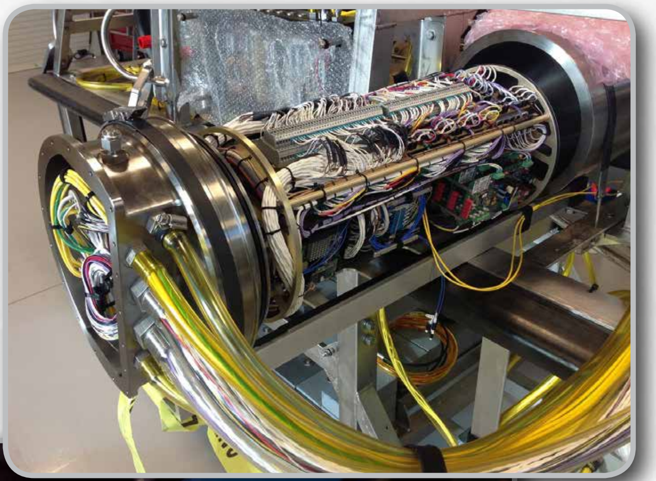


Figure 7. The "central nervous system" of *Seirios*. *Photo by Bobby Mohr/Courtesy NOAA OER*

Figure 6. OER Engineers piloting *D2* when the vehicle reached the depth rating of 6,000 m for the first time, Puerto Rico Trench. *Photo by Art Howard/Courtesy NOAA OER*

Applied Excellence In Data Management

By Sharon Mesick, Susan Gottfried, Brendan Reser, and Katharine Woodard

Data are tangible and enduring assets that illustrate the return on investment in ocean exploration. Drawing upon 15 years of experience managing the NOAA Office of Ocean Exploration and Research (OER) expedition data, and employing expertise from across the agency and extramural partners, OER's data management practices deliver rapid and unfettered data access, facilitate efficient and effective long-term data preservation, support resource management decisions, and inspire further exploration and research.

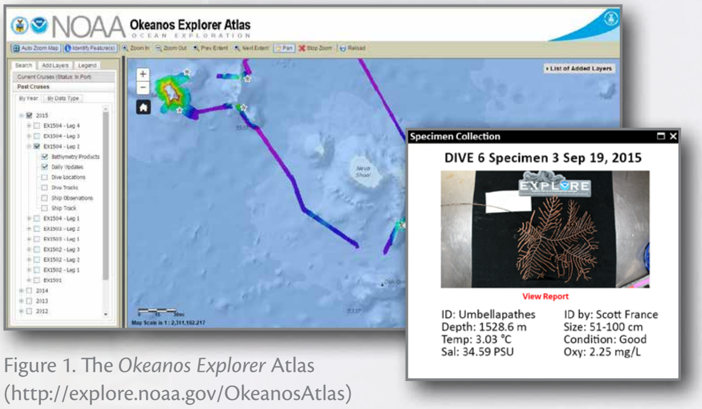
CHAMPIONING DATA STEWARDSHIP

The OER Data Management Team implements and freely shares cutting-edge tools and techniques developed to meet NOAA-wide data stewardship requirements. In partnership with NOAA's National Centers for Environmental Information (NCEI), OER's compiled multidisciplinary data collections are documented, discoverable, easily accessible, independently understandable—and freely available in perpetuity.

The NOAA Plan for Increasing Public Access to Research Results describes the program activities required to meet policy objectives identified by the White House Office of Science and Technology Policy Memorandum *Increasing Access to the Results of Federally Funded Scientific Research*. It reflects the high standards implemented by the team over many years. The team's award-winning End-to-End (E2E) data management workflow achieves OER program goals and mission needs and addresses many of the Administration's Open Data Initiatives.

Through the use of telepresence-enabled exploration, video and environmental data collections are available in near-real time to mission scientists participating from shoreside locations, broadening scientific analysis and enabling remote mission guidance. The public can also maintain situational awareness through the *Okeanos Explorer* Atlas (Figure 1). The display is updated as the mission progresses, providing mission context and visual integration with other regional data. Geospatial data services are created at the end of each mission so that users may embed OER data into their own websites and applications.

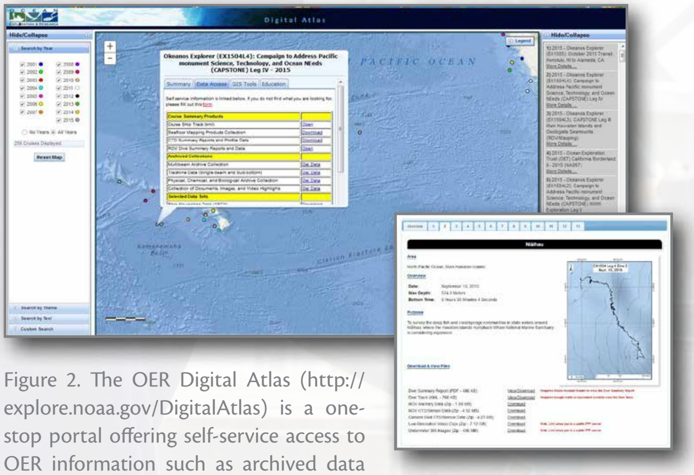
OER's E2E data management workflow demonstrates a documented model of success for how a broad range of scientific data, information products, and services can meet the diverse needs of different user communities. The OER Digital Atlas (Figure 2) is a self-service data access portal that provides access to the long-term, quality-controlled OER data collection. More than 250 OER missions are represented, including the complete *Okeanos Explorer* collection of more than 65 missions executed over eight years. Collections include multidisciplinary environmental data, images, video, educational materials, plans and reports, and links to peer-reviewed scientific publications.



DIVE 6 Specimen 3 Sep 19, 2015

ID: Umbellapathes
Depth: 1528.6 m
Temp: 3.03 °C
Sal: 34.59 PSU
ID by: Scott France
Size: 51-100 cm
Condition: Good
Oxy: 2.25 mg/L

Figure 1. The *Okeanos Explorer* Atlas (http://explore.noaa.gov/OkeanosAtlas) delivers situational awareness during expeditions. The geospatial display provides context for expedition activities, including the specimen collection shown here.



Okeanos Explorer (EX1504L4): Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE) Leg IV - 2015

Figure 2. The OER Digital Atlas (http://explore.noaa.gov/DigitalAtlas) is a one-stop portal offering self-service access to OER information such as archived data collections back to 1999, peer-reviewed publications, educational materials, and related resources. A Data Request form is available for further assistance.

INNOVATING VIDEO DATA MANAGEMENT

Video data collected by OER's remotely operated vehicle *Deep Discoverer* reveal details of the deep ocean environment that, when combined with spatial, temporal, and sensor data, add value for scientific data reuse, support habitat characterization, and impact resource management decisions. Ensuring easy public access to large volumes of video is a significant challenge. The team has developed an innovative and extensible video data management solution that involves pairing full-resolution video data segments with low-resolution versions suitable for online streaming. A single, detailed metadata record provides customized discovery and access to each video data pair through a simple yet effective access portal. Users can readily locate video segments of interest and immediately preview and download streamed data. The corresponding full-resolution data are also available through an online ordering system that notifies the user when the larger volume files are ready for download. This self-service method empowers users to find and freely access a wide range of environmental data (Figure 3).

formerly the National Oceanographic Data Center (NODC) ... more on NCEI

You are here: Home › NOAA Okeanos Explorer - Video Data Access Portal

NOAA Okeanos Explorer - Digital Video Access Portal

This video data access portal allows you to perform a granular search for the videos collected by the submersibles launched from the NOAA Okeanos Explorer and subsequently order the same.

Date Range

Start date: (YYYYMMDD)

End date: (YYYYMMDD)

Depth Range

Min. Depth (in meters):

Max. Depth (in meters):

Location Coordinates

Hold the "shift" key and drag to select an area.

Select Theme(s)

Geology
Life and Ecosystems
Marine Archaelogy
Technology

Select Location(s)

Hendrickson Canyon
Lindenkohl Canyon
McMaster Canyon
Norfolk Canyon
Okeanos Canyon

Select Keyword(s)

Benthic Ecosystems
SCS
SQU

Select Cruise

EX1404L2
EX1404L3

N: 90
W: -180
E: 180
S: -90

Figure 3. A Video Data Access Portal enables easy discovery and ready access to video data collections. Users may stream low-resolution video or request online delivery of high-resolution video data files.

PIONEERING *OKEANOS EXPLORER* SAMPLING OPERATIONS

As part of OER's Sample Pilot Project, the team rapidly developed and field-tested the Sampling Operations Database Application (SODA). The database offers a comprehensive approach for documenting the biological and geological sample collections. The streamlined and standardized data entry process efficiently produces accurate metadata, summary reports, and digital files, and provides tracking capabilities as samples are divided and submitted to sample repositories. During the Hohonu Moana: Exploring Deep Waters off Hawai'i expedition (**see pages 68–73**), the team provided onboard sampling operations assistance (Figure 4), on-scene training, and shoreside monitoring. This experience allowed the team to refine the sampling database through practical use to meet the needs of scientists and expedition participants.

SECURING FUTURE SUCCESS

In 2015, the team focused on training the next generation of shipboard data managers (Figure 5). Cross training ensures program longevity and provides the opportunity for personnel with various backgrounds to bring their expertise to bear on this diverse program.

Okeanos Explorer has served as a testbed for state-of-the-art data acquisition systems, innovative data products, and data management processes and procedures since it was commissioned in 2008. The ship and specialty teams are examples of what can be accomplished through system integration and optimization, near-real-time data dissemination, rapid archival throughput, and open access to information. As new data collection technologies emerge and data sets grow ever larger, the OER Data Management Team will continue to refine, adapt, and innovate new data management capabilities, ensuring OER information availability is both prompt and enduring.

Figure 4. National Centers for Environmental Information team member Katharine Woodard joined the *Okeanos Explorer* expedition to field test the new sampling database. Here she works with live samples. *Photo credit: Art Howard/ Courtesy NOAA OER*

Figure 5. From left, Andy O'Brien, Katharine Woodard, Brendan Reser, and Susan Gottfried participate in a training session for the next generation of data managers aboard *Okeanos Explorer*. Also involved, but not pictured, were Matt Dornback and John Relph. *Photo credit: Art Howard/ Courtesy NOAA OER*

Okeanos Explorer 2015 Field Season Overview

By Kelley P. Elliott, Brian R.C. Kennedy, Meme Lobecker, and Jeremy Potter

EXPLORATION OF THE US CARIBBEAN, HAWAIIAN ARCHIPELAGO, AND OFFSHORE JOHNSTON ATOLL

During the 2015 field season, NOAA and partners conducted 12 systematic exploration cruises using NOAA Ship *Okeanos Explorer* (Figure 1). The season started in February with a transit from Rhode Island through winter storms to the US Caribbean where a major expedition was launched to explore largely uncharted deep-sea ecosystems and seafloor in the vicinity of Puerto Rico and the US Virgin Islands. In May, the ship transited through the Panama Canal and into the Pacific where the first expedition of a major multiyear foundational science effort focused on deepwater areas of US marine protected areas in the central and western Pacific. Despite a series of emergency ship repairs, we had a very successful field season addressing national priorities in two regions, engaging communities of scientists new to telepresence, working with partners to establish new Exploration Command Centers (ECCs), and implementing a pilot sampling program.

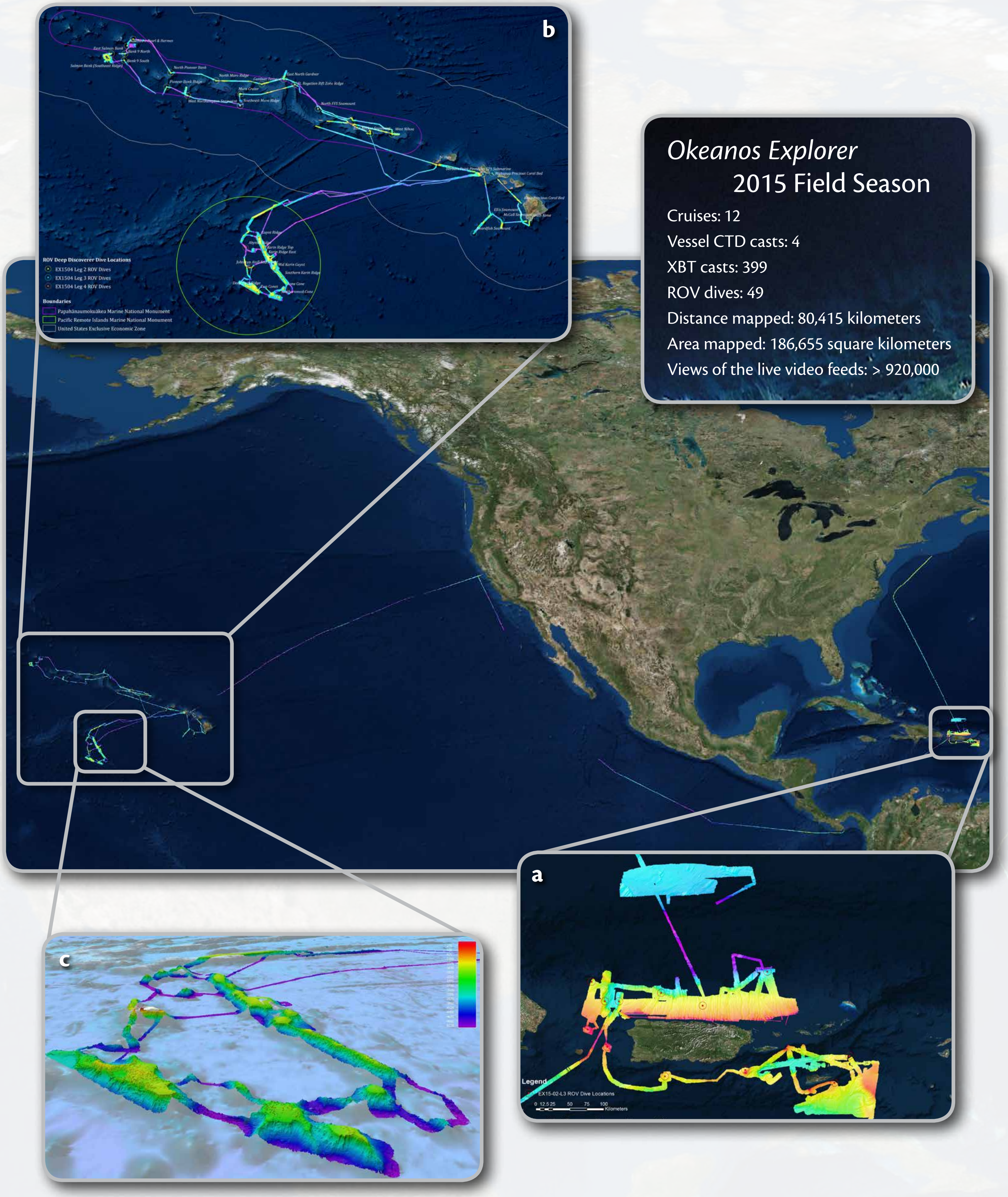
Three expeditions in spring were part of Océano Profundo 2015: Exploring Puerto Rico's Seamounts, Trenches, and Troughs in the Caribbean (**see pages 64–67**). Two cruise legs mapped priority areas put forward by the ocean science, management, and exploration communities during a 2012 workshop hosted by NOAA and the Ocean Exploration Trust. The remotely operated vehicle (ROV) surveys and mapping of the region built on previous work by the US Geological Survey and E/V *Nautilus*, continuing exploration to deeper depths to collect critical deepwater environmental data to inform federal and local resource managers. Expedition highlights included an ROV dive to 6,000 m—the maximum depth rating of ROVs *Deep Discoverer* and *Seirios*. The first full-trench-depth conductivity-temperature-depth (CTD) data set was collected in the understudied hadal zone of the Puerto Rico Trench while also supporting deployment of the deep-diving free vehicle developed by Wilford Schmidt through a grant to the University of Puerto Rico at Mayagüez.

