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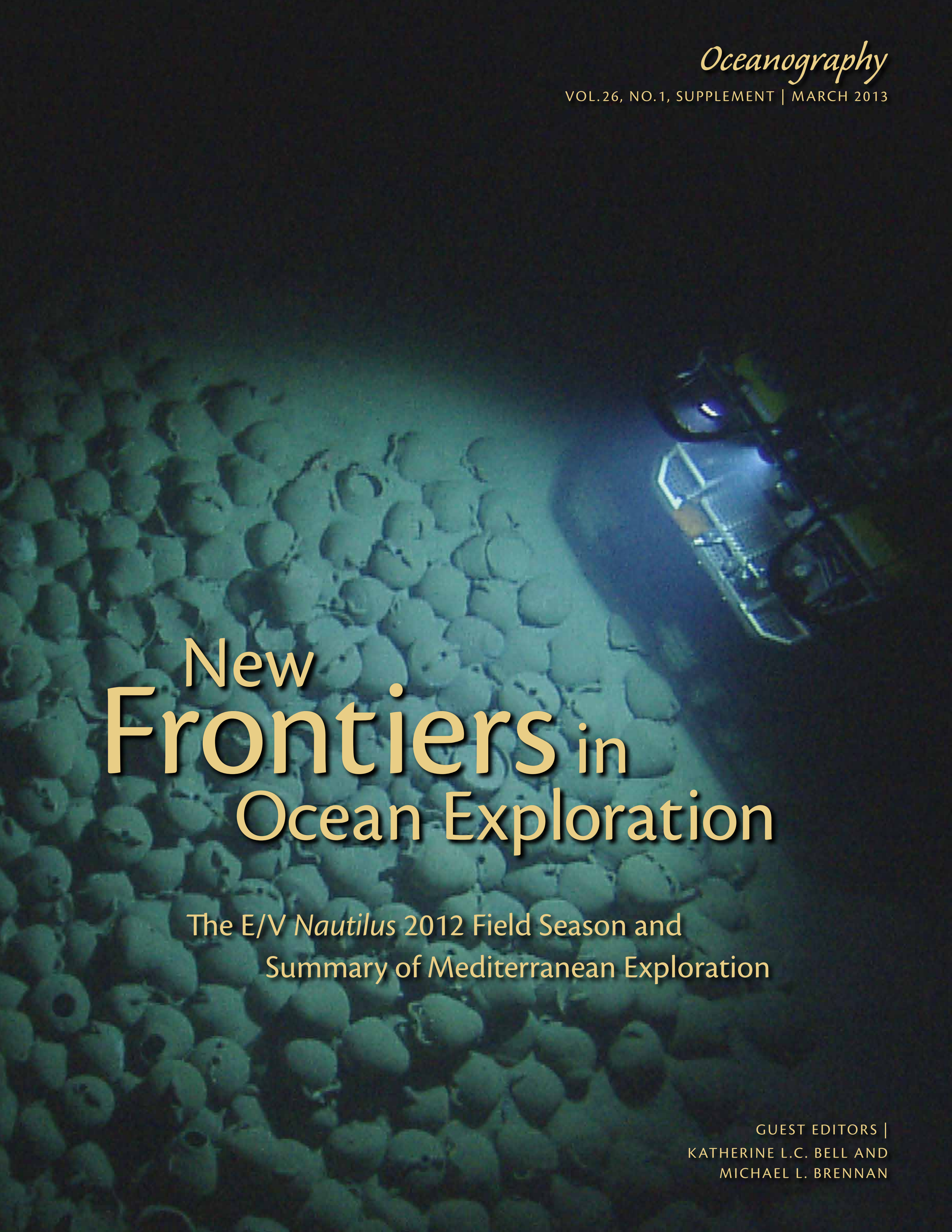

New Frontiers in Ocean Exploration

The E/V *Nautilus* 2012 Field Season and Summary of Mediterranean Exploration

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FOREWORD

By Robert D. Ballard

Exploration Vessel *Nautilus* is about to enter its fifth year of operations when it begins a multiyear program of exploration in the Gulf of Mexico and the Caribbean Sea in June 2013. During the past four years, *Nautilus* and its Corps of Exploration have focused on the Black, Aegean, and Mediterranean Seas, with a short expedition into the North Atlantic in 2011.

Three primary factors guided this operational history. When *Nautilus* arrived in the Mediterranean Sea in late 2008, it had limited capabilities for supporting remotely operated vehicles (ROVs) in deep water. Because *Nautilus* is privately owned by the Ocean Exploration Trust and does not operate under a US flag, the Trust found support from private sources to fund major improvements in the ship's infrastructure and capabilities, which became more challenging with the onset of a global recession.

During its first operating season in 2009, *Nautilus* had to anchor in relatively shallow water (100–200 m) to launch the *Hercules/Argus* vehicle system, greatly limiting its ability to explore. Prior to its second operational season in 2010, *Nautilus* underwent a major overhaul in an Istanbul dry dock that included the installation of a dynamic positioning system to make it possible to hold station. In 2011 and 2012, additional improvements were made to enhance the habitability of the ship and to replace vehicle and satellite support vans with a permanent ROV shop and hangar facilities.

Early 2013 found *Nautilus* back in an Istanbul shipyard for installation of a number of sensor systems needed to support its future exploration program, including hull mounting of a Kongsberg EM 302 multibeam sonar and a Knudsen subbottom profiler.

The second reason for basing *Nautilus* in the Mediterranean Sea in 2009 was its potential for easy access to the Indian Ocean, the most unexplored ocean basin in the world, from its base of operations in Turkey via the Suez Canal and the Red Sea. However, due to the recent rise in piracy in the Gulf of Aden and Northwest Indian Ocean, the Trust found that it was too dangerous to explore these seas.

The third reason for working in this area of the world was the Trust's desire to pioneer the emerging field of deepwater archaeology and its efforts to locate deepwater trade routes of the ancient world and highly preserved ancient shipwrecks in the depths of the Black Sea. You will learn more about this highly successful program within this issue. Although *Nautilus* is now ready to transition to work on the high seas, the Trust is beginning a new exploratory program in this region based on the discoveries its team has made over the last 25 years of work in the Mediterranean and Black Seas, and the development of new autonomous underwater vehicles (AUVs). The program in deepwater Mediterranean archaeology is now underway using AUVs supported by smaller and less expensive boats.

With the Indian Ocean and Western Pacific still inaccessible via the Suez Canal, *Nautilus* will leave the Mediterranean Sea for the Caribbean and Gulf of Mexico in late April 2013 to begin a new chapter in its efforts to explore the unknowns of the world ocean.

INTRODUCTION

By Katherine L.C. Bell

This third *Oceanography* supplement summarizes the fourth and final year of E/V *Nautilus* operations in the Mediterranean Sea. It includes articles about our research and exploration during the 2012 field season in the fields of archaeology, geology, biology, and chemistry, and describes our future plans.

The opening pages detail the technology required to conduct telepresence-enabled expeditions, including *Nautilus*, ROVs *Hercules* and *Argus*, and the shore-based Inner Space Center (ISC). We provide much more detail on the ship and vehicle systems in this issue (pages 4–9) as we broaden our user base. In 2013, major new systems that will come online include an EM302 swath multibeam mapping system and Knudsen 3.5 and 15 kHz subbottom profiler and echosounder, which will give us significantly more flexibility to explore uncharted territory. For the past several years, *Hercules* has served as a test platform for the development of precision seafloor mapping, and this season was no exception (pages 10–15). Previous systems were improved and there were new experimental additions, all of which significantly enhanced our ability to characterize an area upon discovery, whether it was a shipwreck, hydrothermal vent, or cold seep. The ISC served as the shore-based hub for both *Nautilus* and NOAA Ship *Okeanos Explorer* (pages 16–17). The ISC's support of an *Okeanos* cruise using the AUV *Sentry* was an incredible success, both scientifically and educationally, as a team of scientists, engineers, and students worked with the shipboard team to conduct complex AUV operations at sea. Work that the ISC has been doing to support *Nautilus* and *Okeanos Explorer* will prove invaluable as US research vessels with telepresence capability come online in the summer of 2013.

The second section describes education and outreach programs related to *Nautilus* (pages 18–21). Strategic partnerships with a number of organizations, including the Sea Research Foundation, JASON Learning, and National Geographic Society enable us to offer a broad range of educational opportunities to learners of all ages and levels. From live exploration on our website, *Nautilus* Live, to Educators at Sea, to high school Argonauts and Honors Research students, to undergraduate and graduate science and engineering interns, we are very excited to inspire, engage, and educate a global audience with a wide range of interests, backgrounds, and education levels.

The core of this supplement chronicles the 2012 *Nautilus* field season. Because it is *Nautilus'* final year in the Mediterranean region, we include longer pieces on previous and ongoing research in this area. Brennan and Ballard (pages 24–27) describe advances in deepwater archaeology over the past 25 years, as well as the potential for elucidating trade patterns from the discovery of large numbers of shipwrecks. As was proven in 2000, the Black Sea holds a wealth of well-preserved archaeological sites due to its deep anoxic waters, and ongoing research on the chemistry of the oxic, suboxic, and anoxic sediment and waters of the Black Sea is beginning to show how the physical and chemical environments relate to the preservation of cultural materials (pages 28–29).

Nautilus first visited the Anaximander Mountains (pages 30–35) and Eratosthenes Seamount in 2010 (pages 36–41), and returned again in 2012, following up on geological and biological discoveries made in these tectonically complex regions. We also observed hundreds of amphorae (ceramic vessels used to transport goods during ancient times) and discovered a shipwreck dating to the 4th to 5th century BCE, proving that ancient mariners braved open waters as they navigated the Eastern Mediterranean Sea (pages 42–43). Although we did not return to Santorini in 2012, much work has been done since the initial discovery of hydrothermal vents

in both the Santorini and Kolumbo calderas in 2006, which has led to a deeper understanding of this volcanic system (pages 44–49).

The final section of the supplement looks to the future. In November 2012, the *Nautilus* team worked with the NOAA Office of Ocean Exploration and Research to host a workshop on Telepresence-Enabled Exploration of the Caribbean Region (pages 50–55). This workshop was the latest in a series to engage the scientific community to identify poorly understood regions that have a high probability of scientific discovery. Fifty workshop participants contributed to the final report, which will be used by the *Nautilus* and *Okeanos Explorer* programs to guide upcoming work in the Caribbean region.

The *Nautilus* team spent four successful years in the Mediterranean region, building partnerships and making new discoveries. While we are sorry to leave, we hope that the legacy of telepresence will enable us to engage our Mediterranean partners as we explore new waters, and we look forward to building new partnerships in the Caribbean Sea and Gulf of Mexico. As always, we invite you to share in the excitement of discovery through our ocean exploration programs during the 2013 field season and beyond.