After passing through the Panama Canal and into the Pacific, 24-hour-a-day mapping during transits revealed several previously unmapped knolls along the East Pacific Rise, and a survey of opportunity collected sea surface salinity values to calibrate and validate salinity observations made from space using satellites. Unplanned stops were made on the West Coast for emergency repairs, and by the end of June, *Okeanos Explorer* had arrived in Pearl Harbor; the team was ready to start the Hohonu Moana: Exploring Deep Waters off Hawai'i expedition.

From July to September, four cruises and 49 ROV dives were conducted to explore unknown and little known deepwater areas of the Hawaiian Archipelago and offshore of Johnston Atoll. The expedition—which included an extensive level of cross-NOAA support and collaboration—targeted priorities in support of NOAA, interagency, and academic partners. The expedition team collected environmental data in the Papahānaumokuākea Marine National Monument (PMNM), the recently expanded Johnston Atoll Unit of the Pacific Remote Islands Marine National Monument (PRIMNM), the Geologists Seamounts Group, and the main Hawaiian Islands (**see pages 68–73**).

(above) A squid, *Walvisteuthis youngorum*, is imaged at 900 m depth in the water column off Northeast Gardner Pinnacles in the Northwestern Hawaiian Islands. No species of *Walvisteuthis* had previously been seen in situ, and only two identifiable adult/subadult specimens of *W. youngorum* have been collected. *Photo credit: NOAA OER*

(left) ROV *Deep Discoverer* places a piece of an unknown *Corallium* coral collected at 2,078 m depth into one of its bio boxes during a dive on a ridge extending south of Pioneer Bank in the Northwestern Hawaiian Islands. Following collection, the boxes are sealed to keep specimens insulated for their return to the surface. *Photo credit: NOAA OER*



Okeanos Explorer
2015 Field Season

Cruises: 12
Vessel CTD casts: 4
XBT casts: 399
ROV dives: 49
Distance mapped: 80,415 kilometers
Area mapped: 186,655 square kilometers
Views of the live video feeds: > 920,000

Figure 1. Areas explored during the NOAA Ship *Okeanos Explorer* 2015 field season. (a) Summary map showing ROV dive sites and bathymetric data acquired during three cruises conducted during the 2015 Océano Profundo expedition in the Caribbean. Credit: *NOAA OER.* (b) Summary map showing work conducted during four cruises as part of the 2015 Hohonu Moana expedition. During the course of three months, 65 days at sea were spent conducting mapping and 49 ROV dives in the Hawaiian Archipelago and offshore of Johnston Atoll. Credit: *NOAA OER* (c) Oblique three-dimensional view of color-coded bathymetry mapped within the Johnston Atoll region during the 2015 field season, with depths in meters and 3x vertical exaggeration. Background bathymetry from Sandwell et al. (2014). Mapping focused on seamount and ridge features, with Hutchinson and Johnston Seamounts shown in the bottom of the image, Johnston Atoll left-center, and the >300 km long and mostly flat-topped Karin Ridge shown along the right side.

Figure 2. A new Exploration Command Center was brought online at NOAA's Inouye Regional Center for the 2015 Hohonu Moana expedition. Here, NOAA Pacific Islands Fisheries Science Center (PIFSC) fishery biologist Bruce Mundy provides background information about the expedition to visiting groups. Allen Andrews of PIFSC, at the upper left-center facing the audience, also gave talks to visiting groups about the biology of the deepwater corals and sponges seen during the expedition. *Photo credit: Nick Pawlenko/NOAA*

Background photo credit: Art Howard/ Courtesy NOAA OER

BREAKING NEW GROUND

Hohonu Moana was an expedition of many firsts, including the first time the *Okeanos Explorer* team conducted telepresence-enabled operations in the central Pacific region. Thanks to the work of our partners at the University of Hawaii at Manoa and the NOAA Inouye Regional Center, two new Exploration Command Centers were brought online and will continue to support science participation during the 2016 and 2017 field seasons (Figure 2).

A pilot program to collect limited physical samples with ROV *Deep Discoverer* was initiated during the Hohonu Moana expedition. The objective of these sampling operations is to maintain a balance between covering adequate distance during a dive, obtaining sufficient close-up imaging, and collecting limited samples in a minimally invasive way while recognizing the scientific need for physical and biological sample collection. Limited rock samples were collected to provide more information about the origin and age of the seamounts and geologic features in the region. Biological sampling was limited to potential new species or new animal records for the Hawaii region. The 69 samples collected highlight how much remains to be explored and discovered in the deep ocean. Evaluation of 2015 sample activities will inform operations in future years.

New ways of leveraging telepresence continue to be tested by the *Okeanos Explorer* team and community, and 2015 marked the first time a formal graduate-level class was conducted using telepresence. Students from Florida Atlantic University's Harbor Branch Oceanographic Institute (HBOI) actively participated in many aspects of the cruise from HBOI's Exploration Command Center. They helped plan ROV dives, explored the seafloor with ROVs, recorded observations and cruise activities, and became familiar with telepresence.

During the ship's transit in October from Hawaii to California for winter repair and dry dock, experts on shore at the University of New Hampshire and at the NOAA Office of Ocean Exploration Research (OER) headquarters in Silver Spring, MD, tested remote management of mapping operations. The onboard crew collected data over previously unmapped seamounts and supported a National Science Foundation project to measure small displacements of the seafloor associated with rapid events such as earthquakes and landslides.

WINTER UPGRADES

During the winter dry dock, the ship will be outfitted with five new Kongsberg EK 60 fisheries sonars, two Teledyne RDI acoustic Doppler current profilers, and a CTD designed for use underway. These new tools will provide the ship with additional capabilities to characterize the water column of new areas. New hardware for the ship's VSAT satellite dish will also be installed and should stabilize the vessel's ship-to-shore connection and improve the shoreside participation experience.

LOOKING TO THE FUTURE

Operations in the Hawaii region in 2015 laid a foundation for working in the Pacific and initiated the Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE). CAPSTONE is a major multiyear foundational science effort focused on deepwater regions of US marine protected areas in the central and western Pacific (Figure 3). The investment provides timely, actionable information to support decision making based on reliable and authoritative science, and is an opportunity for the nation to further characterize the uniqueness and importance of these national symbols of ocean conservation. In 2016, field activities will focus primarily in the western Pacific, with significant effort in and around the Marianas Trench Marine National Monument, the Wake Island portion of PRIMNM, and additional work in PMNM. OER plans to continue the campaign into 2017 by shifting field activities to the central Pacific, focusing efforts on additional US Pacific Remote Island Areas, the National Marine Sanctuary of American Samoa, Rose Atoll Marine National Monument, and the Phoenix Islands Protected Area.

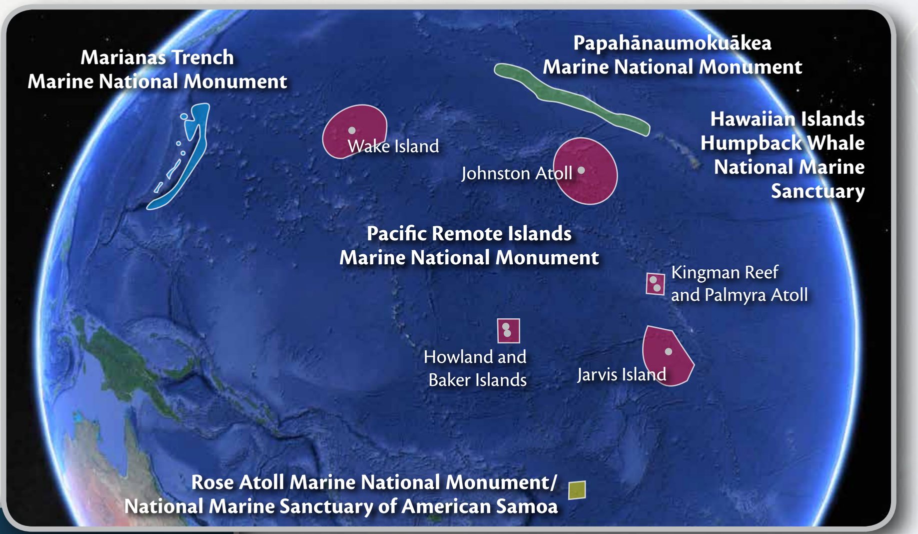


Figure 3. Google Earth image of the US Marine National Monuments and national marine sanctuaries in the central and western Pacific. These are the primary geographic areas of CAPSTONE operations between 2015 and 2017.

This beautiful hydromedusa from the genus *Crossota* was seen at about 3,900 m depth during a dive on the west wall of Mona Canyon, located northwest of Puerto Rico. *Credit: NOAA OER.*

2015 Strategic Mapping Exploration in the Caribbean Sea and Pacific Ocean: Complementing Existing Data and Supporting ROV Operations

By Meme Lobecker, Lindsay McKenna, and Derek Sowers

Detailed seafloor maps are essential for exploration and baseline characterization of the ocean environment. Recent advances in satellite altimetry have led to improved worldwide bathymetric maps (Sandwell et al., 2014); however, their resolution is often not fine enough for research and exploration purposes. Thus, hull-mounted shipboard sonars remain the industry standard for efficient and effective high-resolution seafloor mapping.

Each field season, the NOAA Office of Ocean Exploration and Research (OER) utilizes NOAA Ship *Okeanos Explorer* to conduct several mapping expeditions, opening the door to new discoveries, insights, and knowledge of previously unknown areas. For the 2015 field season, the vessel operated three scientific sonars. The primary mapping system is a high-resolution 30 kHz Kongsberg EM 302 multibeam sonar for mapping bathymetry as well as seafloor and water column backscatter. The EM 302 can achieve resolutions of 50 m or better in water depths between 50 m and 5,000 m. The two other sonars on *Okeanos Explorer* include a 3.5 kHz Knudsen Chirp sonar and an 18 kHz Simrad EK 60 split-beam sonar. In 2016, the ship will be field testing four of the five new EK 60 water column sonars and two new acoustic Doppler current profilers.

During the 2015 field season, *Okeanos Explorer* mapped over 185,000 km^2 of seafloor in the Caribbean and Hawaiian exploration areas and during all transits in between, collecting over 750 GB of sonar data. These data will support long-term ocean management goals and will provide insight into the geologic and ecological characteristics of each area. In the Caribbean, *Okeanos Explorer* mapped over 37,500 km^2 of seafloor around Puerto Rico and the US Virgin Islands, revealing new details about rugged canyons along shelf breaks, seamounts, large slumps, and slope failures. In the Hawaiian region, over 31,000 km^2 of new high-resolution sonar data were collected in the recently expanded Pacific Remote Islands Marine National Monument's Johnston Atoll Unit, including Johnston Seamount (Figure 1), Karin Ridge, and Horizon Tablemount. The data were used for remotely operated vehicle (ROV) dive planning on subsequent 2015 *Okeanos Explorer* cruises, and also to support the ongoing US Extended Continental Shelf Project as well as overall monument management goals. Maps showing all recent bathymetric data are included in articles in this supplement.

In recognition of NOAA's integrated approach to ocean mapping, following the sentiment "map once, use many times," the OER mapping team aims to utilize existing bathymetric data and add new data to previously mapped areas. During the planning stages of the 2015 *Okeanos Explorer* field season, the mapping team was given the rare assignment to explore areas that had previously largely been mapped by modern multibeam sonars. The US Geological Survey had been conducting surveys and combining all available bathymetric data in the vicinity of the Puerto Rico trench for several years (Andrews et al., 2014). Vast regions of the Papahānaumokuākea Marine National Monument had been recently mapped by other NOAA ships and the Schmidt Ocean Institute's R/V *Falkor*, and the data were synthesized by the Hawaii Mapping Research Group at the University of Hawaii at Manoa. Care was taken to ensure that any new mapping conducted in the 2015 field season complemented existing data sets.