TECHNOLOGY

Exploration Vessel *Nautilus*

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 4,300 meter (14,108 feet) Rochester A307573 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
- Hatlapa hydrographic winch
- Bonfiglioli knuckle-boom crane, 4.2 ton capacity, two extensions
- A-frame, 6 ton capacity

TELEPRESENCE TECHNOLOGY

VSAT | 2.4 meter tracking ELSP antenna capable 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 | One Sony BZR-800 high definition pan/tilt/zoom camera mounted in the Control Van and on the aft deck; one Marshall Electronics VS-570-HDSDI high definition camera with pan/tilt/zoom, and microphone for interaction 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

SATELLITE ROOM

AREA | 30.5 square meters (328.3 square feet)

WORKSTATIONS | Three workstations for data, video, and satellite engineers; electronics workbench

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

DATA STORAGE | 27 terabyte disk storage for nonvideo data

EMERGENCY COMMUNICATIONS | Iridium phone

DATA LAB

AREA | 36 square meters (387.5 square feet)

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

PRODUCTION STUDIO

AREA | 16.5 square meters (177.6 square feet)

VIDEO TELECONFERENCING UNIT | Cisco C90

SWITCHER | Ross CrossOver16

CONVERTER | BrightEye Mitto scan converter

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)
- ThermoSafe 560 dry ice machine (planned for 2013)

MICROSCOPE |

- Nikon SMZ800 trinocular microscope, 6.3× zoom, Vari-Mag C-mount camera adapter with additional 2.5× ocular
- Dual output cold-light source
- Nikon D300 SLR camera
- HDMI out for sharing microscope video with shore

HAZMAT |

- Fume hood/ventilation to be upgraded in 2013
- Chemical and waste storage to be upgraded in 2013
- Carry-on, carry-off chemical policy

ROV HANGAR

AREA | 24 square meters (258.3 square feet)

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

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

LIFTS | 2 × 2-ton overhead manual chainfall lifts

STORAGE | Storage for spares and other equipment

ROV WORKSHOP

AREA | 18 square meters (193.8 square feet)

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

STORAGE | Storage for spares and other equipment

Hull-Mounted Systems

KONGSBERG EM302 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°

PLANNED INSTALLATION | March 2013

KNUDSEN ECHOSOUNDER & SUBBOTTOM PROFILER

PROFILER | Knudsen 3260 Chirp Echosounder/ Subbottom profiler

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

PLANNED INSTALLATION | March 2013

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 | 1.0° (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 meter (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), 12 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 *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 TRANSIT SPEED | 1 meter/second (2 knots)

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

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

VEHICLE SENSORS & NAVIGATION

GYRO | Ixsea Octans fiber optic north-seeking

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

CTD | Sea-Bird FastCAT 49

OPTODE | Aanderaa 3830

TEMPERATURE PROBE | Woods Hole Oceanographic Institution high temperature probe (0°–500°C)

USBL NAVIGATION | TrackLink 5000MA system

DOPPLER NAVIGATION & ALTITUDE | RDI Workhorse Navigator Doppler Velocimeter, 600 kHz

FORWARD-LOOKING SONARS |

- Mesotech 1071 profiling sonar, 600 kHz
- TriTech Super SeaPrince 675 kHz

IMAGING & LIGHTING

STANDARD IMAGING SUITE |

- Insite Pacific, 6,000 msw rated, Zeus Plus with 18× zoom lens, Ikegami HDL-45A with zoom, pan, and tilt
- Insite Pacific, 6,000 msw rated, Titan Rotate-Tilt standard definition camera (bubble camera)
- Two Insite Pacific NOVA utility cameras and one Insite Pacific Aurora utility camera

LIGHTING |

- Two Deep Sea Power & Light 400 Watt HMI with dual-ballast, 12,000 lumens, forward mounted
- Two Deep Sea Power & Light Matrix-3 LED lamps, 20,000 lumens, forward mounted
- Two Deep Sea Power & Light Multi-Sealite, incandescent. One aft on sample box.

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

HIGH-RESOLUTION MAPPING SUITE |

- Nonstandard mapping sensors
- 1375 kHz BlueView multibeam, 90° total swath
- Two stereo Prosilica still cameras, one b&w, one color; 1,024 × 1,360 pixels; 29° × 39° field of view
- Green laser sheet with dedicated camera; 532 nm; 100 mW; 45° line generating head; inclined plane
- Raytrix R5 light field camera

MANIPULATORS AND SAMPLING

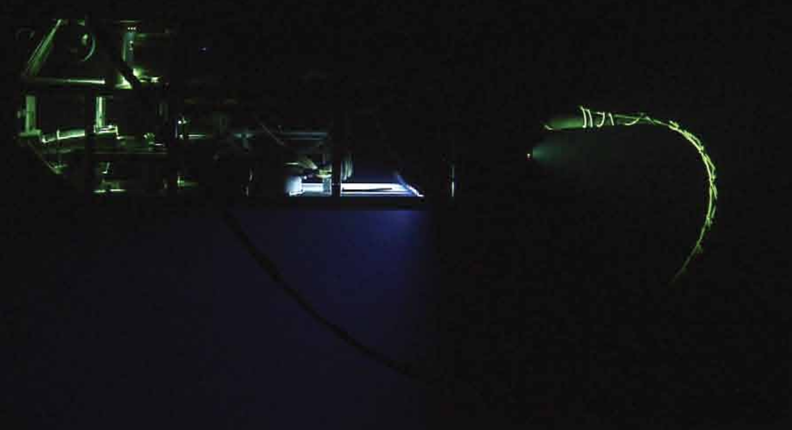
MANIPULATORS |

- Kraft Predator: Hydraulic, seven function, six degrees of freedom, force feedback
- ISE Magnum: Hydraulic, seven function

SAMPLING TOOLS |

- Mission configurable
- Up to eight 6.35 centimeter (2.5 inch) inner diameter, 28 centimeter (11 inch) long push cores
- Up to three 5 liter Niskin bottles
- Custom sampling tools can be integrated

ELEVATORS | Mission configurable; free ascent; maximum standard payload 70 kilograms (150 pounds)



Remotely Operated Vehicle *Argus*

GENERAL

DEPTH CAPABILITY | 6,000 meters (19,685 feet), currently limited by cable length

CABLE | 4,000 meters, 0.68” steel cable

SIZE | 3.8 m long × 1.2 m wide × 1.3 m 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

VEHICLE SENSORS & NAVIGATION

USBL NAVIGATION | TrackLink 5000MA system

HEADING | TCM2 magnetic compass, Crossbow magnetic compass

PRESSURE SENSOR | Paroscientific Digiquartz 8CB series

ALTIMETER | Benthos PSA-916

FORWARD-LOOKING SONAR | Mesotech 1071, 325 kHz

SIDE-SCAN SONAR | EdgeTech 4200 MP transducers from *Diana* can be installed by request

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

IMAGING & LIGHTING

CAMERAS |
- One Insite Pacific Zeus Plus high definition camera with Ikegami HDL-45A tilt head and Fujinon HA 10 × 5.2 lens
- Three Insite Pacific standard definition mini utility cameras
- One Insite Pacific low-light ‘fish-eye’, downward looking standard definition camera

LIGHTING |
- Two Deep Sea Power & Light 1,000 Watt HMI, approximately 100,000 lumens each
- Two Deep Sea Power & Light 400 Watt HMI

SCIENTIFIC INSTRUMENT SUPPORT

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

TELEMETRY | Three single mode fiber optic
- Fiber 1 (*Hercules*) eight-channel 1,470–1,590 nm
- Fiber 2 (*Argus*) four-channel 1,510–1,570 nm
- Fiber 3: Spare

DIGITAL DATA CHANNELS |
- *Hercules*: One RS-232, one RS-485, one gigabyte Ethernet (GigE)
- *Argus*: One RS-232, one RS-485, one GigE

NEW TOOLS AND METHODS FOR PRECISION SEAFLOOR MAPPING

By Chris Roman, Gabrielle Inglis, Ian Vaughn, Clara Smart, Donald Dansereau, Daniel Bongiorno, Matthew Johnson-Roberson, and Mitch Bryson

The imaging and mapping capabilities of the ROV *Hercules* have been developed over the past several years to offer multisensor data products with centimeter-scale resolution. The standard suite of mapping sensors now includes 1,375 kHz BlueView Technologies multibeam, color and black-and-white 12-bit 1,360 × 1,024 Prosilica stereo cameras, along with a 100 mW 532 nm green laser sheet and dedicated black and white camera, all of which can be run simultaneously (Figure 1). During the 2012 field season, a Raytrix R5 light field camera and an Ocean Optics STS Microspectrometer were also tested. Mapping data products were created on each cruise of the 2012 season at sites ranging from ancient shipwrecks to a vertical escarpment at Eratosthenes Seamount.

A significant result of *Nautilus* work in the Mediterranean is an array of images and maps of ancient shipwreck sites found during expeditions. Such sites have proven to be excellent test cases for the development of our mapping system. The complexity of the sites, which typically contain objects of relatively common man-made geometries, is ideal for evaluating the data collection and algorithm development. At the end of the 2012 season, we revisited many of the wreck sites previously found around the Bodrum and Datça Peninsulas in southwestern Turkey (Brennan et al., 2012). Between 2009 and 2012, many of the wrecks in this area were mapped as our surveying capabilities were being developed. The 2012 season provided an opportunity to image nearly all of the sites again with our current tools. During three days of operations, we were able to map 22 sites with some combination of stereo imaging, multibeam acoustics, and structured light

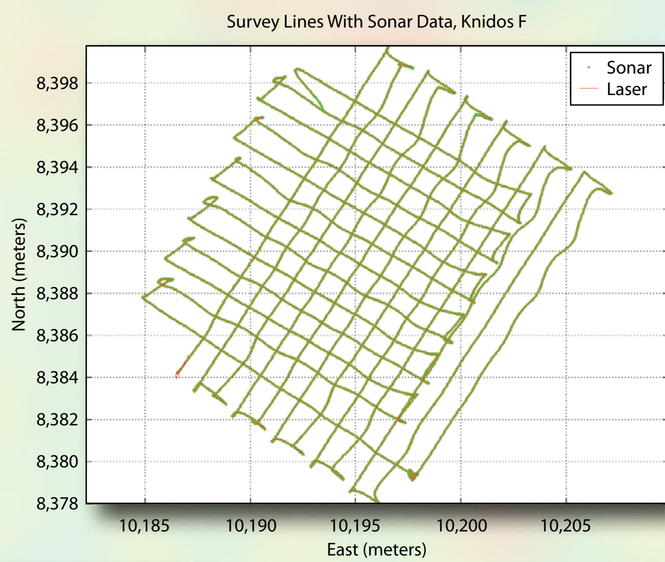
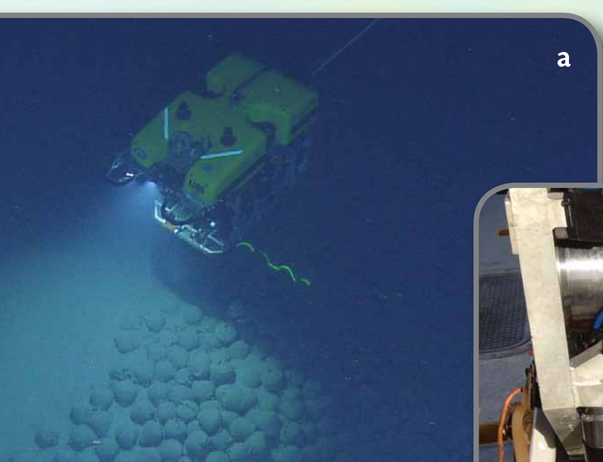


Figure 2. Vehicle trajectory for the Knidos F survey.