Where existing multibeam coverage was available, the sonars were used creatively. For example, in order to determine the sediment

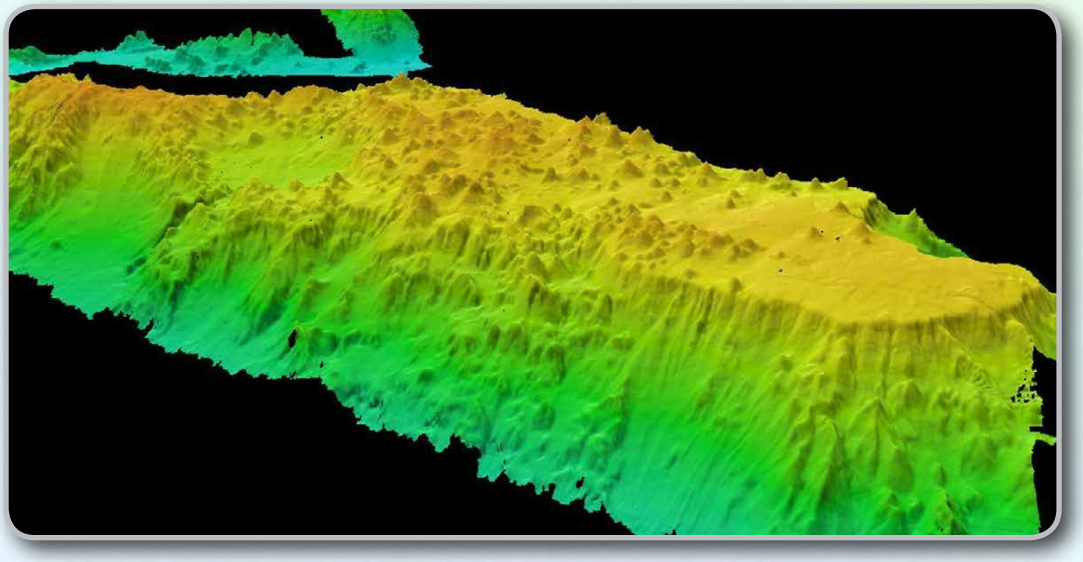


Figure 1. Multibeam bathymetry of a portion of Johnston Seamount. VE = 3x, grid resolution 50 m.

thickness within a 6 km wide crater discovered 46 km east of Maro Reef in the Northwestern Hawaiian Islands on a 2014 *Falkor* cruise (Figure 2), *Okeanos Explorer* acquired a series of subbottom profile transects (Figure 3). Little to no sediment was found in the crater (Figure 4), indicating that its formation is likely more recent than the surrounding 65-million-year-old Cretaceous seamounts.

An ROV dive was conducted to further explore the Maro Reef crater and ground truth the sonar data, providing an illustrative example of the partnership between mapping and ROV exploration. The dive track was selected and planned during a telepresence-enabled video conference call between scientists aboard the ship and on shore using maps made with high-resolution bathymetric data collected by R/V *Falkor* and made available by the Schmidt Ocean Institute. The ROV's exploration began on the crater floor at the inner base of the eastern wall, climbed upslope, explored the crater's eastern summit, and briefly ascended the outer wall before returning to the ship (Figure 5). The ROV video footage can be used to ground truth what the sonars are remotely detecting.

All mapping data collected by OER on *Okeanos Explorer* during the 2015 field season are publicly available from the NOAA National Centers for Environmental Information archives. A variety of data formats, several of which can be opened using open source software, are available to members of the scientific community and the general public.

ACKNOWLEDGMENTS. All figures were created using QPS Fledermaus three-dimensional visualization software; a free version is available at http://www.qps.nl. Unless otherwise noted, multibeam data shown in all images were collected by R/V Falkor, *which shares its scientific data through NOAA NCEI.*

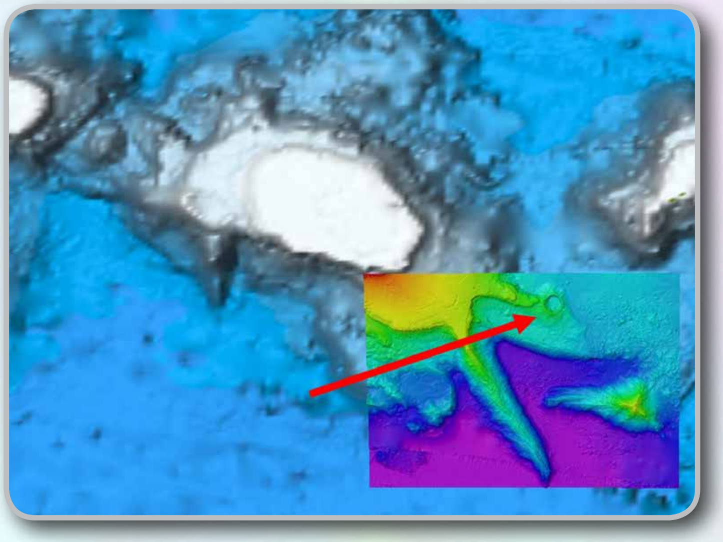


Figure 2. High-resolution multibeam bathymetry overlain on low-resolution satellite bathymetry at Maro Reef in the Northwestern Hawaiian Islands. The red arrow points to a crater.

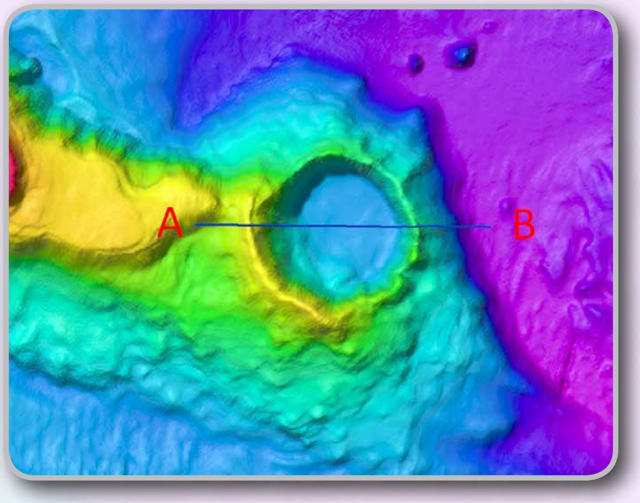


Figure 3. Bathymetric map of the submarine crater 46 km east of Maro Reef. Line A–B indicates one subbottom data transect.

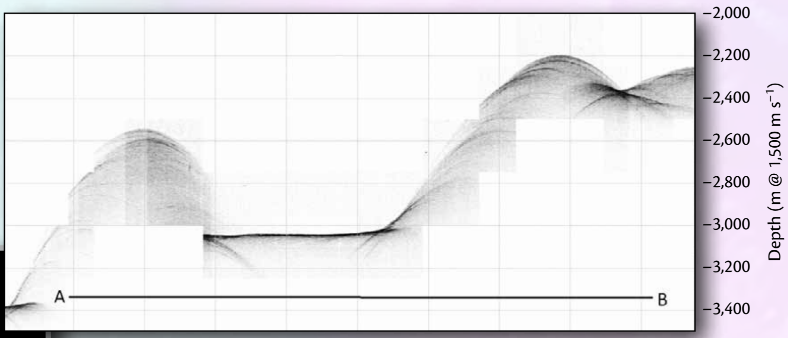


Figure 4. Subbottom profiler data revealing very little sediment coverage on the crater floor. The line was run east (A) to west (B).

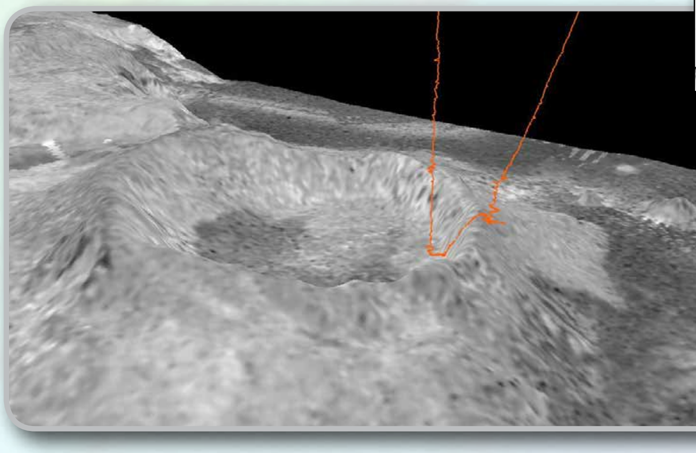


Figure 5. ROV *Deep Discoverer* dive track (orange) overlain on bottom backscatter data of the 6 km wide submarine crater.

Océano Profundo 2015: Exploring Puerto Rico's Seamounts, Trenches, and Troughs

By Brian R.C. Kennedy, Andrea M. Quattrini. Michael J. Cheadle, Graciela Garcia-Moliner, Jason Chaytor, Michael Ford, Meme Lobecker, Derek Sowers, Lindsay McKenna, Kasey Cantwell, Wilford Schmidt, Manuel Jiménez, Amanda W.J. Demopoulos, Timothy M. Shank, Michelle Schärer-Umpierre, Christopher L. Mah, and the *Okeanos Explorer* Onshore Science Team

Numerous seamounts and submarine canyons, as well as the deepest trench in the Atlantic Ocean, lie just offshore of Puerto Rico and the US Virgin Islands (USVI). Few of these features have been explored in detail, despite their proximity to land and the fact that much of the region has been previously mapped with multibeam sonars (Andrews et al., 2014). Two community-based workshops identified the need to collect critical baseline information about this region to better understand its deepwater ecosystems, geological processes, and potential geohazards. Acting on the recommendations from the broader management and scientific communities, NOAA's Office of Ocean Exploration and Research (OER) launched a three-leg expedition called Océano Profundo 2015 to explore and characterize deep waters around Puerto Rico and the USVI. From February to April 2015, an interdisciplinary team of federal, state, and academic scientists working aboard NOAA Ship *Okeanos Explorer* as well as on shore collaboratively investigated the geology and biodiversity of this underexplored region of the US Exclusive Economic Zone.

Puerto Rico and the USVI are bounded to the north by the 8.4 km deep Puerto Rico Trench, formed by the obliquely subducting North American Plate, and to the south by the Muertos Trough and the Caribbean Plate. Consequently, the region is geologically active, with a history of destructive earthquakes and tsunamis. During Océano Profundo, *Okeanos Explorer* mapped over 37,500 km² of seafloor with high-resolution multibeam sonar, revealing new details about rugged submarine canyons, seamounts, slumps, and slope failures (Figure 1). The expedition also included some of the deepest remotely operated vehicle (ROV) dives ever conducted in the Puerto Rico Trench and the first ever exploration of two seamounts in this region.

The first Océano Profundo leg and most of the second leg were dedicated to collecting high-resolution multibeam bathymetry, backscatter, and subbottom data over poorly mapped areas of the seafloor. These efforts included collecting some of the first ever multibeam data from the northern side of the Puerto Rico Trench and offshore of St. Croix in the vicinity of Saba Valley. New high-resolution bathymetric maps of submarine canyons along the slope off the north side of the island were also completed.

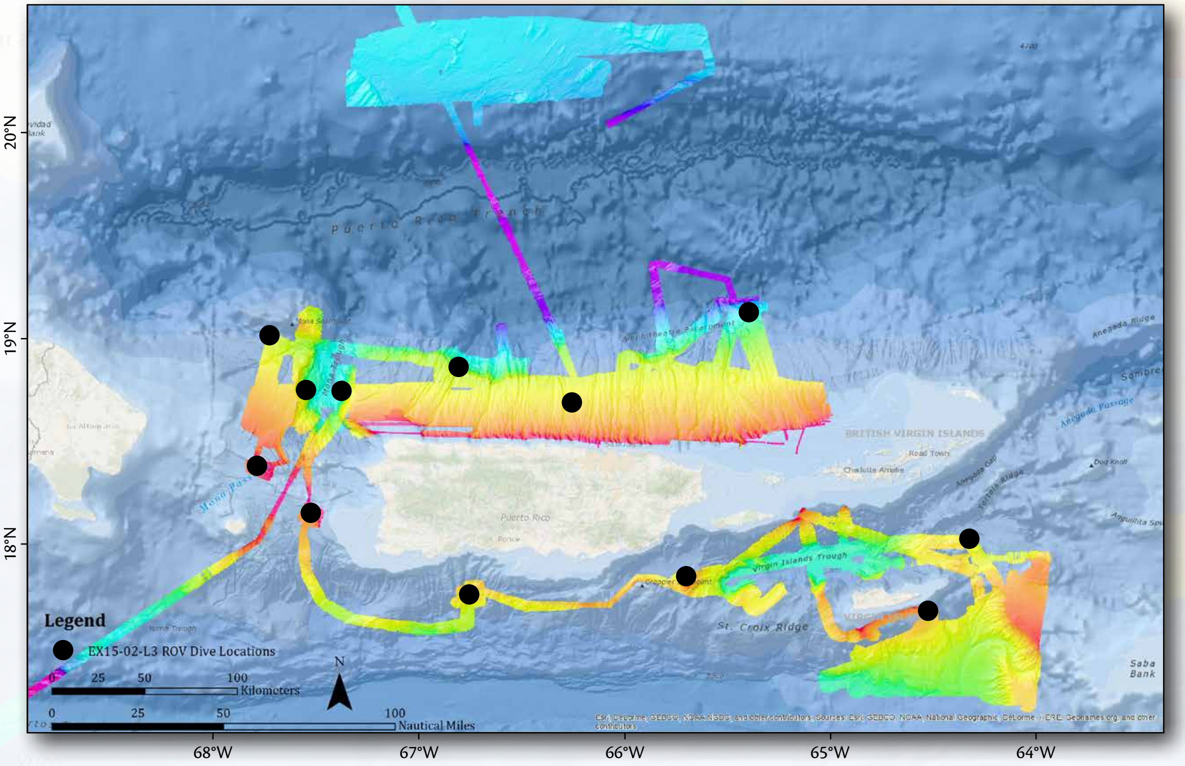


Figure 1. During the Océano Profundo 2015 expedition, NOAA Ship *Okeanos Explorer* conducted 12 ROV dives and mapped over 37,500 km² of seafloor with multibeam sonar. *Credit: NOAA OER*

Figure 2. During Leg 2 of Océano Profundo, *Okeanos Explorer* conducted deepwater trials for the University of Puerto Rico at Mayagüez's newly developed free vehicle technology. *Photo credit: NOAA OER*

During the second leg of Océano Profundo, OER partnered with researchers at the University of Puerto Rico at Mayagüez to conduct deepwater trials of newly developed free vehicle landers (Figure 2). The goal of this ongoing project is to create low-cost sampling packages that are robust enough to explore the hadal zone. Even with modern technologies, very few data collection methods are currently available to scientists exploring these very deep waters because extreme hydrostatic pressure makes operations difficult and expensive. The free vehicle deployments conducted during Océano Profundo included the first full-depth (8,375 m) conductivity-temperature-depth (CTD) casts in the Puerto Rico Trench, identifying what appears to be the boundary between North Atlantic Deep Water and Antarctic Bottom Water at 6,750 m depth (unpublished data of author Schmidt and colleagues).

The third Océano Profundo leg used the ROV *Deep Discoverer* (*D2*) to characterize the biology and geology of the area and to ground truth previously gathered sonar data. During 12 dives, *D2* explored different areas, depths, and geological settings, gathering critical baseline data to inform resource management and future research. Three major areas were explored: the Puerto Rico Trench, Mona Passage, and the area south of Puerto Rico and the USVI. The dives traversed elements of the Jurassic to Eocene island arc volcanics that form the region's basement, and the Oligocene to Recent clastic and carbonate strata, the upper part of which forms the extensive carbonate platform rimming Puerto Rico and the USVI. By exploring varied geomorphological and geological environments in such a dynamic region, the dives allowed scientists to develop a better understanding of submarine geologic processes. This information will contribute to our understanding of the region's geologic evolution and will be incorporated into a regional geohazard assessment.

IN SITU OBSERVATIONS

A variety of foundation species such as deep-sea corals, tunicates, and sponges were observed during the ROV dives, but sessile colonization was extremely patchy both within and across dives. Large portions of hard bottom habitat had no obvious colonization. Demosponges and hexactinellid glass sponges were the most common sessile species, having a patchy distribution on hard substrates down to 4,000 m water depth. At least 50 species of deep-sea corals were identified, including octocorals (e.g., plexaurids, pennatulaceans, isidids), antipatharians (black corals), stylasterids (lace corals), and scleractinians (e.g., *Madrepora, Enallopsammia).* Several symbioses were also noted. For example, squat lobsters (galatheoids), brittle stars (ophiuroids), and polychaetes were specifically associated with corals (Figure 3). Many of these species were not observed on surrounding substrates. Predatory tunicates with polychaete associates provided another novel example of potential symbiosis.

Midwater transects were conducted during three ROV descents at 100 m intervals from 800 m to 1,200 m depth. These transects captured detailed images of numerous midwater species, mostly from the mesopelagic zone. Two notable observations included a large (~10 cm diameter) pelagic foraminifera at 900 m depth and a ~1 m long squid, *Asperoteuthis acanthoderma,* encountered at 800 m depth (Figure 4). The ability to observe fragile midwater fauna that would be damaged using traditional sampling methods illustrates the utility of exploring the pelagic zone for increasing knowledge of this poorly studied environment.

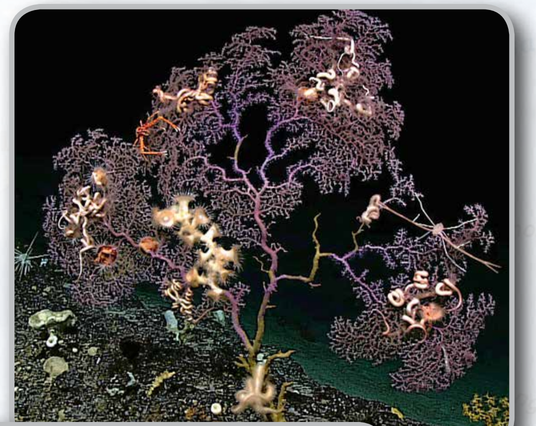


Figure 3. Throughout the expedition, brittle stars and squat lobsters were commonly observed associated with deep-sea corals. *Photo credit: NOAA OER*

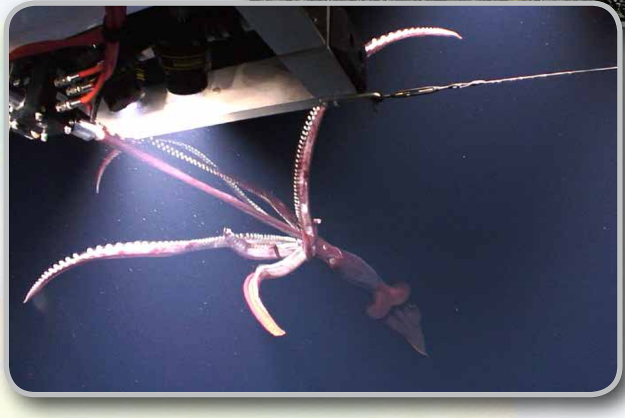


Figure 4. A ~1 m long squid, *Asperoteuthis acanthoderma,* imaged at 800 m depth in Mona Canyon. *Photo credit: NOAA OER*

Many benthic and midwater species were imaged for the first time in their natural habitat. High-definition video provides valuable information about live colorations and species' behaviors. Additionally, at least two new species were observed, but there are likely more new species to be described in the region. During a dive in Guajataca Canyon along the Arecibo Amphitheater, three individuals of a new species of benthic ctenophore were observed between 3,800 m and 3,900 m depth. This species is in the process of being formally described. Also, a new species of wrasse (family Labridae) was observed at 363 m and at 457 m depth in Mona Passage. A species description is in progress for this labrid, which was recently collected off Curaçao (Carole Baldwin, Smithsonian Institution, *pers. comm.*, 2015). *D2* also imaged many species that were either thought to be rare and/or were not previously known to occur in the region. Two fishes, Shaefer's anglerfish (*Sladenia shaefersi)* and the jellynose *(Ijimaia* sp.), had not been previously recorded around Puerto Rico (Figure 5). Notably, the starfish *Laetmaster spectabilis* was seen at 3,915 m depth along the east wall of Mona Canyon (Figure 6). This is one of the rarest known sea stars, previously identified from only one or two specimens collected at 1,878 m depth off Cuba (Perrier, 1881).

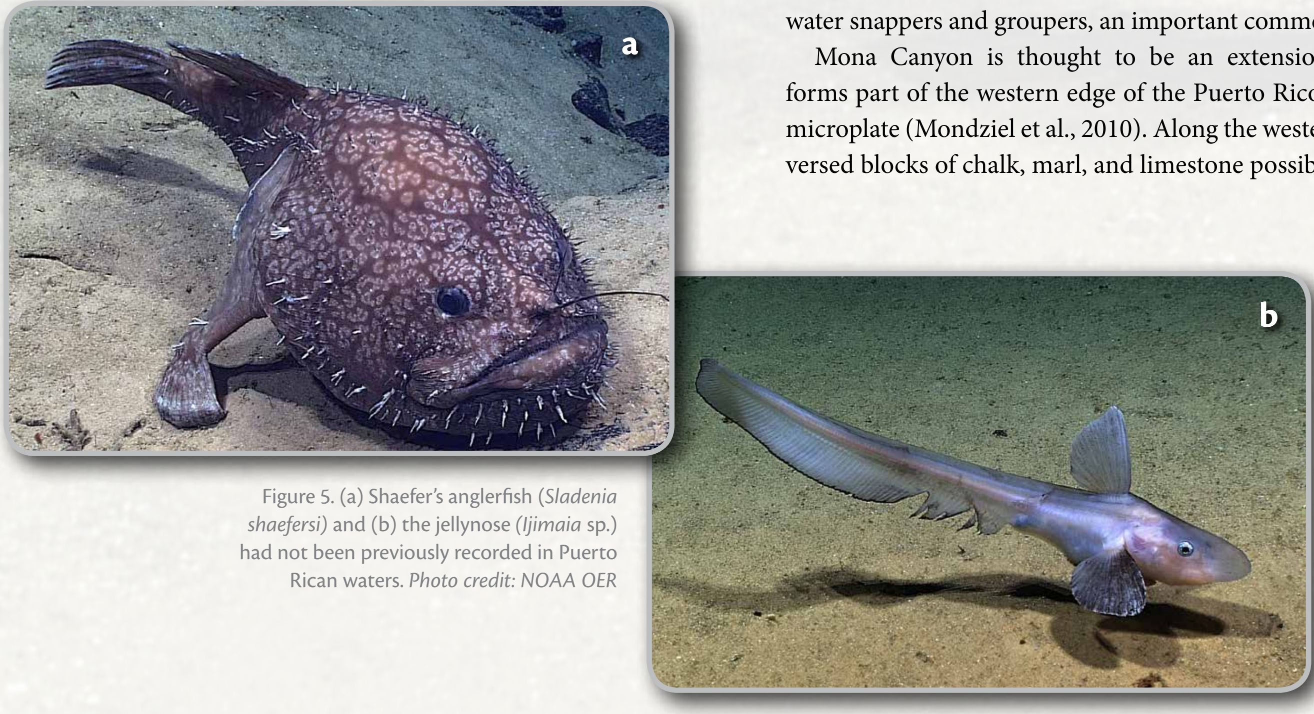


Figure 5. (a) Shaefer's anglerfish (*Sladenia shaefersi)* and (b) the jellynose (*Ijimaia* sp.) had not been previously recorded in Puerto Rican waters. *Photo credit: NOAA OER*

Puerto Rico Trench

Three dives were conducted on the carbonate platform north of Puerto Rico, two of which were on the south wall of the Puerto Rico Trench at 3,400 m to 6,000 m depth. The dive in Guajataca Canyon along the Arecibo Amphitheater traversed 600 m of the carbonate platform sequence. Small debris flows with rounded cobbles and localized failure of the rock face were also documented. Foundation species were relatively rare along hardbottoms in the area; however, sponges were the most abundant sessile fauna observed, and a few colonies of bamboo coral were documented. Here, *D2* made its deepest dive to 6,000 m, its maximum rated design depth. Although *D2* collected valuable imagery and CTD data in the water column, the dive ended before the ROV made contact with the seafloor.

Mona Passage

Five dives were conducted in the area of Mona Passage, a high-priority area for exploration identified by both the Caribbean Fishery Management Council and the US Geological Survey. Two dives surveyed the west and east walls of Mona Canyon (3,200 m to 4,000 m depth); one dive explored the easternmost continuation of Septentrional Fault (3,200 m to 3,700 m depth); and two dives were conducted in 300 m to 600 m of water to survey habitats of deep-water snappers and groupers, an important commercial fishery.

Mona Canyon is thought to be an extensional rift, and it forms part of the western edge of the Puerto Rico-Virgin Islands microplate (Mondziel et al., 2010). Along the western wall, *D2* traversed blocks of chalk, marl, and limestone possibly derived from

Figure 6. The sea star *Laetmaster spectabilis* was documented at 3,915 m depth along the east wall of Mona Canyon. This species has not been recorded since it was initially described 130 years ago. *Photo credit: NOAA OER*

failure of shallower sections of the canyon wall (Figure 7). One ROV dive explored the eastern wall of Mona Canyon, traversing basement rocks that form Puerto Rico's core—a very different rock sequence than the carbonates seen at similar depths on the west wall. Although colonization by sessile fauna was sparse, faunal abundance was greater on the manganese-iron hydroxide coated faces of large, angular rock slabs observed at the deepest and shallowest depths of the dive than on the outcrops present at intermediate depths.

Of particular geological interest was the karst terrain that began at approximately 400 m depth, possibly a result of subaerial exposure of the carbonates during a sea level lowstand. Demosponges appeared to be most abundant at the "Platform" and "Pichincho" sites compared to other sites surveyed. Fishes were most diverse and abundant at these relatively shallow depths, including queen snapper (*Etelis oculatus*) and various species known to co-occur in fisher's catches (i.e., houndsharks and bigeye).

South of Puerto Rico and the US Virgin Islands

Along the eastern wall of Guayanilla Canyon, south of Puerto Rico, *D2* imaged several well-defined, small-scale slope failures along 20 m wide, arced headwall scarps in the steeply dipping outcrops of bedded carbonates (Figure 8). The first ever ROV surveys of Whiting (500 m to 1,300 m depth) and Exocet (2,400 m to 2,900 m depth) Seamounts were also conducted. These "seamounts" were formed by tectonic extension at the margin of the Puerto Rico-Virgin Islands microplate. *D2* traversed the bounding fault scarp of Whiting Seamount and documented both plutonic and volcanic rocks from the Jurassic-Eocene arc basement.