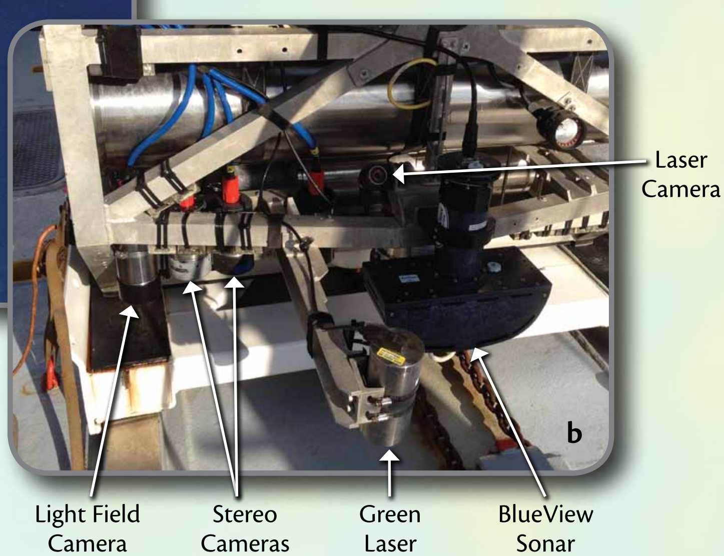


Figure 1. (a) A *Hercules* laser survey. (b) The arrangement of mapping sensors on the *Hercules* remotely operated vehicle.

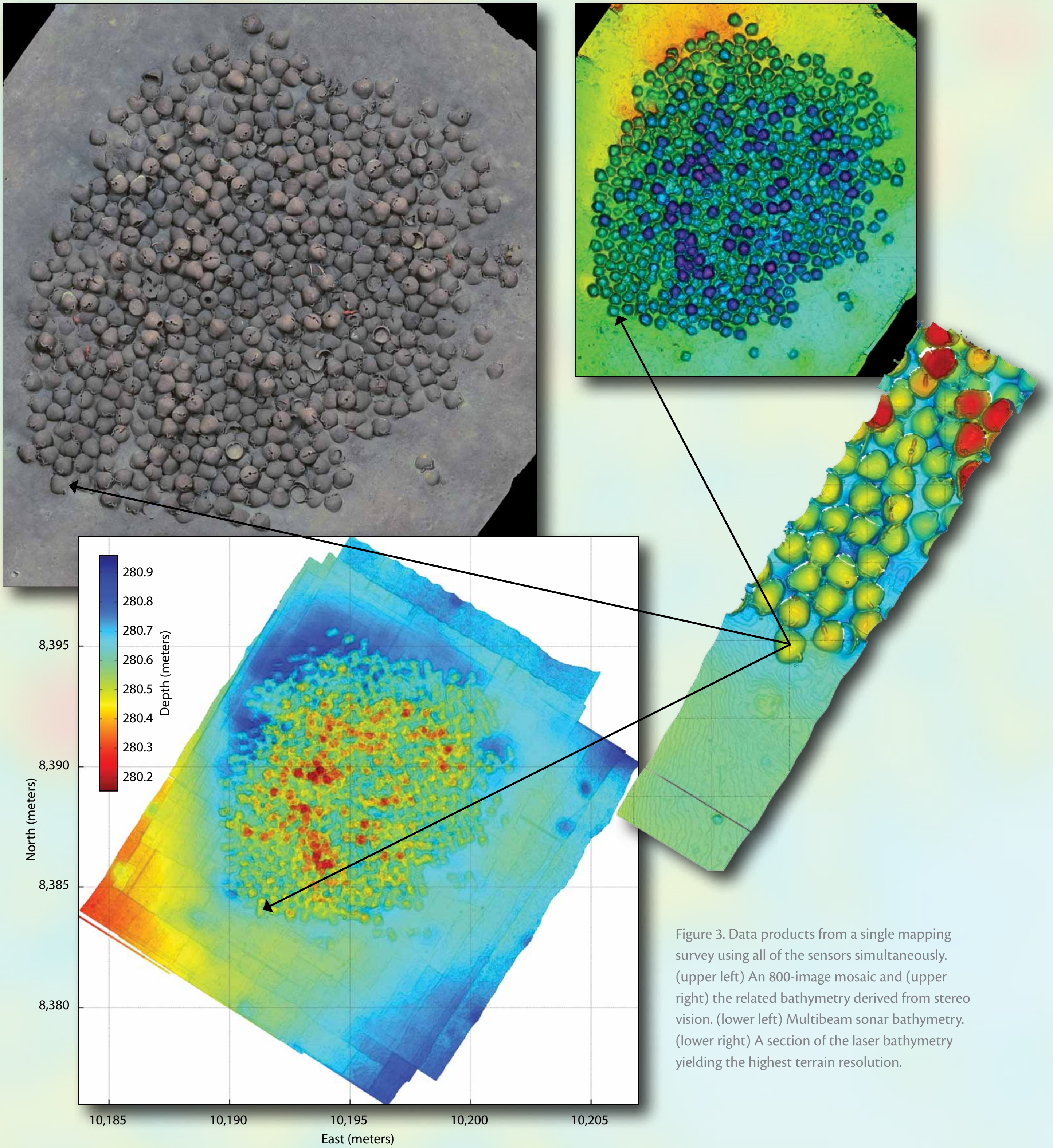


Figure 3. Data products from a single mapping survey using all of the sensors simultaneously. (upper left) An 800-image mosaic and (upper right) the related bathymetry derived from stereo vision. (lower left) Multibeam sonar bathymetry. (lower right) A section of the laser bathymetry yielding the highest terrain resolution.

laser imaging. Our current system, which can run all three technologies at once, provided a significant gain in efficiency over previous years. We mapped almost all of the sites, generally ~10 × 30 m in area, in under an hour each. The surveys were typically designed to achieve more than 200% overlapping coverage with the cameras and swath multibeam. Several sites were surveyed in a "checkerboard" pattern of overlapping and orthogonal track lines to provide multiple vantage points and reduce occlusions in the complex scenes (Figure 2). Available data products include stereo photomosaics, stereo-derived bathymetry, multibeam sonar bathymetry, and laser bathymetry (Figure 3). Navigation processing for photomosaics and bathymetric maps relies on recently developed Simultaneous

Localization And Mapping (SLAM) algorithms. These approaches filter vehicle navigation measurements from the RDI Doppler velocity log (DVL), Paroscientific depth sensor, and IXSEA Octans fiber-optic gyroscope using constraints derived from the camera images, multibeam sonar, or laser data. The result is a better-constrained navigation solution. For the stereo-vision products, we used a SLAM algorithm (Mahon et al., 2008) to estimate the position of the camera rig for each pair of stereo images. Once this action is completed, a second refinement step optimizes the positions to further reduce errors associated with reprojecting scene points visible from multiple camera locations back into their original images using a stereo bundle adjustment algorithm. This step results in a globally optimized set of camera positions, given the visual features, and reduces the negative effects of linearization in the SLAM filter. This step also refines the lens distortion calibration parameters that are applied to each image during point projections. The improvement in point consistency suggests the method is compensating for small parameter changes that occur due to the pressure forces on the camera housing while operating in deep water.

This final result is used to generate the full-vision-based structural model used for reconstruction. We employ a previously developed scene reconstruction technique (Johnson-Roberson et al., 2010) with a modification to operate in full three dimensions. This step is needed to preserve the visual quality of the model in the highly structured wreck scenes. Through the use of state-of-the-art model parameterization and texture antialiasing, distortions in the final result can be minimized while maintaining the resolution of the original source imagery in the complete mosaic (Lévy et al., 2002; Sheffer et al., 2005). The mosaic can be displayed as a downward projection, or draped on the scene structure as a textured three-dimensional model.

For the bathymetry maps, we continue to use a SLAM algorithm that creates short sequences of multibeam pings or laser line profiles to match the terrain and refine the navigation estimates (Inglis et al., 2012). The same concept applies for both multibeam bathymetry, which provides the most sensor coverage, and structured light laser data, which provide the highest resolution. The ability to collect mapping data simultaneously from several sensors supplies a direct way to compare results and makes the fusion of visual and acoustic data possible.

We completed surveys similar to those conducted on shipwreck sites (Figure 3) at many other complex sites in 2012 (e.g., see discussion of the seamounts of the Anaximander Mountains on page 30 and Eratosthenes Seamount on page 36). While working at Eratosthenes Seamount, we again found a significant number of gouges on the flat and mostly featureless seafloor. They are thought to be caused by foraging of Cuvier's beaked whales. The markings were present along several of the visual transects and also observed in the side-scan sonar. The side-scan data are currently being reviewed to estimate the spatial density of the marks. To better characterize the patterning of the marks, we compiled three separate high-resolution photomosaics in areas with both fresh and aged marks. The mosaics indicate a consistent pattern for gouges of similar apparent age. Several sequences of at least three to six marks have been observed, all with the same approximate spacing (Figure 4). This pattern seems to indicate a single animal making repeat gouges in the seafloor on a single dive. Across all three sites, the spacing and curvilinear arrangement were observed, and the mosaics provided a new look at these features. We took several push cores in these survey areas to evaluate the sediment content. We are looking at the cores, side-scan data, and this new observation of the patterning to evaluate whether the gouges are in fact related to a feeding behavior.

In an effort to investigate new imaging technologies, we packaged a light field camera and used it to collect evaluation images. Also known as plenoptic cameras, light field cameras offer a range of impressive post-capture capabilities, including depth estimation and filtering (Dansereau and Bruton, 2004), noise reduction (Dansereau et al., 2013), video stabilization (Smith et al., 2010), and isolation of distractors (such as fish, drifting organisms, swaying vegetation, and dynamic lighting; Dansereau and Williams, 2011). The cameras' optics also simultaneously offer wide aperture and wide depth of field imaging compared with conventional cameras (Ng et al., 2005; Bishop and Favaro, 2012). The goals of these first field trials were to establish the viability of using light field cameras in underwater applications and to confirm some of the theoretical advantages they present. The camera we employed was a commercially available Raytrix f/2.4 4-megapixel monochrome light field camera. We tested it at the shipwreck sites in the Bodrum area and compared the photos directly with those taken using conventional cameras.