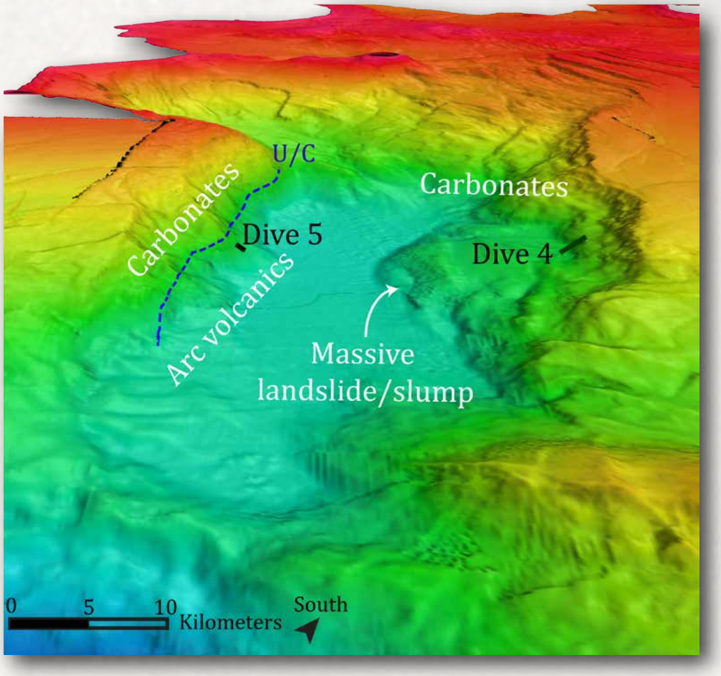


Figure 7. Two dives were conducted in Mona Canyon (dive transects represented by thick black lines). Dives 4 and 5 traversed platform carbonates and the volcanic/plutonic basement, respectively. Dive 4 also documented the top of a massive 5 km landslide visible in the bathymetry. The blue dashed line shows the unconformity between the volcanic/plutonic basement and the overlying carbonates in the east wall of the canyon. Bathymetry is shown with no vertical exaggeration. *Credit: NOAA OER*

Near the end of Océano Profundo, a NOAA National Ocean Service research group conducting mapping operations using NOAA Ship *Nancy Foster* discovered a series of enigmatic 100 m to 200 m diameter mounds south of St. Croix. Capitalizing on *Okeanos Explorer*'s telepresence capabilities, operations were adjusted to investigate these geological features of unknown origin. Although their origin remains a mystery, an ROV dive confirmed that they consist of carbonate and documented the highest biodiversity of deep-sea corals observed during the expedition.

BEYOND EXPLORATION

Data collected during Océano Profundo provide insights into geological processes around Puerto Rico and the USVI and expanded our knowledge of deepwater biodiversity in this region. Mapping and ROV exploration of seamounts, canyons, and trenches offer the opportunity to better understand potential geohazards and improve our capabilities to predict their impacts. An increased understanding of the geologic setting of the region provides additional context for understanding benthic communities. In addition to documenting new and rare species, observations made during Océano Profundo will help resource managers understand the current status of communities that are vulnerable to anthropogenic impacts. Baseline characterization data collected can also be used to better understand connectivity within the region. Although much has been learned from our initial observations, this expedition also revealed the high probability for further discoveries in the region and the need for additional exploration. As with every *Okeanos Explorer* mission, all data collected are now publicly available through NOAA's National Centers for Environmental Information and are awaiting further analysis by the scientific community.

Figure 8. ROV *Deep Discoverer* documented headwall scarps of small-scale slope failures in Guayanilla Canyon. *Credit: NOAA OER*

CAPSTONE's First Year— 2015 Hohonu Moana: Exploring Deep Waters off Hawai'i

By Christopher Kelley, Scott France, Frank Parrish, Daniel Wagner,
Mackenzie Gerringer, and Michael Garcia

The deeper biological and geological resources in both the Papahānaumokuākea Marine National Monument (PMNM) and the Johnston Atoll (JA) area of the Pacific Remote Islands Marine National Monument (PRIMNM) are poorly known. Since the 1980s, manned and unmanned vehicles have been used to conduct survey dives at each monument, but most were shallower than 1,000 m. Interest in what biology exists below 1,000 m depth increased significantly in 2003 when a large, high-density coral and sponge community was discovered in PMNM at 1,800 m depth (Amy Baco-Taylor, 2003), and two similar communities were found in 2007 (NOAA, 2009). These communities were located on volcanic ridges within the 1,000–2,500 m depth range where cobalt-rich ferromanganese crusts (Mn crusts) form over hard substrate. Mn crusts represent a vast mineral resource that will likely be targeted in the future by the deep-sea mining industry.

The group planning for the Honohu Moana (i.e., deep ocean) expedition, the first year of the CAPSTONE project (Campaign to Address the Pacific monument Science, Technology, and Ocean NEeds) recognized the need to explore for more of these communities in order to understand how and where they form, and their species compositions. We prioritized exploration surveys for these communities on Mn-crusted ridges, volcanic cones, and guyots to acquire: (1) information on the deepwater resources within PMNM and PRIMNM, (2) proxy data for unprotected Mn-crust communities that exist outside the monuments, and (3) information for the Deep Sea Coral Research and Technology Program (DSCRTP). Aside from the Office of Ocean Exploration and Research (OER), several other NOAA offices provided critical funding and support to enable this first CAPSTONE expedition: DSCRTP, the NOAA Fisheries Pacific Islands Fisheries Science Center, the Pacific Islands Regional Office/Marine National Monument Program, and the National Ocean Service Office of National Marine Sanctuaries. DSCRTP supported a seven-day cruise in the main Hawaiian Islands (MHI) and the Geologist Seamounts to further our understanding of deep-sea corals and sponges. Finally, CAPSTONE collected video and rock samples for the purpose of resolving the geologic histories of the PMNM, PRIMNM, and the Geologist Seamounts. Below, a summary of each of the three remotely operated vehicle (ROV) cruises is followed by descriptions of the main biological and geological discoveries.

Exploration of PMNM's Deep Ridges for High-Density Coral and Sponge Communities

Eighteen ROV *Deep Discoverer* (*D2)* dives were conducted during NOAA Ship *Okeanos Explorer* cruise EX1504 Leg 2 (Figure 1a). The dives targeted ridges extending from seamounts and banks in, or just outside of, PMNM at depths ranging from 1,096 m to 4,829 m (Figure 1b). Ridge crests were hypothesized to be suitable for the development of large, high-density coral and sponge communities because they provide consistently oriented topography (i.e., the crest runs in the same direction for long distances) where current flow is accelerated. We conducted 13 dives on seamounts or banks that had never before been surveyed at any depth. One of these dives was on an enigmatic crater off the southeast coast of Maro Reef, whose origin had been a mystery since it was first discovered in 2002. Three dives were conducted on what were believed to be Cretaceous age seamounts (80–90 million years

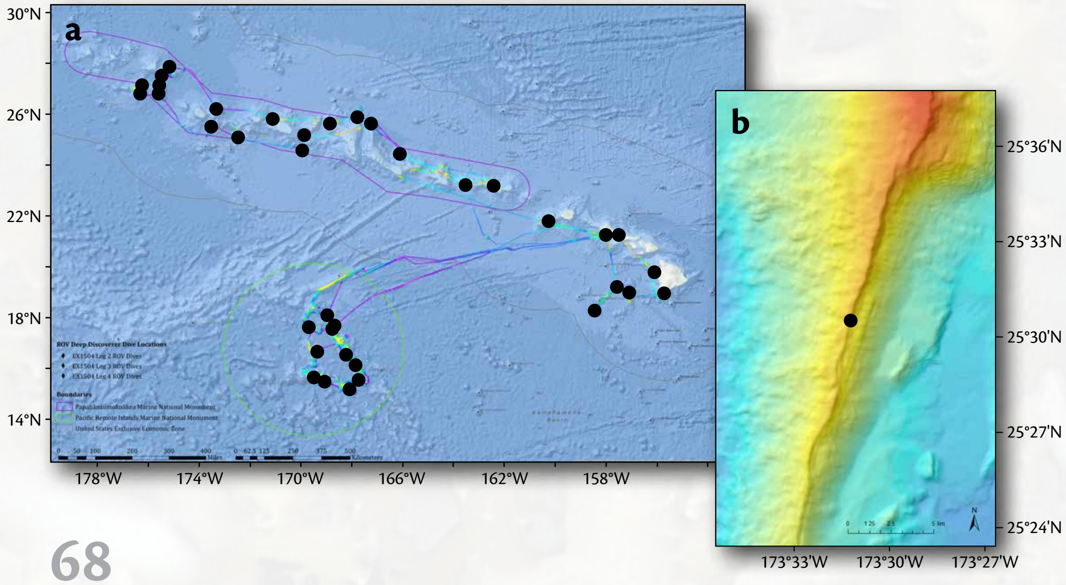


Figure 1. (a) Locations of ROV dives (black dots) within and near the Papahānaumokuākea Marine National Monument during *Okeanos Explorer* cruise EX1504 Leg 2 for CAPSTONE (Campaign to Address the Pacific monument Science, Technology, and Ocean NEeds). (b) Example of a ridge targeted for a dive during this cruise. *Data compilation by John R. Smith, ArcGIS images by Christopher Kelley*

old), all of which are guyots (i.e., flat-top seamounts) that are thought to have already been present on the seafloor when the neighboring Hawaiian volcanoes formed 60 million years later (Kelley et al., 2015). The last dive of the cruise was conducted on a ridge extending into a constricted channel between two banks where current velocity was predicted to be high.

This cruise included a pilot effort, with the ROV *D2* limited to sampling potential new species and obtaining new records and rock samples for the Hawaii region to provide more information about the origin and age of the seamounts. These first ever collections yielded 23 cnidarians, 11 sponges, 2 echinoderms, 31 rocks, and associated organisms found on these specimens that together weighed 170 kg.

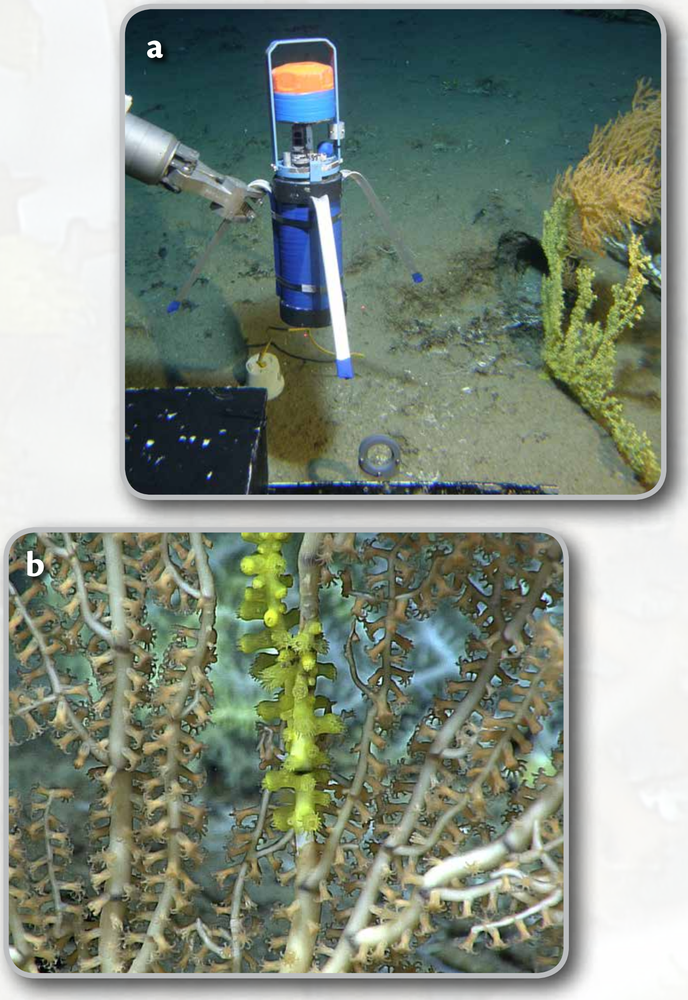
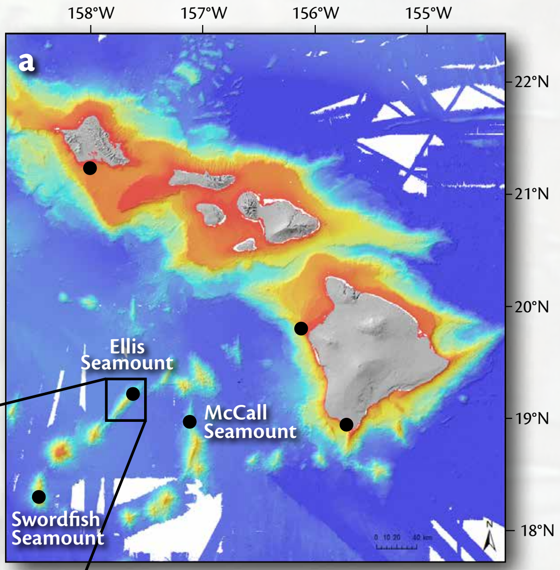


Figure 2. (a) ROV *D2* recovers an acoustic current meter equipped with a particulate sensor and a thermograph. (b) A study of the growth processes of gold coral, like the one shown here in the process of overgrowing a bamboo coral, was part of the CAPSTONE project. *Image provided by Frank Parrish, originated from NOAA HURL Archives*

Instrument Recoveries, Transects in the MHI, and Exploration of the Geologist Seamounts for the DSCRTP

The next ROV leg, EX1504 Leg 3, was the first cruise conducted by OER funded entirely by another NOAA program, the DSCRTP. Six ROV dives were completed, all using telepresence-enabled shore-based science participation. This cruise also had two significant departures from previous exploration projects. First, two dives were conducted off Oahu and the Big Island of Hawaii to relocate and recover instruments that had been deployed by human-occupied submersibles several years earlier (Figure 2a). In addition, colonies of gold coral (*Kulamanamana haumeaae*, Family Parazoanthidae) located near the instruments were imaged with lasers in order to obtain growth rate data (Figure 2b). Second, in another dive off the Big Island, we obtained data on the colonization and growth of corals on lava flow substrates of known ages. Because this area had been explored previously and the coral community characterized, we moved the ROV rapidly over the bottom to complete a 2,000 m long transect, a record for *D2*. Furthermore, all three dives took place between 300 m and 500 m depth, far shallower than the ROV typically operates.