Conditions were generally favorable for imaging, with mostly clear water and the occasional appearance of stirred up sediment that reduces the image quality due to backscatter in proportion to light intensity. For this reason, we were particularly interested in the light field camera's improved light gathering ability. To test the camera, we mounted it alongside the conventional cameras, but operated it with less than half (roughly 0.4 times) the illumination. The light field camera performs well despite the significant reduction in illumination power (Figure 5). The camera's achievable depth of field was also confirmed by imaging over a range of altitudes. One capture provides the ability to computationally manipulate the image focal depth during post processing and to direct attention to any distance between the camera and the seafloor (Figure 6). These initial deployments yielded experimental support for the enhanced light gathering and depth filtering capabilities of light field cameras. Looking ahead, we expect these attributes to present a significant advantage in reducing illumination power budgets, increasing imaging ranges, or allowing better images in turbid conditions with water column distractors. During the off season, additional experiments

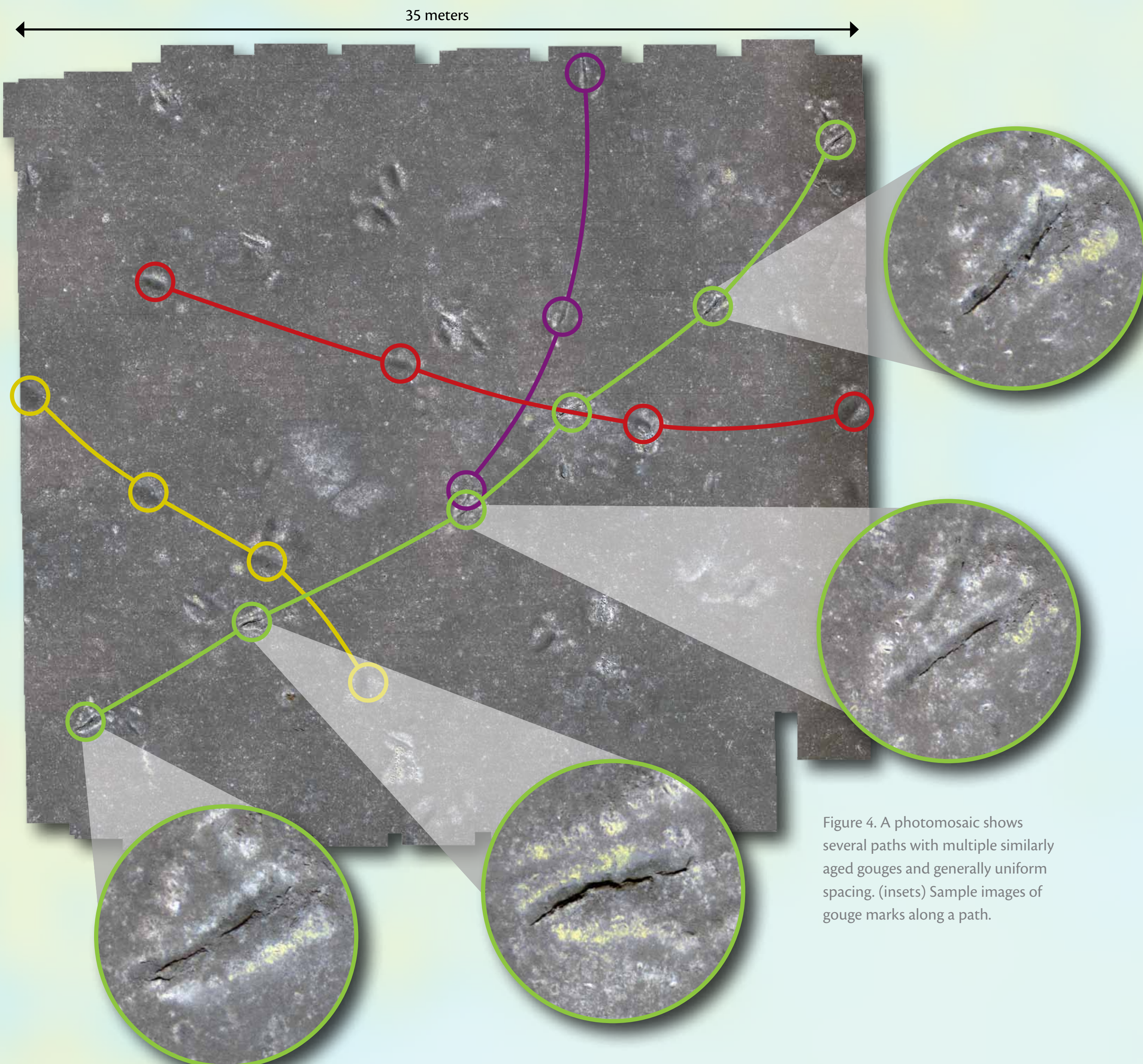


Figure 4. A photomosaic shows several paths with multiple similarly aged gouges and generally uniform spacing. (insets) Sample images of gouge marks along a path.

will be performed in a test tank to better understand the camera's in-water performance.

During the 2012 field season, we also incorporated a downward-facing spectrometer into the camera system. Spectrometers are point measuring hyperspectral optical devices. The STS Microspectrometer tested was capable of detecting 1,024 bands of light within the near ultraviolet/visible/near infrared spectrum in the range of 330–830 nm. Measurements with the spectrometer were taken simultaneously with the downward-facing stereo cameras during several surveys. We were able to collect measurements at three sites: a bacterial mat site near the Athina Mud Volcano, a Byzantine shipwreck, and the site of the gouge marks (Figure 4). The high spectral resolution available with the spectrometer allows for greater discrimination of bottom type, as different materials often exhibit subtle differences in their spectral reflectance. Because the spectrometer is only a point-measuring device, we obtain one large pixel

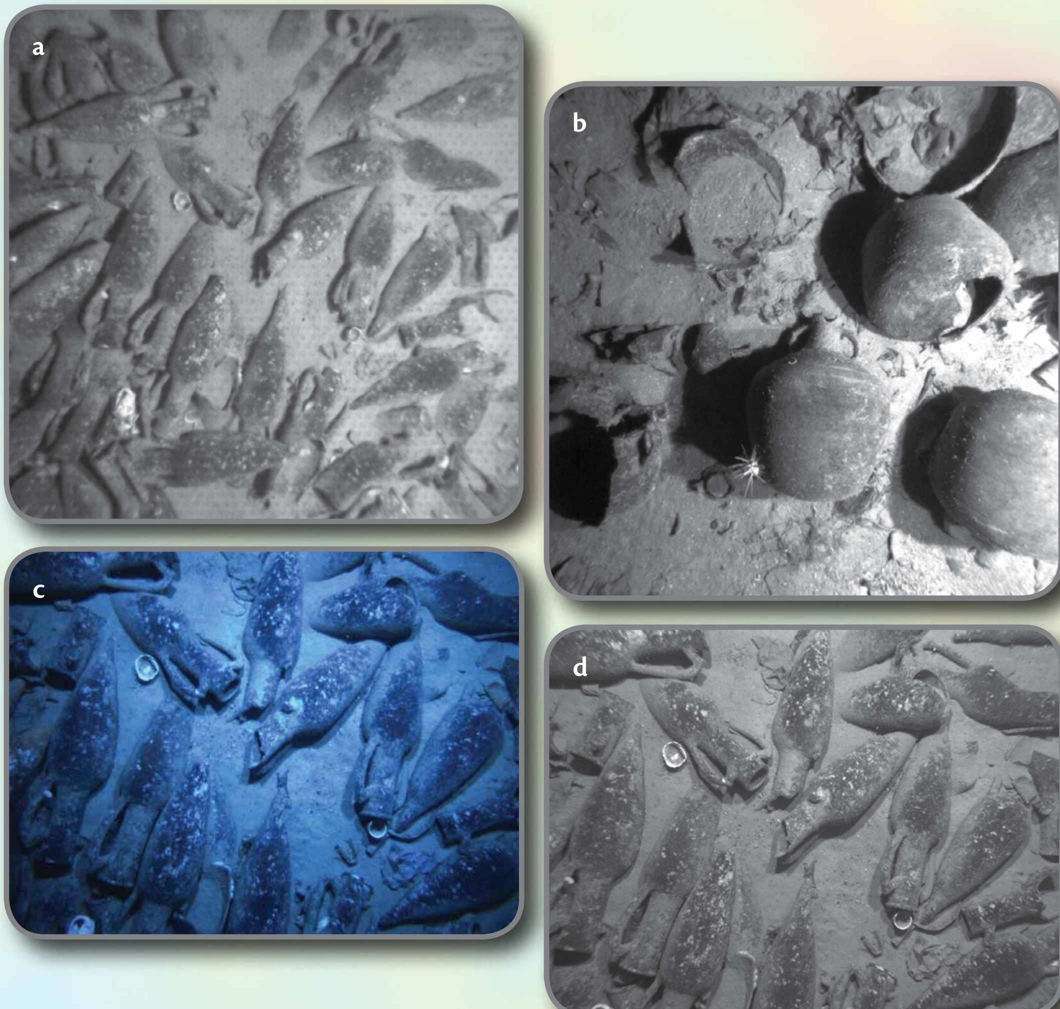


Figure 5. Test images of amphorae show the potential of light field cameras to facilitate underwater imaging. Light field imagery (a,b) required roughly 0.4 times the illumination needed for the conventional color (c) and monochrome (d) imagery.

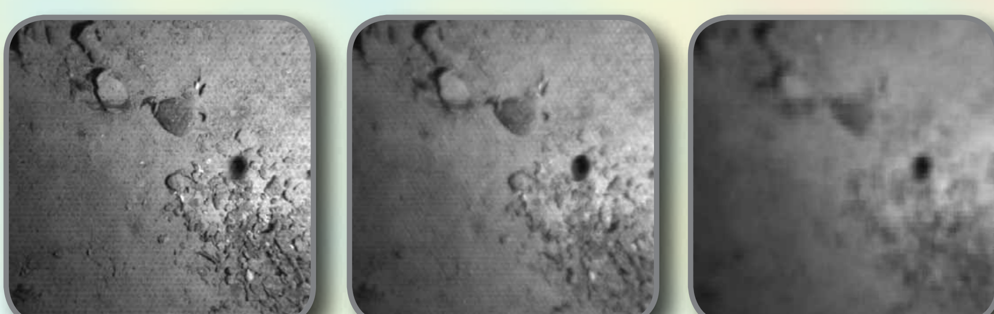


Figure 6. Images created from a single light field capture. (left) Image created at the calibrated focal depth with the seafloor in focus. (middle) Image focused at the black particle in the mid water. Note the seafloor is out of focus. (right) Image focused in the very near field, leaving the bottom and particle out of focus.

for each image location such that multiple materials can be "mixed" within the one pixel footprint. In the remote-sensing realm, there are techniques to spectrally unmix the material constituents of that pixel. Using this information, we are able to determine the fractional abundances of each material/end member within the pixel. Our initial results from the Athina bacterial mat data set show we are able to unmix the spectral data to resolve the abundance of the materials within the scene. We used the N-FINDR algorithm (Winter, 1999) to resolve the most pure end members in the data set. The extracted end members are not necessarily pure in their material makeup but rather the most spectrally distinctive from the other measured spectra. The spectra of the end members were found, along with the corresponding RGB imagery (Figure 7). We are further processing these data sets, including using the stereo RGB image data to assist in the spectral unmixing. These initial results show we can gather high spectral measurements alongside the high spatial resolution imagery from the RGB cameras.