The next three dives were exploratory and deeper (954–2,700 m), returning to the main CAPSTONE priorities of surveying for large, dense coral and sponge communities on Mn-crusted ridges. The dive sites were on three previously unexplored Geologist Seamounts: McCall's, Swordfish, and Ellis, located approximately 160 km south of Honolulu (Figure 3). Dredged rock samples on several other seamounts in this group indicated they did not form at the same time as the main Hawaiian Islands, but rather are much



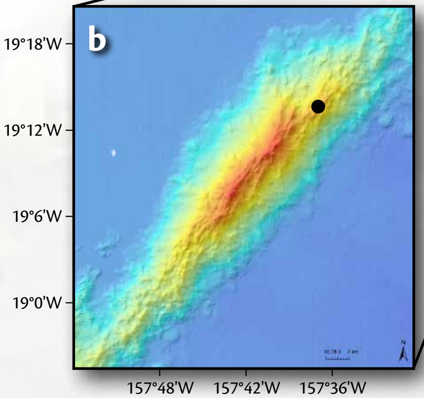


Figure 3. (a) Locations of ROV dives in the main Hawaiian Islands during EX1504 Leg 3. (b) Ellis Seamount in the Geologist Seamounts group. *Data compilation by Paul Johnston, ArcGIS images by Christopher Kelley*

older (Dymond and Windom, 1968), having originated south of the equator and been carried to the vicinity of the Hawaiian Islands by the northwest movement of the Pacific Plate (Sager, 1992). The last dive was conducted on the hull of World War I submarine S-19 that was intentionally scuttled in 1938 and now serves as relatively new hard substrate on which deep-sea corals can colonize (Figure 4). Though the intact hull provided a glimpse of how such communities pioneer settlements, this dive was not focused on biology but rather on providing an opportunity for NOAA marine archaeologists to observe the condition of the vessel. Finally, a flowmeter was recovered from the vessel, and the pilots practiced deploying and recovering a mock-up of a tilt meter for use on future dives.

Limited biological and geological collections continued on this cruise, yielding nine cnidarians, one sponge, and 11 rocks.

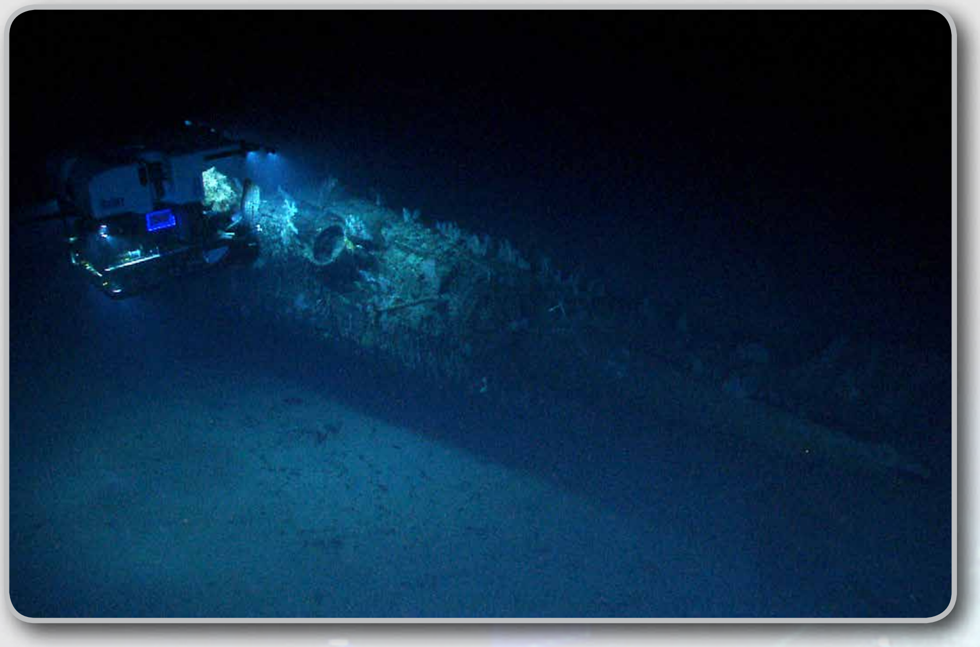


Figure 4. NOAA's ROV *Deep Discoverer* shines its lights on USS *S-19* resting at ~ 415 m depth. The World War I submarine was intentionally scuttled in 1938. *Credit: NOAA OER*

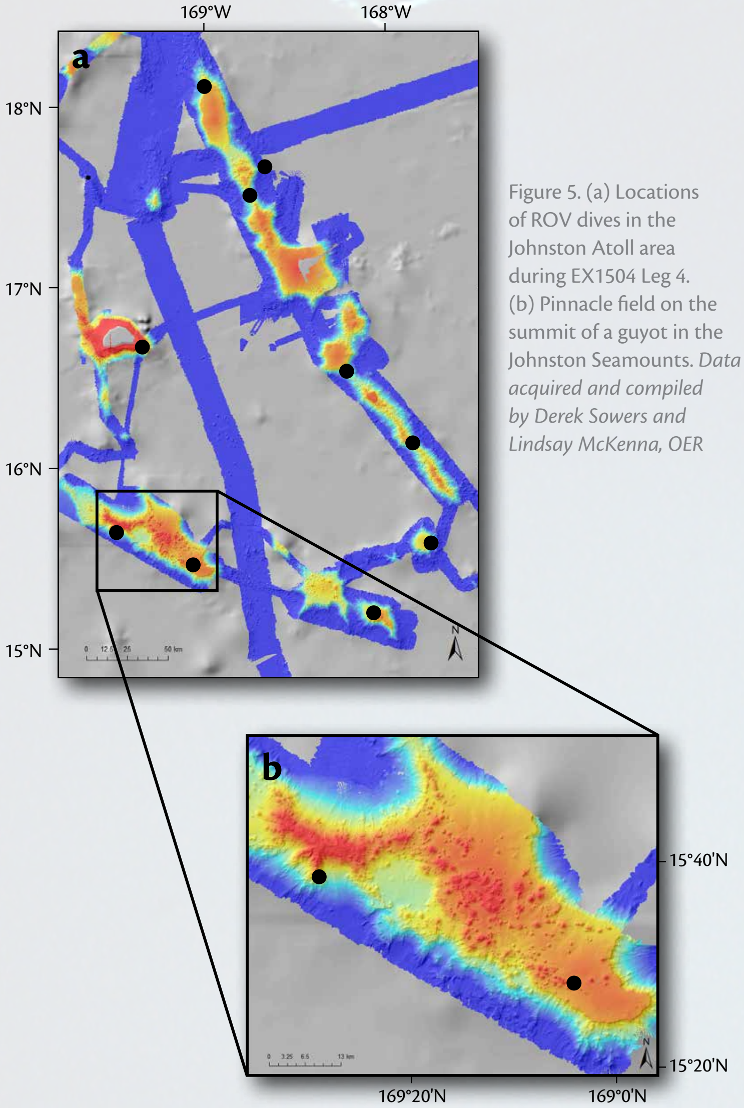


Figure 5. (a) Locations of ROV dives in the Johnston Atoll area during EX1504 Leg 4. (b) Pinnacle field on the summit of a guyot in the Johnston Seamounts. *Data acquired and compiled by Derek Sowers and Lindsay McKenna, OER*

Exploration of the Guyots, Volcanic Cones, and Deep Ridges in the Johnston Atoll Area of the PRIMNM

Thirteen dives were completed during EX1504 Leg 4, the third and final ROV cruise. Two dives in the MHI were shallow (327–538 m depth) and 11 dives in the Johnston Atoll area of PRIMNM were deeper (1,495–4,239 m depth; Figure 5a). One of the shallow dives was used to recover more instruments off Oahu and the other to survey an unexplored pinnacle off Niihau at the request of the Hawaiian Islands Humpback Whale National Marine Sanctuary. Around Johnston Atoll, the dives continued the work of the earlier EX1504 Leg 1 mapping cruise that acquired high-resolution multibeam data in this monument area. One dive was conducted up the main slope of the atoll, and four others surveyed several guyots, the predominant type of seamount within this monument area. Guyots were of particular interest since this type of topography will likely be the first targeted for Mn-crust extraction by the deep-sea mining industry in the future (NOAA, 2015). Three of the guyot dives focused on small pinnacle features arising from the flat summits (Figure 5b) where it was hypothesized that accelerated current flow would promote formation of high-density coral and sponge communities. The remaining six dives were used to survey various types and depths of ridge topography. Over the course of all 13 dives, the ROV collected 15 cnidarians, eight sponges, two echinoderms, and 26 rock samples.

Summary of Biological Findings from the First Year of the CAPSTONE Project

Small, dense coral and sponge patches are common in deeper water, and were generally associated with local topography such as pinnacles, blocks, boulders, and ledges. However, extensive high-density communities (Figure 6) are much rarer because they presumably require sizable continuous topography conducive to their development. Only a few of these latter communities had been discovered prior to 2015, three of which were on ridges that provide long, narrow, mostly sediment-free substrate that intersects with and accelerates bottom currents. Determining whether extensive high-density coral and sponge communities could be consistently found on ridge topography was one of the CAPSTONE project priorities in 2015. This hypothesis is supported by ROV surveys that increased the number of known large-scale high-density coral and sponge communities on ridges from three to 11. However, not every ridge that we surveyed had such communities, nor were the densities of the animals consistent, even on the same ridge. The surveys suggested that other contributory factors determine suitability for large community development, including ridge depth (Table 1), substrate coherency, ridge orientation, and geographic location. No extensive communities were observed during ridge surveys below 2,500 m depth (Table 1), and sites where loose pebbles, cobbles, and boulders were present had much lower densities of corals and sponges compared with sites where consolidated bedrock was observed.

Ridge orientation, particularly with respect to prevailing deep bottom currents, is likely an important factor, but additional investigation is needed because flow rates and directions are very poorly understood below 100 m depth in this region. Data from the instruments recovered during Legs 3 and 4 (i.e., an acoustic Doppler current profiler and various flow meters) should help us understand the roles of flow rate and direction in the development of coral communities. Placing more of these instruments in and adjacent to known communities will provide comparative data on the importance of environmental factors that might influence the settlement and growth of coral patches.

Table 1. Summary of dive depths and observations of the density of communities.

DEPTH RANGE	# DIVES	LOW DENSITY	MEDIUM DENSITY	HIGH DENSITY
1,000–1,500 m	3	33%	33%	33%
1,500–2,000 m	14	14%	50%	36%
2,000–2,500 m	9	22%	22%	56%
2,500–3,000 m	4	100%	0%	0%
> 3,000 m	2	100%	0%	0%

Basin-scale oceanographic patterns need to be considered as well. They could explain the paucity of high-density communities observed in the Johnston Atoll monument area, known as a low-productivity region of the Pacific (NOAA, 2008). The numbers of corals observed on pinnacles arising from Johnston-area guyots was surprisingly low compared to the number seen on other pinnacles at similar depths surveyed around Hawaii (Amy Baco-Taylor, The Florida State University, *pers. comm.*, 2015). These low numbers of corals were also in stark contrast to the high-density coral and "rock pen" (see Williams and Alderslade, 2011) community observed on a shallower pinnacle off Niihau. Each pinnacle by itself represents a small-scale patch of habitat, but a loosely connected, large-scale community may exist where pinnacles are clustered in close proximity. Unfortunately, the few dives on this type of topography could not substantiate this hypothesis.

Another unknown aspect of both deep- and shallow-water coral and sponge communities is how they evolve. Do the ecological concepts of succession and climax communities apply in the deep sea? The 2,000 m long dive transect was conducted to provide additional data for a study that is trying to answer that question (Meagan Putts and Samuel Kahng, Hawaii Pacific University, unpublished data from study in progress). Lava flowing into the water off the Big Island blanketed wide swaths of seafloor and, consequently, created new substrate for coral communities at 450 m depth. The dive transect crossed both older substrate and new substrate, thereby providing information on resettlement, recovery, and early phases of deep-sea coral community development.

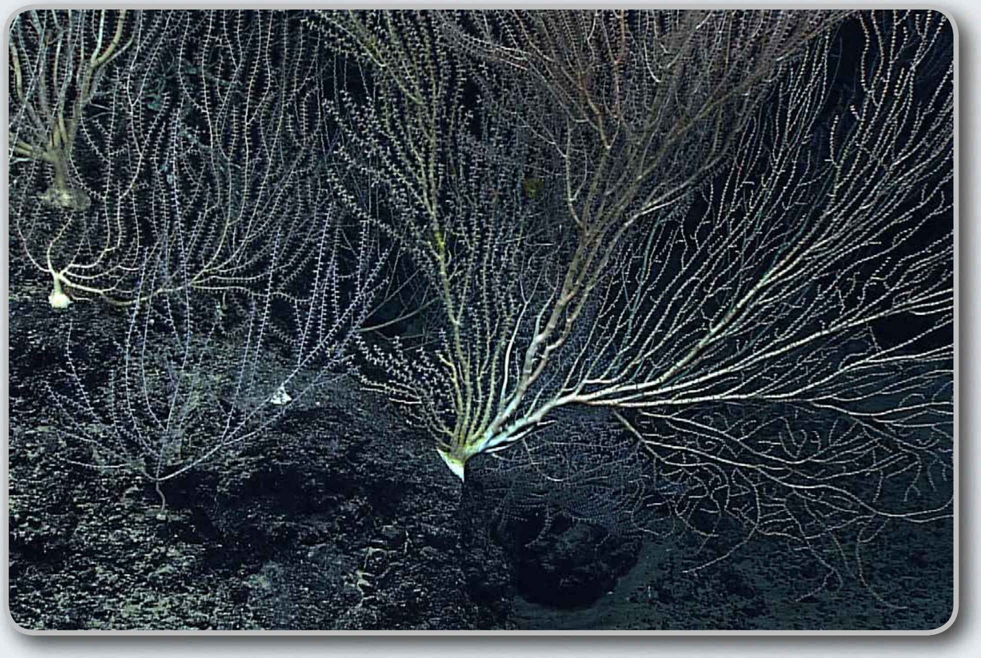


Figure 6. Example of a high-density coral community discovered on Ellis Seamount. *Credit: NOAA OER*

The concept of succession seems to apply to gold coral communities because they must grow over other existing corals to become established (Parrish, 2015). Mature gold coral communities, where many of the other species, primarily bamboo corals, have been overgrown, could be quite old (Roark et al., 2006). Overgrowth and the establishment of a long-lived but slow growing gold coral colony is a two-step process. The goal of reimaging previously marked colonies during Leg 3 was to acquire data on the first phase of gold coral growth.

As seen across each of the three ROV cruises, these deep-sea coral and sponge communities offer important habitat for associated fauna. Many of the coral and sponge colonies encountered had numerous echinoderms (ophiuroids, crinoids, and asteroids), crustaceans, mollusks, and ctenophores in their midst. Both alive and dead, the structures of the sponges and corals provide prime habitat for filter feeders, grazers, and predators. These associated fauna are important to consider for future management of the monuments.

The ROV imagery and specimens collected during the dives resulted in numerous potential new records or new species for the central Pacific. Most, if not all, of the species recorded in the Johnston area were new records for that area. Determining which animals are new records for Hawaii will require additional lab work by specialists. Below we summarize, by taxonomic group, what we believe at this stage to be potential new records or new species for the waters surrounding Hawaii and for this region as a whole (Figure 7).

- SPONGES: Twenty-two specimens were collected during the cruises, of which nine Hexactinellida and three Demospongiae are believed to be new records/species based on preliminary spicule preparations. In addition, three more Demospongiae and 15 more Hexactinellida were recorded but not collected; these have not been identified to any known central Pacific species and may therefore be new records/species.
- CNIDARIANS: A very conservative estimate that does not include the gorgonian family Isididae, which is diverse and difficult to identify from images, nor any of the midwater cnidarians, is 16 new records/species, including one anemone, one soft coral (Alcyoniidae), six antipatharians, three gorgonians, and five hydrozoans.
- ECHINODERMS: A conservative estimate is 22 new records/species that include six asteroids, six crinoids, and at least 10 holothuroids.
- ARTHROPODS: A conservative estimate is eight new records/species collected, including one lithodid crab, six squat lobsters, and one hermit crab.
- OTHER INVERTEBRATES: Potential new records/species include one mollusk (Solenogastre) and at least one polychaete worm.
- FISHES: A total of 179 fishes were observed throughout the expedition. Preliminary identifications indicate that at least 68 fish species in 42 families were recognized, several of which were large range extensions from known records. The images of three deep-sea fish families, Ophidiidae, Macrouridae, and Synaphobranchidae, are particularly noteworthy. There have been very few observations of fishes living deeper than 1,000 m in Hawaiian waters and the broader central Pacific (i.e., Chave and Mundy, 1994; Yeh and Drazen, 2009). One species of macrourid encountered on this expedition was known only from the holotype, collected in 1902 from USFC *Albatross* (Tomio Iwamoto, California Academy of Sciences, *pers. comm.*, September 21, 2015). Other noteworthy observations include a nettastomatid eel of the genus *Venefica*, seen both in PMNM and off Johnston Atoll, the ophidiid *Leucicorus lusciosus* (Figure 7d) and the ophidiid *Eretmichthys pinnatus*, which was not previously known from the central Pacific.

Summary of the Geological Observations and Rocks from the PMNM and Geologist Seamounts

The rock samples and accompanying video images collected in the monument area and the Geologist Seamounts will provide new insights into the geologic history of these areas. The focus of the dive programs in the PMNM and Geologist Seamounts on ridges allows comparison of their morphological features with those on MHI ridges. The most striking observation for both dive areas was the preservation of primary pillow lava morphology, with only minor mass wasting, despite the old ages of rocks (10 to 28 million years old in the PMNM, according to Garcia et al., 2015; 83–85 million years old, according to Sager and Pringle, 1987). In contrast, the main Hawaiian Islands have undergone dramatic mass wasting along many ridges (e.g., southwest rift zone of Mauna Loa; Moore et al., 1994). The development of Mn crusts on PMNM rocks is extensive (>1 cm in some cases), as would be expected for older submarine rocks. Mn-crust growth rates are estimated at 2.5 mm per million years in Hawaiian waters (Moore and Clague, 2004). Lavas from the older Geologist Seamounts (McCall, Ellis, and Swordfish; Figure 3) have remarkably thin Mn crusts (typically <1 cm; many cases <0.2 cm), suggesting a younger age for the rocks. While they are assumed to have formed as near-ridge seamounts (Sager and Pringle, 1987), geochronological analyses are planned to determine their ages.

A white rock collected from Swordfish Seamount has been identified as a fragmental siliceous deposit, not unlike some erupted during the post-shield stage on MHI volcanoes (e.g., Puu Waawaa on Hualalai; Cousens et al., 2003). A 5 km wide, 500 m deep crater was surveyed and sampled on the east rift zone of the eastern side of Maro Reef. The crater is undraped by later volcanism and has well preserved crater morphology. Thus, it is assumed to be a late-stage feature, perhaps like Diamond Head crater on Oahu, although it is five times larger and its floor is 3,000 m below sea level. More work is needed to understand the origin of this enigmatic feature.

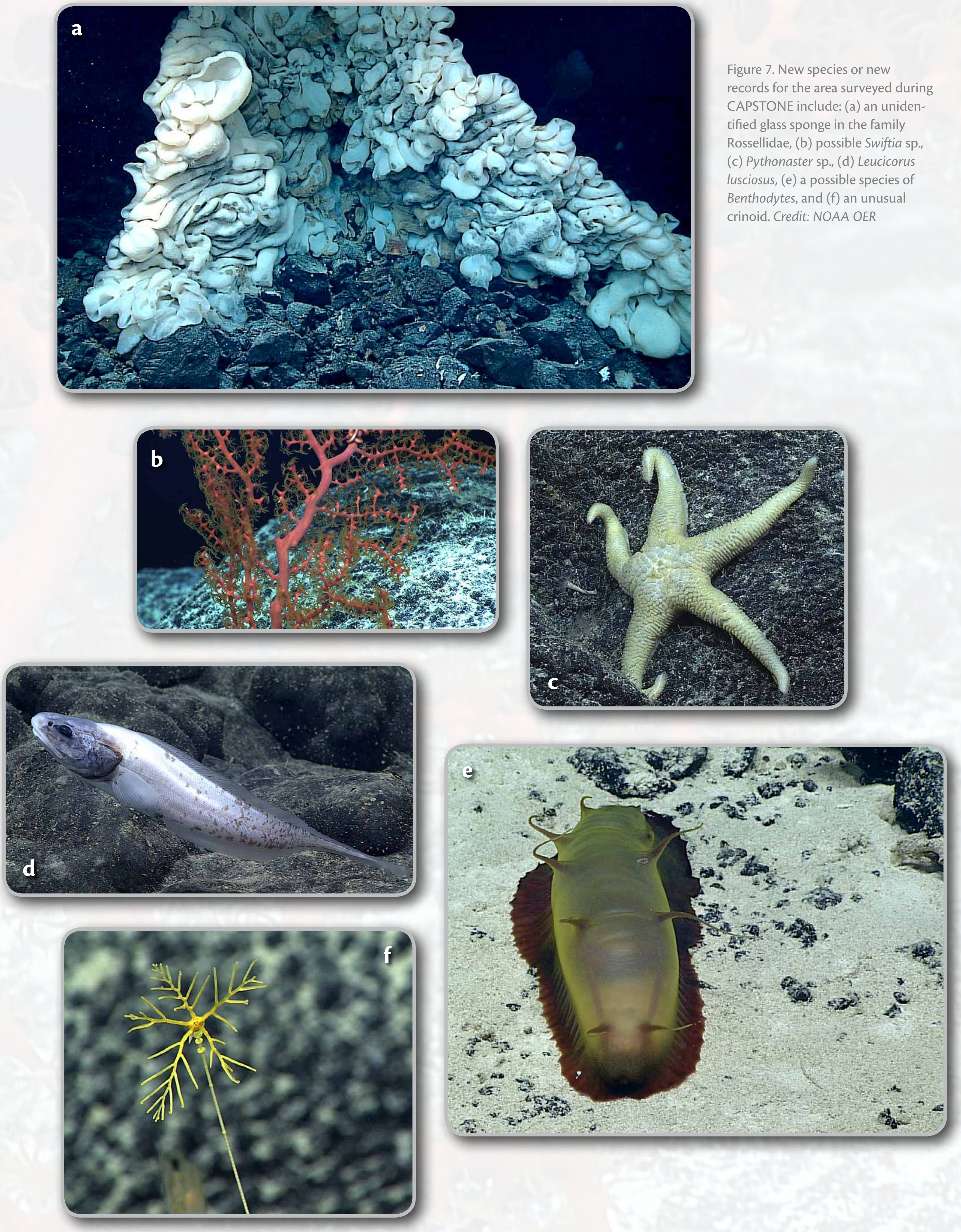


Figure 7. New species or new records for the area surveyed during CAPSTONE include: (a) an unidentified glass sponge in the family Rossellidae, (b) possible *Swiftia* sp., (c) *Pythonaster* sp., (d) *Leucicorus lusciosus*, (e) a possible species of *Benthodytes*, and (f) an unusual crinoid. *Credit: NOAA OER*

Okeanos Explorer Engages Far and Wide in 2015

By Paula Keener, Emily Crum, and Heidi Hirsh

A foundational objective of NOAA's Office of Ocean Exploration and Research (OER) is to reach out in new ways to deliver information about deep ocean exploration to the scientific community, decision makers, and the public at large. NOAA's strategic plan calls for engaging and educating members of the public to improve their ability to make scientifically informed environmental decisions.

The entry point for public engagement with NOAA Ship *Okeanos Explorer* is through the Ocean Explorer website (http://oceanexplorer.noaa.gov). It provides context for the science conducted at sea so that anyone can follow along with an expedition and understand the value of ocean exploration. The site received over 7.8 million visits in 2015—a season that included capturing over 300 images and 50 videos, writing more than 120 daily updates and logs, and delivering educational materials such as lessons and webinars.

The most popular online content associated with *Okeanos Explorer* expeditions is real-time video streamed from the remotely operated vehicle (ROV) *Deep Discoverer (D2)*, which is accessible to anyone with an Internet connection. For the first time, video streams were also delivered through YouTube, receiving over 920,000 views as virtual online explorers around the world followed discoveries and logged nearly 130,000 hours of total viewing time. OER also continued to use other social media tools. OER's Facebook account grew by nearly 200% in "Likes," surpassing 46,000, and OER's Twitter followers increased by more than 35% to over 64,000.

Figure 1. Educators learn about ocean exploration in Puerto Rico's deep ocean using the unique technological assets and capabilities of NOAA Ship *Okeanos Explorer. Credit: NOAA OER*

Also a first, OER hosted two Reddit "Ask Us Anything" sessions in 2015, where users were invited to ask questions of scientists who were on board *Okeanos Explorer* during expeditions to Puerto Rican and Hawaiian waters. Scientists and expedition coordinators answered over 100 questions, providing another opportunity for public engagement in expeditions.

OER continued to expand media interactions, reaching broader audiences. News releases alerted media to the start of expeditions, while "Exploration Alerts" emails informed over 150 media representatives, social media managers, and public affairs contacts of activities and discoveries. Local media in Puerto Rico and Hawaii toured *Okeanos Explorer* to learn about the ship's capabilities and to interview scientists.

These activities resulted in significant media coverage of *Okeanos Explorer* expeditions, with stories generated from numerous outlets, including CNN, NBC Nightly News, and The Weather Channel, to Grist, io9, and Gizmodo. One video from the Puerto Rico expedition produced by the online magazine *Quartz* received over 22 million views, evidence that the media played a vital role in telling the story of the value and wonder of ocean exploration.

During *Okeanos Explorer*'s transit to Puerto Rico for the Océano Profundo 2015: Exploring Puerto Rico's Seamounts, Trenches, and Troughs expedition (**see pages 64–67**), education materials were translated into Spanish in preparation for an educator professional development offering (Figure 1). These materials include the lesson *Exploring LIVE With the NOAA Ship Okeanos Explorer* and the supporting video *Why Do We Explore?* (*Explorando EN VIVO con el Barco Okeanos Explorer de NOAA* and *Porque' Exploramos?*, respectively). Planned in partnership with the Puerto Rico Sea Grant College Program and held at the Puerto Rico Tourism Company in Old San Juan, the session was designed to explain why we explore in the context of ocean and human health, climate change, and energy, and how NOAA uses science with technology aboard *Okeanos Explorer* to systematically characterize unknown ocean areas offshore of Puerto Rico.

A pre-mission webinar with science team leads Christopher Kelley and Daniel Wagner gave educators the opportunity to learn about the expedition and education materials designed to support video feeds from the ROV *D2* to classrooms throughout the world. Educators and students joined the expedition in real time via telepresence as scientists explored deep ocean areas off

Figure 2. Educators on Saipan learn about deep-sea ecosystems in the Marianas Trench Marine National Monument and why it is important to explore these little known special places in their own backyard. *Credit: Heidi Hirsh, NOAA Fisheries, Pacific Islands Regional Office*

Figure 3. Educators tour the bridge of *Okeanos Explorer* during an ocean exploration professional development session held at NOAA's Inouye Regional Center on Oahu, Hawaii. *Credit: NOAA OER*

Puerto Rico. Teresa Paulsen, a high school science teacher from Wisconsin, was on board and blogged, "My goal is to learn as much as I can on this expedition! There is no better way to motivate students to become lifelong learners and scientific thinkers than to show them how exciting real research can be."