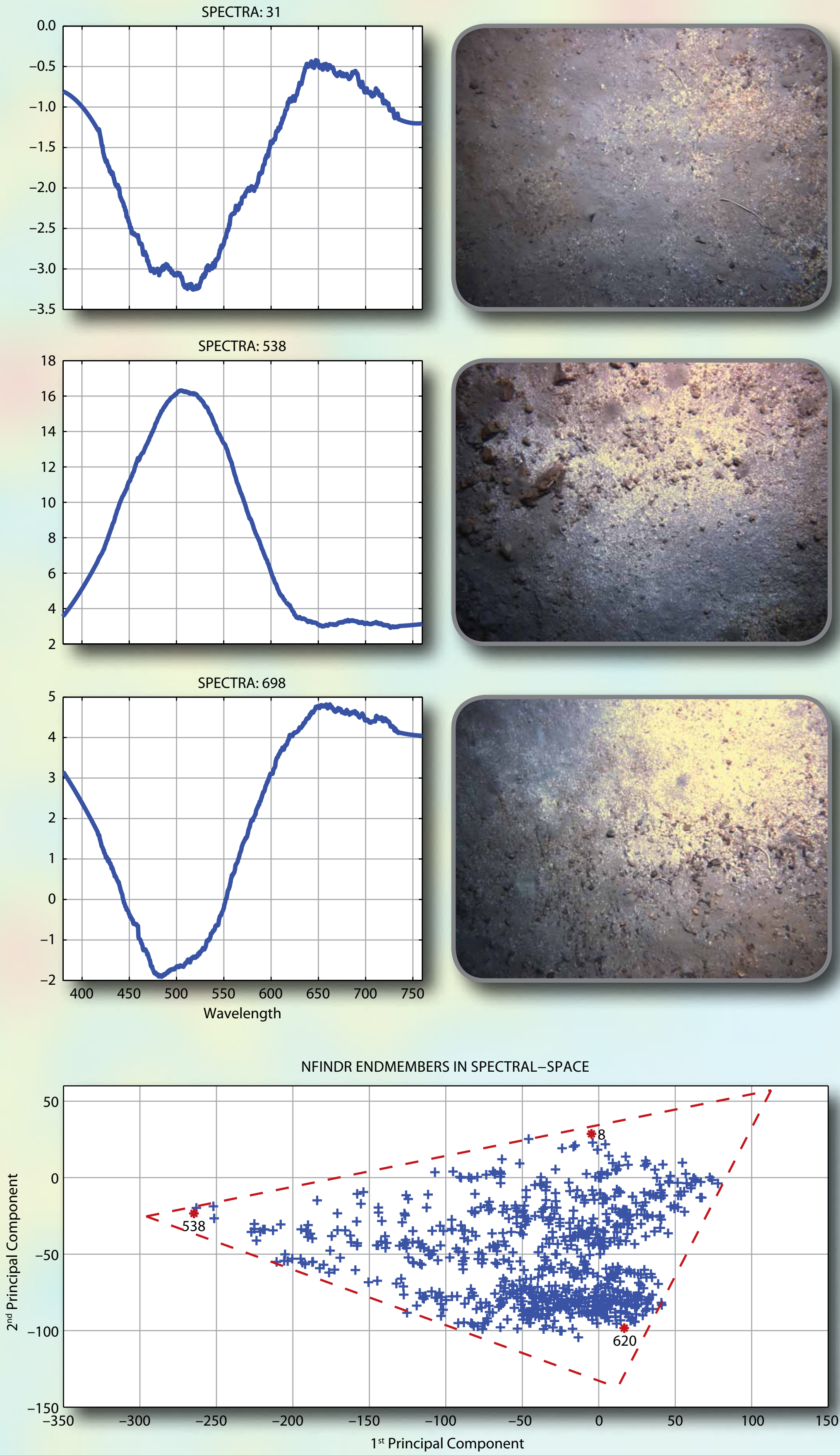


Figure 7. Example images and the accompanying spectra that are end members of the set of collected images within a survey.

THE UNIVERSITY OF RHODE ISLAND

INNER SPACE CENTER

Supporting Telepresence Operations in 2012

By Dwight F. Coleman, Bob Knott, Derek Sutcliffe, and Alex DeCiccio

The University of Rhode Island Inner Space Center serves as the hub for live ship-to-shore telepresence operations for E/V *Nautilus* and NOAA Ship *Okeanos Explorer*. The primary scope of 2012 operations was to provide technical, scientific, and engineering support for (1) the live exploration missions conducted on board the *Okeanos Explorer* and at the ISC and (2) video production and delivery of live and recorded educational outreach programming in collaboration with educators onboard *Nautilus* through the *Nautilus* Live portal. ISC staff trained and helped coordinate teams of onshore researchers and production specialists engaged in the exploration programs.

NOAA's Office of Ocean Exploration and Research required ISC support in July 2012 during an expedition that explored portions of the Blake Plateau off the southeastern United States using the AUV *Sentry*, operated by the Woods Hole Oceanographic Institution. A large team of scientists and students were at the ISC for the duration of the cruise, analyzing the latest data sets and providing direction from shore. In addition, the ISC served as the hub for the *Nautilus* Live program where, in collaboration with Sea Research Foundation's JASON Learning, live education productions were developed and distributed through Internet webcasts at www.nautiluslive.org, as well as through streaming broadcasts to a variety of venues, including Mystic Aquarium and a number of distributed partner sites through a network of Exploration Centers.

The ISC facility can be custom configured to meet user needs for every project, including accommodation of a large group of researchers dedicated to a specific mission. One illustrative example of several teams of people working together in a busy environment to accomplish multiple goals was the summer 2012 period when both

Okeanos Explorer and *Nautilus* were operating at the same time. The ISC Mission Control facility was bustling with scientists and students actively participating in the Blake Plateau *Sentry* exploration project. Several student watchstanders provided technical support to both *Okeanos Explorer* and *Nautilus* from within Mission Control. During this time, the video production team for *Nautilus* Live was operating in the ISC production control facility and studio to develop educational content and deliver educational programming to the Internet and partner sites.

The ISC was also used for specialized training and to introduce participants in the Ocean Exploration Trust Educator at Sea program to the facility's technical capabilities. Because the ISC and *Nautilus* technical spaces use similar technologies, this training prepared the educators for onboard participation in ROV operations and for delivering *Nautilus* Live programming. Dozens of educators were introduced to the functionality of the technical systems, including the voice intercom, video switching and routing, computer and data control, and software, and to on-camera techniques for communicating about expedition scientific and technical operations.

All ISC-supported shipboard missions in 2012 emphasized developing and improving telecommunication and data processing protocols, data management and video archiving workflows, and video highlights. Prototype systems and workflows for data management and archiving were improved, including implementation of new storage area network servers and storage devices, tape archives, and Web-based tools for data access and video and photo galleries. Undergraduates from different departments at the University of Rhode Island (particularly Ocean Engineering and Marine Biology) were employed to test the new systems and workflows while they were on watch supporting the various missions. This active participation provided valuable hands-on technical and operational experience for the students within a team-based organizational structure. This educational program continues throughout the year at the ISC whether the ships are active or not, and it has been expanded to include University of Rhode Island Harrington School of Communications students who are studying film media, video production, journalism, and communication.

NAUTILUS EDUCATION AND OUTREACH

By Alexandra Bell Witten, Katherine L.C. Bell, Amy O'Neal, and Katrina Cubina

In 2012, the *Nautilus* Exploration Program continued its broad-scale outreach as well as K–12 science, technology, engineering, and mathematics (STEM) education efforts, undergraduate and graduate internships, and on-the-job training. Several organizational partners, which included the National Geographic Society, Sea Research Foundation, and JASON Learning, presented our work to the public using numerous types of media, such as the Internet, film, television, magazines, and books, as well as live theater shows at aquariums and museums, to reach the broadest audience possible. These media allow us to inspire millions of people with moments of discovery, capture their imaginations, and hopefully to lead them further down the path toward higher education as well as environmental and STEM literacy. As a result of these combined efforts, the *Nautilus* Exploration Program reached over two million people in 2012.

The most direct connection was made via the *Nautilus* Exploration Program's website, www.Nautiluslive.org. During the expedition, we broadcast 24-hour coverage of *Nautilus* from July 9 to September 4 for a total of 58 days (1,400 hours) of live exploration—4,200 hours of live video streaming from three separate feeds on the ship. The website hosted 110,735 visitors, including 45,000 unique site viewers and a total of 470,745 page views. The expedition team fielded 11,100 questions submitted through the interactive "Participate" option on the website.

Educators at Sea

The mission of the Ocean Exploration Trust (OET) Educator at Sea program is to capture the excitement of ocean exploration for audiences of all ages and to inspire and motivate the next generation of explorers in an effort to address the shortage of students entering STEM fields. During the 2012 field season, 12 Educators at Sea joined the expedition team. They came from across the United States, from museums and aquariums in Virginia, and from public and private schools in California, Connecticut, Illinois, Tennessee, Texas, Virginia, and Washington. On most legs, three Educators at Sea were embedded with the expedition team, one of them a veteran from the previous year who served as trainer and mentor for the new Educators.

Educators at Sea supported all of our educational outreach activities and provided professional development to schools, after-school programs, and informal sites across the country and internationally. Their role was to translate the science and exploration happening on board in an engaging way that would connect *Nautilus* Live website visitors to the ship.

Prior to going to sea, Educators at Sea participated in a four-day workshop at the University of Rhode Island Graduate School of Oceanography that was designed to inform and empower them to be effective communicators while on the ship and to give them the necessary tools to translate their experiences back to the classroom. There were three major components to the professional development the educators received: (1) expedition science and career awareness, including mini lectures by expedition scientists and engineers about their fields of study, their career pathways, and their science goals for the upcoming expedition; (2) communications and website training, including hands-on technical tutorials on how to use the *Nautilus* Live website platform, training on how to use technical systems related to their roles on board the ship, and on-camera training for interacting with live audiences ashore; and (3) training for classroom application of *Nautilus* Live content and programming, including curricular materials from JASON Learning, and for integration of varied technologies, such as smart boards, iPads, tablets, or social media, into their teaching methods.

Educators at Sea contributed to the content of the *Nautilus* Live website and interacted with shore-based groups at schools, aquariums, museums, and science

centers. They were also responsible for developing curricular materials related to *Nautilus* expeditions to use with their students and to share with each other. Educators are designing and implementing these plans throughout the 2012–2013 academic year, and submitting sample lessons to OET to be posted and shared with the Educator at Sea community.

During the 2012 field season, Educators at Sea hosted 329 *Nautilus* Live theater shows for a total audience of 13,403 people. They created 57 photo albums, uploaded 545 photographs, wrote 34 blogs, and participated in most of the 36 additional live events/interactions with schools, museums, and other venues.

In 2012, OET hired David Heil & Associates to review the Educator at Sea program and to assess the *Nautilus* Exploration Program outreach and education activities. The evaluation included assessing the Educator Workshop and interviewing every educator prior to going to sea, while at sea, and post cruise. The evaluators also conducted focus group interviews with team members on board *Nautilus* and assessed the new pre- and post-cruise student tests developed for use in Educators at Sea classrooms. They also developed and implemented an online survey available on the *Nautilus* Live website to assess the *Nautilus* Exploration Program's ability to inspire and engage students in STEM learning. The preliminary results are very encouraging and the final report will be available in June 2013.

Classroom and After-School Programs

JASON Learning and its after-school program Immersion Learning continued to be OET's primary partners for educational programming at the middle and high school levels. Their curricula cover all of the basic science, math, and engineering principles, as well as standards required of STEM education programs serving middle school grades in all 50 states.

In 2012, seven students and three educators were selected as JASON Project Argonauts from high schools, technical schools, and Boys & Girls Clubs in Virginia, Texas, Michigan, and Wisconsin, and internationally from China and Romania. One student was selected through a partnership with the Boy Scouts of America. Prior to going to sea, the students attended a camp to prepare them for participation in an oceanographic research expedition aboard *Nautilus*. The students then participated at sea in one of two groups: one group sailed off the southern coast of Turkey in July, and the second group explored the seafloor off Cyprus in August.

While on the ship, Argonauts undertook research projects and participated in live, interactive webcasts with shore-based audiences via the *Nautilus* Live website. The work of the Argonauts aboard *Nautilus* was also featured through blogs, photos, and live events at www.jason.org.

In 2012, Immersion Learning published a 99-page *Nautilus* Live activity book that includes eight activities, maps, and science content standards guides that focus on *Nautilus* ocean exploration field programs. As a companion to this resource book, Immersion Learning published *Nautilus Mania!*, designed for students and including hands-on activities and games focused around *Nautilus* expeditions.

Beginning in 2014, OET, the Sea Research Foundation, and JASON Learning will collaborate on a more integrated *Nautilus*-based program that will focus on STEM education with a goal of increasing overall scientific literacy at the community-wide level.

Winning 2012 patch design by Madeleine Gates, 13 years old, San Diego, California.

Honors Research Program

Five Honors Research Program students were selected to participate in this inaugural program in July and August 2012. Students were selected through a competitive process and came from schools in Virginia, Texas, California, and Washington. Because this program is for honors-level and high-achieving students, competitive STEM public schools received special encouragement to have their teachers, school counselors, or administrators nominate students. A sixth student was selected from Cape Henry Collegiate School in Virginia Beach to participate at sea.

The program was comprised of two components. The land-based portion was held at the University of Rhode Island's Graduate School of Oceanography where students worked with Marine Research Scientist Rob Pockalny on a data processing and visualization project. Specifically, they developed software that would plot data collected by the ROV *Hercules* in three dimensions. The second component of the program was the shipboard experience. Students spent seven to eight days at sea on *Nautilus* and split their time between assisting researchers on data watches, processing samples, and testing the data visualization program using live data. The three-dimensional maps they developed were also used on subsequent legs of the expedition.

In addition to their campus and shipboard experiences, Honors Research Program students were accompanied by chaperones for weekend field trips, including visits to Mystic Aquarium's *Nautilus* Live Theater, Brown University, and the Rhode Island School of Design.

At the end of the program, the students prepared a comprehensive report on the data project they undertook and presented their findings to school and community audiences upon their return home.

Science & Engineering Internships

OET's Science & Engineering Internship Program trains undergraduates and graduate students studying ocean science and engineering in the at-sea environment. Science interns work on board *Nautilus* with a wide array of scientists, learning how to make scientific observations and process digital data and physical samples. ROV engineering interns work with *Nautilus* engineers and learn how to maintain and operate the ROVs *Hercules* and *Argus*. The video engineering interns stand watch with the *Nautilus* video production team and learn to operate and maintain our real-time exploration video.

In 2012, a total of 22 undergraduates and graduate student interns, including two from the Marine Advanced Technology Education Center, participated in the *Nautilus* Exploration Program to be trained in oceanographic science and engineering. The interns came from the University of Rhode Island, the University of Delaware, the Massachusetts Institute of Technology–Woods Hole Oceanographic Institution Joint Program, Bates College, Luther College, Monterey Peninsula College, Long Beach City College, Middle Tennessee State University, Texas A&M University, the University of New Hampshire, the University of Puerto Rico, the University of Sydney–Australian Centre for Field Robotics, and universities in England, Turkey, and Cyprus.

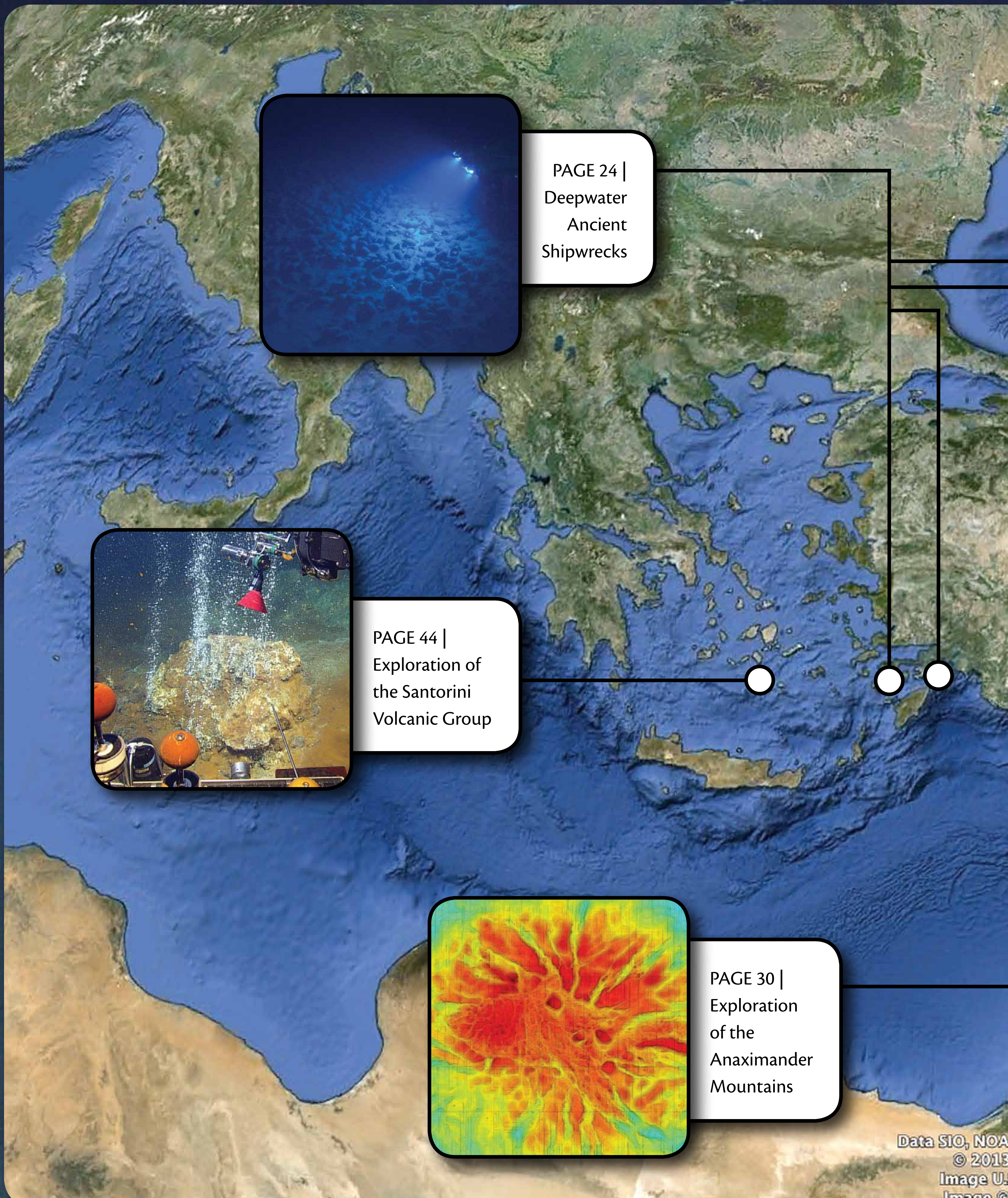
At sea, the interns served as watchstanders and as vehicle and video engineers, navigators, and data loggers. Others helped to process data and samples and develop high-resolution maps. Altogether, the undergraduate and graduate student interns represented over 25% of the total number of expedition team members participating in the *Nautilus* Exploration Program.

Role Modeling and Life-Long Learning

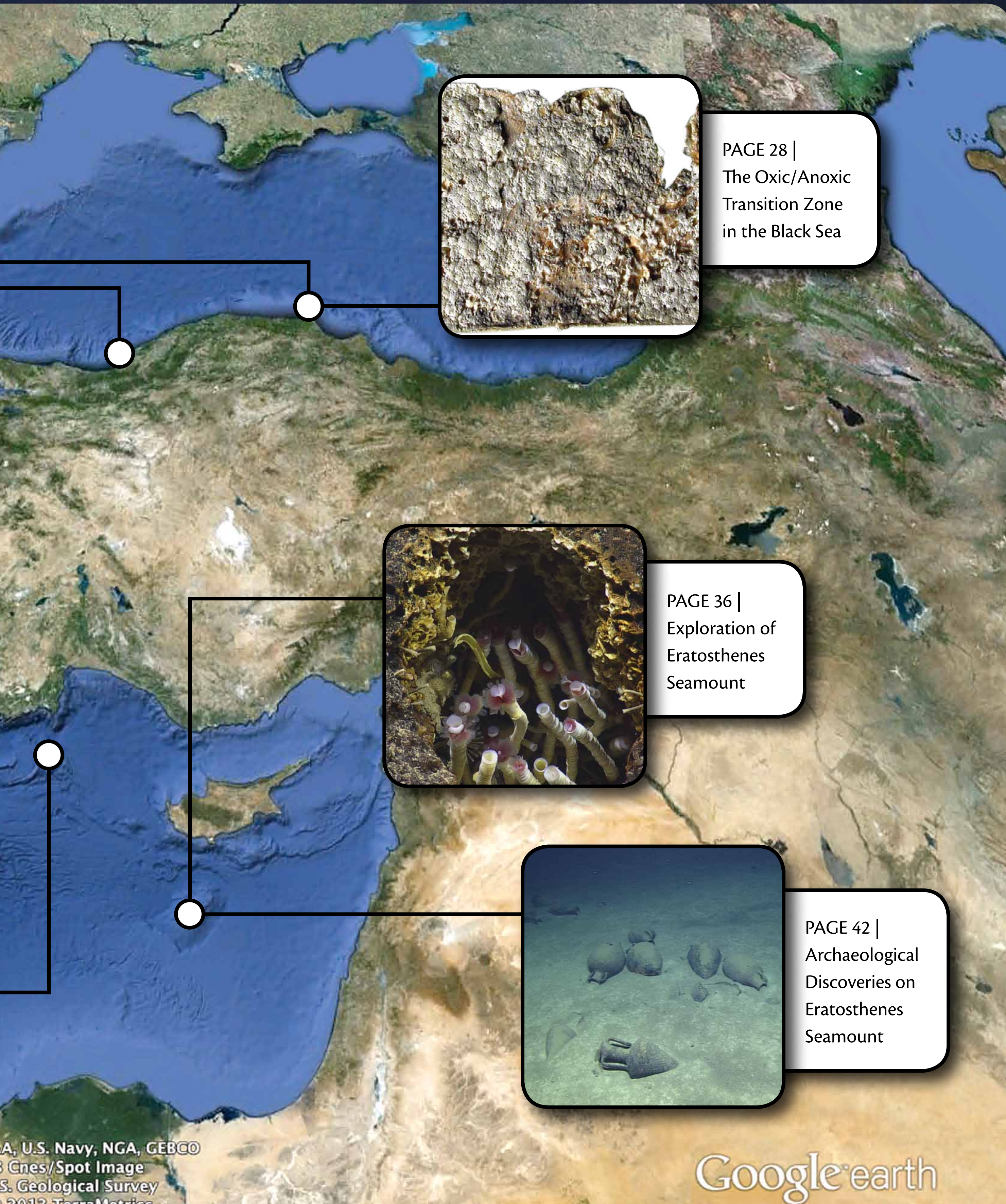
OET and its partners represent a wide range of educational organizations that collectively offer lifetime learning opportunities to capitalize on the interest sparked by this live access. They emphasize role models from across the array of professions found on the ship and on shore, supporting and participating in our expeditions. The essential element of all of these programs is the effort to engage and inspire children by giving them a compelling "view over the shoulder" of scientists and engineers working at sea, and to show children the path to putting themselves on a future ship of exploration.