After departing Puerto Rico, *Okeanos Explorer* headed to Hawaii for the Campaign to Address Pacific monument Science, Technology, and Ocean NEeds (CAPSTONE), a multiyear science effort focused in deep waters of the US marine protected areas in the central and western Pacific. To introduce CAPSTONE, educators from Saipan and Guam participated in a professional development offering (Figure 2) entitled, *Why Do We Explore the Marianas Trench Marine National Monument (MTMNM)?* The course was hosted by the Commonwealth of the Northern Mariana Islands Public School System and Guam Department of Education, and designed and offered by OER and NOAA's Marine National Monument Program. It introduced educators to the first expedition in the CAPSTONE series, Hohonu Moana: Exploring the Deep Waters off Hawai'i expedition (**see pages 68–73**).

Educators learned about submarine features and ecosystems within the MTMNM. Topics included climate change, ocean acidification, submarine volcanoes, and hydrothermal vents. Educators also learned how *D2* reveals discoveries in real time through telepresence. Their anticipated follow-on will reach nearly 6,800 students.

An educator professional development offering was held on Oahu in partnership with the Waikiki Aquarium and Hawai'i Institute of Marine Biology, with the expedition science team lead Christopher Kelley discussing the importance of exploration in the region. A Family Night was also held at Waikiki Aquarium, drawing nearly 300 Oahu residents who were interested in learning more about ocean exploration.

New Exploration Command Centers (ECCs) were established at the University of Hawaii at Manoa and the NOAA Inouye Regional Center to enhance participation by scientists, students, and the public ashore through telepresence (Figure 3). Students and faculty at the College of Charleston's Science Center also joined dives in a modified ECC.

The field season also provided opportunities to train the next generation of explorers. It was the first time at sea for most of the 17 graduate students and undergraduates from throughout the United States, including Puerto Rico, who participated in this program, where they learned about deepwater sonar and data acquisition during mapping expeditions. Using telepresence technology, OER also offered presentations and workshops on *Okeanos Explorer* with highlights from the field season to expand participation of groups who are underserved by and underrepresented in the ocean sciences and related careers.

Epilogue

By Robert D. Ballard and Alan P. Leonardi

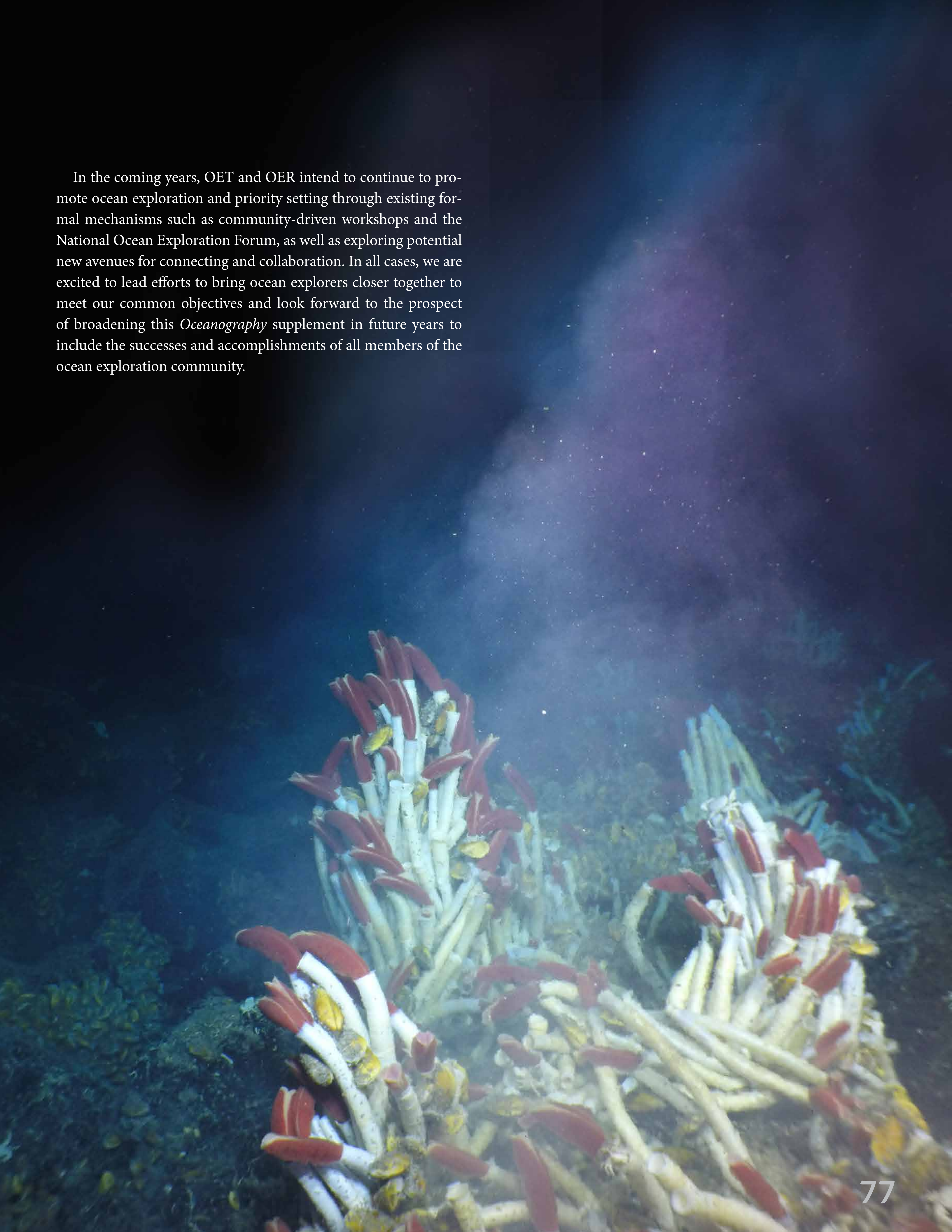
The Ocean Exploration Trust (OET) and the NOAA Office of Ocean Exploration and Research (OER) are key elements of a national ocean exploration program, providing infrastructure and support to meet the broad exploration needs of the ocean science community. As the narrative in this supplement illustrates, OET and OER together maintain and operate E/V *Nautilus* and NOAA Ship *Okeanos Explorer*—the only federally supported vessels dedicated to systematically exploring our largely unknown ocean for the purpose of discovery and the advancement of knowledge—and make them available to meet the priorities identified by the broader exploration community. OET and OER also maintain and operate "telepresence" capabilities designed to allow scientific participation from shore-based Exploration Command Centers and provide open access to the data and video streams emanating from the vessels and their remotely operated vehicles, mapping systems, and sensors.

Photo credit: NOAA OER

In 2015, both *Nautilus* and *Okeanos Explorer* began operating in the eastern and central Pacific Ocean to meet both NOAA and community-identified exploration priorities. During the 2016 and 2017 field seasons, both vessels will remain in the Pacific Ocean, with OET focusing on priorities identified in the eastern Pacific and OER focusing on central and western Pacific priorities, including exploration in marine sanctuaries, monuments, and protected areas. Beyond 2017, OET will operate *Nautilus* in the central and western Pacific Ocean while OER moves *Okeanos Explorer* back to the Atlantic Ocean to renew focus on previously identified as well as newly emerging priorities for the Gulf of Mexico, the Caribbean Sea, and the Atlantic Ocean.

Beyond our roles in maintaining and operating vessels of discovery and their associated infrastructure, OET and OER also spend considerable effort interfacing with the exploration community to further define exploration priorities, identify the technological advances needed to meet community needs, and foster collaborative relationships among the partner organizations. We are excited with the growth and evolution the exploration community has seen in the past few years and see opportunities for additional partnering with the federal, academic, private, and not-for-profit organizations that both utilize exploration data to meet their missions and also provide additional infrastructure and assets needed to meet our collective exploration goals.

In the coming years, OET and OER intend to continue to promote ocean exploration and priority setting through existing formal mechanisms such as community-driven workshops and the National Ocean Exploration Forum, as well as exploring potential new avenues for connecting and collaboration. In all cases, we are excited to lead efforts to bring ocean explorers closer together to meet our common objectives and look forward to the prospect of broadening this *Oceanography* supplement in future years to include the successes and accomplishments of all members of the ocean exploration community.



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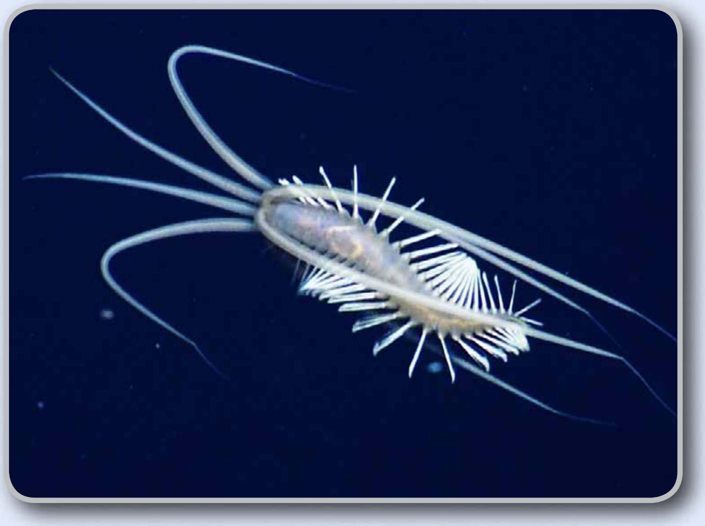

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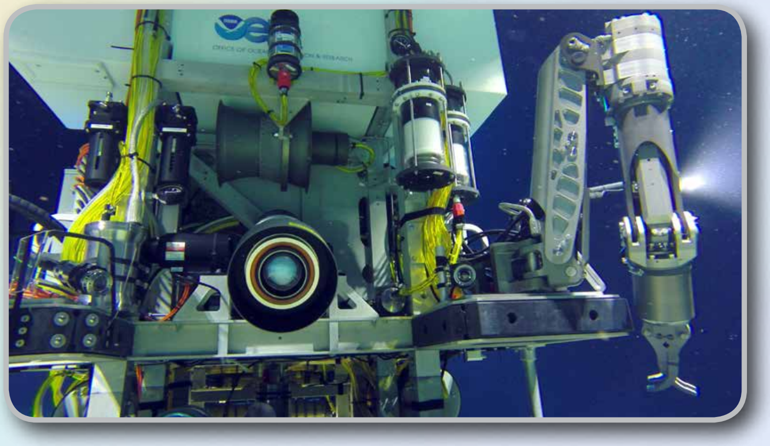

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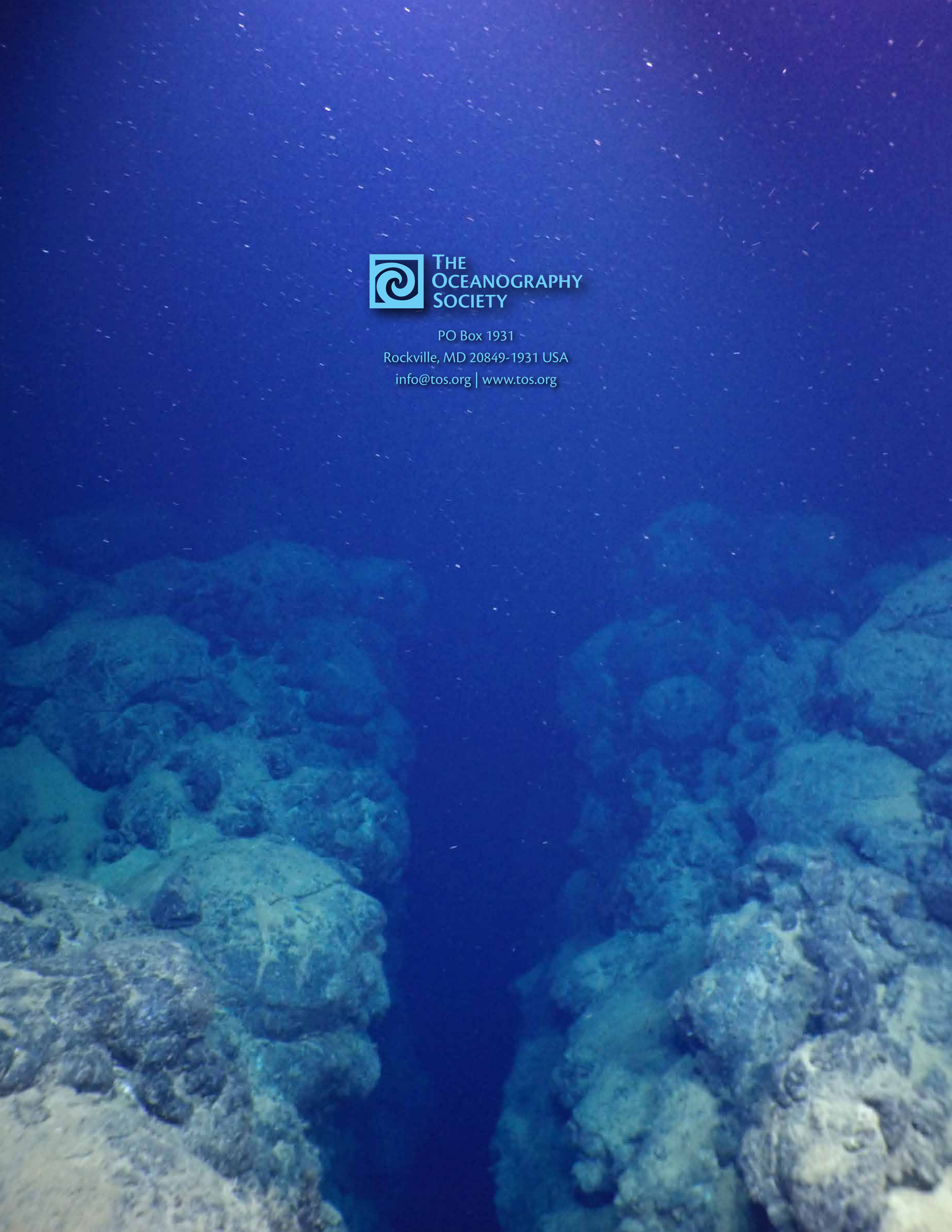

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