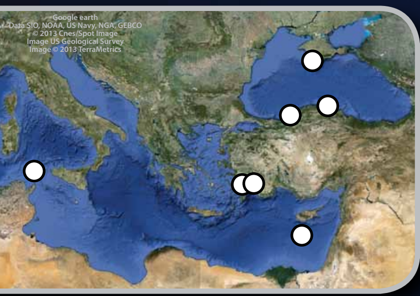
The *Nautilus* Exploration Program encourages and fosters collaborative and collegial professional development and learning. The scientists and engineers on the 2012 expedition team represented many sectors, including industry, consulting firms, self-started engineering design companies, government agencies, and academic and research institutions. They came from institutions across the United States and from 16 other countries. For example, Astronaut Cady Coleman participated in the expedition in a cross-training exercise on telepresence and exploration platforms. During her visit, the *Nautilus* team received a call from the International Space Station, enabling the website audience as well as her colleagues on the ship to experience the connection from the depths of the sea to space. Continuing to partner with a diversity of organizations and individuals will allow us to demonstrate to children that there are many ways in which they can become explorers themselves.

2012 FIELD SEASON AND SUMMARY OF



ONGOING MEDITERRANEAN RESEARCH





Deepwater Ancient Shipwrecks of the Mediterranean, Aegean, and Black Seas: 1988–2012

By Michael L. Brennan and Robert D. Ballard

According to a statistic cited in the 1975 film *Jaws*, most shark attacks occur in three feet (1 meter) of water about 10 feet (~ 3 meters) from the beach. This distance is, of course, a function of where people swim rather than where sharks feed. A similar situation has traditionally governed our view of ancient seafaring—most shipwrecks have been found in shallow water within diving depth along the coast because access to deep water was limited. The wrecks were first found along coastlines by sponge divers, then surveyed and excavated by teams of archaeologists using scuba (Bass, 1966). Therefore, our early understanding of ancient navigation suggested that seafarers hugged the coastline during circuitous transits around the Mediterranean Sea. However, over the past 24 years, as sonar and deep submergence technology has been developed and refined for archaeological work, new discoveries in deep water have shown that ancient mariners also braved open waters in order to traverse shorter distances directly across the Mediterranean.

In 1988, a camera sled named *Argo*, operated by the Woods Hole Oceanographic Institution, was used to conduct a deepwater survey on Skerki Bank, located west of Sicily along a direct path between Naples and Carthage in North Africa (Figure 1). A Roman shipwreck, called *Isis* by its discoverers, was found along with a series of individual amphorae scattered across the bottom in a linear pattern. Subsequent expeditions in 1995, 1997, and 2003 with the research submarine *NR-1* and the ROV *Jason* discovered a total of eight shipwrecks and two such "amphora alleys" on Skerki Bank at depths ranging from 700–850 m (Figure 2; Ballard et al., 2000). The first ancient wreck sites located in deep water, these discoveries provided evidence for a direct path of trade between Rome and Carthage across open water. Additionally, the individual amphorae on the seabed were hypothesized to be cargoes jettisoned by distressed or overburdened ships making this open-water passage.

Further confirmation of deepwater trade routes was found in 2010 and 2012 when *Nautilus* explored the summit of Eratosthenes Seamount south of Cyprus (Figure 1). Over 70 individual amphorae were found across the seamount in 2010

Figure 1. Map of the Mediterranean region. Base map from Google Earth with data from SIO, NOAA, US Navy, NGA, © 2013 Cnes/Spot Image.

Figure 2. An amphora being recovered by the ROV *Jason* from the Roman shipwreck Skerki D in the Mediterranean Sea in 2003.

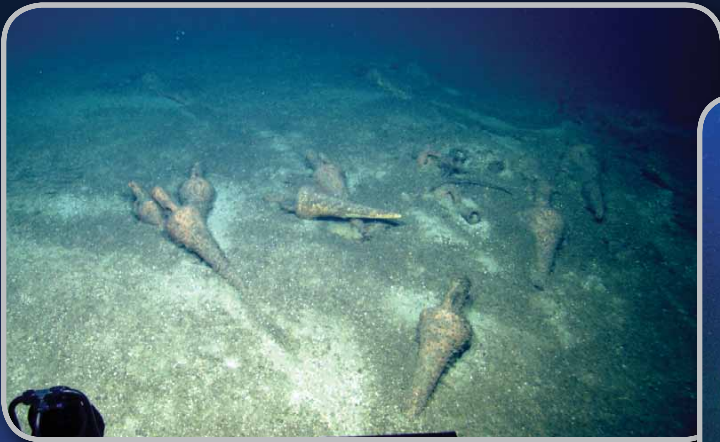


Figure 3. Carrot-shaped amphorae at the edge of the Sinop A shipwreck site, still intact, but pulled off site by trawling activity.

Figure 4. Well-preserved timbers and ship frames of Sinop D in the anoxic zone of the Black Sea.

and more than 150 in 2012, with dates ranging from Bronze Age Canaanite around 2000 BCE to Byzantine and Medieval as late as the 15th century CE, although we are still refining the ceramic dating (Wachsmann et al., 2011; see pages 42–43). These finds show an even greater geographic and temporal range than the amphora alleys on Skerki Bank and signify that ancient mariners commonly sailed across open water over millennia.

Since 1999, expeditions conducted by the Institute for Exploration and the Ocean Exploration Trust's *Nautilus* Exploration Program have also explored the coastal deep waters of the Mediterranean, Aegean, and Black Seas, locating 70 shipwrecks, including those on Skerki Bank. Many of these shipwrecks lie along the approaches to ancient harbors such as Knidos in the southeastern Aegean, and Heraclea and Sinop in the southern Black Sea (Figure 1). Due to the variety of environments and locations in which these wrecks were found, they represent a diverse range of site formation processes and states of preservation. The spectrum of wreck sites is represented by four wrecks found off the coast of Sinop, Turkey, in 2000 and reinvestigated during expeditions in 2003 and 2011. Sinop A is a wreck site consisting of a mound of Sinopean carrot-shaped amphorae at 105 m (344 ft) depth and some small preserved timbers (Figure 3). Trawl scars were visible at the time of its discovery in 2000, and more substantial damage from trawls was noted in 2011. At the other end of the spectrum is Sinop D, which, like Sinop A, dates to the 5th century CE, but is perfectly preserved at 325 m (1,066 ft) depth, well within the anoxic layer of the Black Sea where the lack of oxygen prevents wood-boring organisms from destroying timbers (Figure 4).

Ancient shipwreck sites are typically characterized by a mound of amphorae. After more than a millennium under water, the sites have reached an equilibrium with the surrounding marine environment until what remains are the inorganic and inert elements of the ship, usually ceramic cargo containers, ballast stones, and cooking wares. These sites are often in the shape of a ship, because when the hull disintegrates, the stacked cargo slumps to the sides but still maintains a rough profile of the vessel. The 26 premodern wrecks found off Knidos, Turkey, from 2009–2012 are good examples of these cargo-pile type wreck sites. Some are large wrecks with hundreds of amphorae, such as the Byzantine Knidos A site (Figure 5). Other sites are much smaller, lack the same profile in sonar, and are much more ephemeral on the seabed. These are wrecks of ships that either did not carry a large cargo or carried an organic cargo that has since decayed. This type of wreck site is very

Figure 5. ROV *Hercules* over the large Byzantine wreck, Knidos A.

interesting, as many of the smaller items and artifacts are visible on the surface rather than buried among hundreds of amphorae, such as at Knidos T (Figure 6).

However, shipwreck sites, even in deep water, are in many cases not in a stable environment. Many become slowly buried by sediment, such as Knidos B, or overgrown with corals and sponges, like Knidos B and Gallipoli A (Figures 7 and 8). We have also observed numerous cases in the Aegean and Mediterranean where conger eels have excavated the sediment within an amphora wreck to make hiding places, causing the artifacts to slump into small depressions and contributing to the overall site formation, for example, Knidos L (Figure 9). Yet the most immediate threat to the stability and preservation of shipwreck sites in the coastal deep water of this region is bottom trawl fishing. The Aegean is a relatively shallow sea, much of which is within depths exploitable by trawlers. Hence, few Aegean wrecks we have found are untrawled. Only those in deeper water escape trawl damage, such as at Skerki Bank and Eratosthenes Seamount, or in areas where trawling is either prohibited or impractical, such as the anoxic waters of the Black Sea where there are no fish.

The vast majority of the shipwrecks discovered, however, exhibit some damage from trawls. The weighted nets and trawl doors employed to keep the nets open carve furrows in the seabed that scatter and smash ceramic artifacts when a wreck is run over. Wreck sites that have been trawled only a few times have scattered cargo, broken artifacts at the surface of the wreck, and in some cases clear scars running through the site, visible as either furrows or lines of broken artifacts. Sites that have been trawled more severely begin to lose the ship shape of the amphora pile as artifacts and pieces of ceramics are scattered further across the seabed, to the point that few intact artifacts remain, for example, Marmaris B (Figure 10; Brennan et al., 2012). Continued severe damage fragments and scatters the artifacts to such an extent that in time the site is eradicated.

In the Black Sea, where organic materials are preserved due to the anoxic conditions of the deeper water, wrecks are found with more wooden timbers preserved than those found in more oxygenated conditions. When these sites are trawled, they look very different from those in the Aegean.

Figure 6. Small wreck site of Knidos T, containing a variety of small ceramic vessels, square stone artifacts, and metal chain.

Figure 7. Knidos B, an Archaic Greek shipwreck heavily buried in sediment and overgrown with sponges and corals.

Figure 8. Large amphora pile of the Gallipoli A shipwreck in the northeastern Aegean Sea with the artifacts barely visible beneath the sponges, corals, and other biological growth.

The preserved timbers, with thousand-year-old adze and cut marks often still visible, lie ripped apart in disarticulated piles rather than in the shape of the hull (Figure 11). The most heavily damaged wreck we have explored is the 4th century BCE Eregli E, found in 2011. Recent trawl damage had ripped up timbers preserved under the sediment and exposed human bones, including a tibia, femur, and tooth. Upon our return to the site in 2012, the wreck had been trawled extensively in the intervening 11 months so that the bones were missing, and the site looked almost entirely different from the previous year. We conducted photomosaic and microbathymetry surveys of this wreck both years. These surveys will give us a good quantification of the damage to the site over time, providing the first specific evaluation of trawl damage to a wreck site.

Since 1988, we have found 70 ancient and premodern shipwrecks in this region. They range from the 8th century BCE to the 19th century CE. While we showed in 2003 and 2007 that it is possible to excavate a shipwreck in deep water with an ROV, we are moving toward using high-resolution imaging as our primary way of documenting and preserving shipwrecks in situ. During the 2012 season, we completed work at some sites, such as returning to Eregli E and filling in some gaps in our sonar surveys off Eregli and Knidos. With the departure of *Nautilus* from the Mediterranean after the 2012 field season, we are shifting to a new approach to the sites described here. Beginning in 2013, we are planning to use an AUV to conduct imaging surveys of the seabed with higher resolution sonars than those available on *Nautilus* in order to obtain better coverage and understanding of what remains on the seabed. We hope to be able to use sonar to find and identify objects as small as individual amphorae. This work will allow us to piece together a more complete picture of the ancient paths across the open waters of the Mediterranean, Aegean, and Black Seas. The finds on Skerki Bank provided physical evidence that ancient mariners braved the open seas. Expanding this idea to document the paths of the ships over Eratosthenes Seamount, for example, will also give us a temporal understanding of these routes and their trajectories.

Figure 9. Depression made by a conger eel, visible among the artifacts, in the Knidos L shipwreck site.

Figure 10. Heavily damaged wreck site, Marmaris B, with artifacts broken and scattered across the seabed by trawls. Only a few intact artifacts are visible.

Figure 11. Pile of preserved wooden timbers from the shipwreck Eregli C in the southern Black Sea.

Environmental Characterization of the Oxic/Anoxic Transition Zone in the Black Sea

By Michael L. Brennan, Dennis Piechota, Jane Drake Piechota, and Jeff Emerson

The first few expeditions in the Black Sea focused on acoustic mapping of the paleoshoreline in 1999 and 2000, and then testing the excavation capabilities of the ROV *Hercules* on shipwreck sites off Sinop in 2003 and 2007. Our work there during the past two years has focused on characterizing the environmental conditions at the oxic/anoxic transition zone. Push cores from sediments underlying the oxic, suboxic, and anoxic water layers were collected with *Hercules,* and numerous analyses are being conducted on them in Turkey and the United States, including studies of grain size, microbiology, meiofauna, and geochemistry. These results will help us characterize the processes in these different environments and how they relate to the preservation of cultural materials.

In 2012, we extracted porewater from within the sediment with rhizon filters (Figure 1), which was analyzed for trace element concentrations using an ICP mass spectrometer at the University of Rhode Island. Results include porewater concentrations of iron (Fe) and manganese (Mn) with depth in the sediment cores from the oxic, suboxic, and anoxic layers off of Sinop, Turkey (Figure 2).

Porewater contains trace metals and other elements not locked up in mineral form in the sediments. Therefore, the higher concentration of Fe in the porewaters from sediments underlying the oxic water layer is expected because Fe is bound in pyrite and other iron sulfide minerals in suboxic sediments and even forms in the water column in anoxic waters. Manganese, on the other hand, shows a sharp decline to nearly zero downcore in the suboxic porewater (Figure 2b). This metal is present in both oxic and anoxic waters in either its oxidized or reduced forms, respectively. However, in suboxic zones, Mn acts as a catalyst for the oxidation of organic matter, transporting oxygen across the suboxic zone as MnO_2 particulates (e.g., Glazer et al., 2006). This mechanism is necessary for the cycling of oxygen and sulfide between the oxic and anoxic zones. Thus, we see less Mn in the porewaters of sediments underlying the suboxic waters because this metal is mobile through this zone.

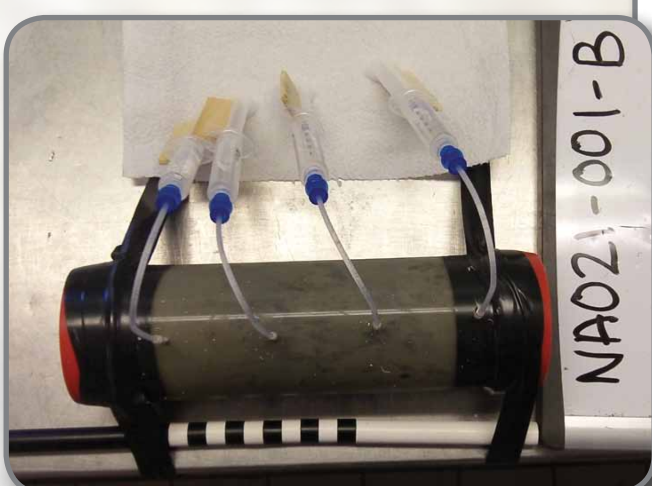


Figure 1 (above). Rhizon filters spaced every 5 cm extracting porewater from sediment core from the Black Sea. *Photo by Jeff Emerson*

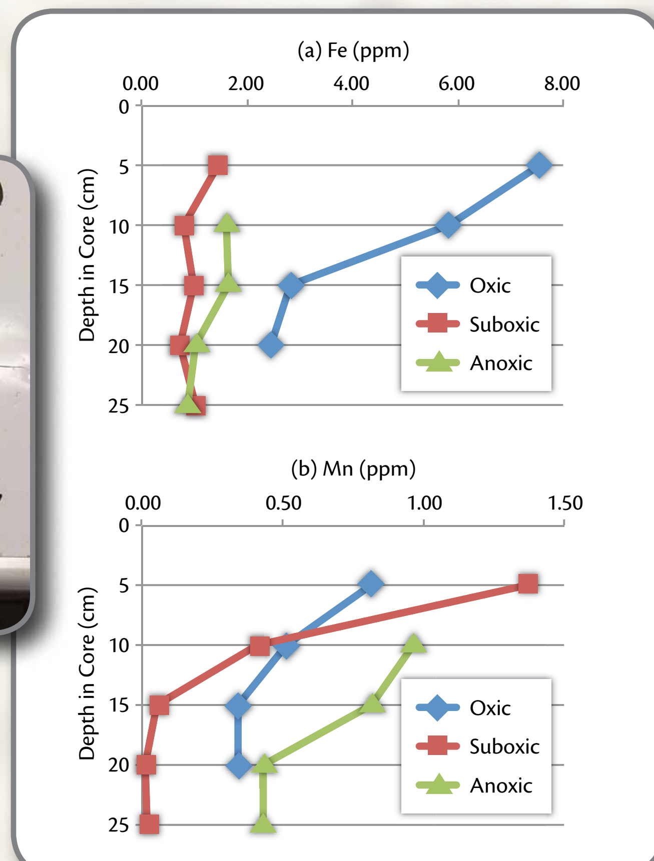


Figure 2 (right). Graphs of element concentrations in porewater with depth in the sediment cores for the oxic, suboxic, and anoxic samples for (a) iron (Fe) and (b) manganese (Mn).

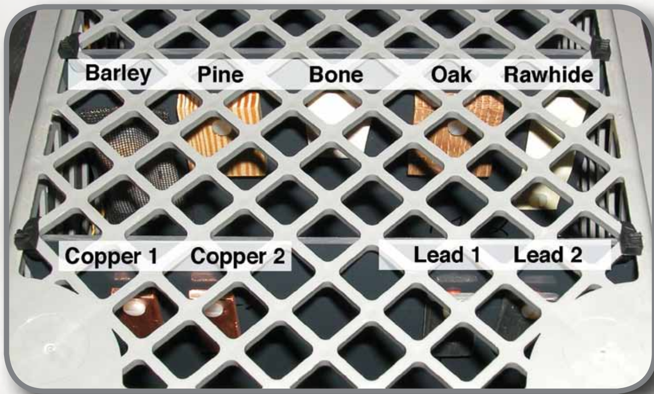


Figure 3. "Twinkie" experiment showing samples arranged on panel within the plastic crate frame. *Photo by Dennis Piechota*

Figure 4. "Kebab" experiment with test samples of wood and steel. *Photo by Dennis Piechota*

In 2007, we also began four sets of long-term, time-series experiments at the Sinop D site to characterize rates of decay and redox reaction on materials that would be found on ancient shipwrecks (Piechota et al., 2010; Brennan et al., 2011). One of the goals of the 2012 expedition was to retrieve the first of these sets to determine the first stage of deterioration after five years in anoxic waters. The experiments were deployed in two forms to look at two parameters. The "Twinkie" contained multiple panels of organic and metal samples inside a plastic frame (Figure 3). These samples reflect materials commonly found on ancient ships or cargoes and also exhibit varying degrees of perishability: barley grains, rawhide, cow bone, white pine, red oak, steel, copper, and lead. This experiment, with one panel of samples on the underside beneath a neoprene membrane and the others above the sediment, was designed to examine the contrasting chemistries of the sediment versus the open water. The "kebab" experiment was designed to study the effect of sediment depth on decay rates with two types of material on a titanium rod, one of steel and one of alternating samples of oak and pine (Figure 4).

Following the recovery of one of each of these three types of experiments, the sample materials were removed from the panels and kebab rods and sealed in anoxic bags for shipment back to the United States. While we are only beginning the analysis of these samples, early observations suggest that the deep Black Sea does not provide a uniform preservation environment. The most dramatic contrast is shown by the rawhide samples (Figure 5). The sample exposed to the loose, fluff layer at the sediment/water interface is nearly consumed by bacterial action, while the sample 10 cm lower and in the sediment shows relatively little alteration. These preliminary results suggest that we cannot visualize the deep Black Sea as a single preservation environment. Instead, we might better see it as three strata: the base of the water column, the organic fluff layer, and the mineral sediment. Each of these layers is likely to alter different material types uniquely and at different rates. The recovery and analysis of the other three sets still in place at Sinop D will continue the time-series experiment and further our understanding of these processes.

Figure 5. Rawhide samples from the recovered Twinkie experiment showing the differences observed between the original sample and those in situ above and beneath the sediment. *Photo by Dennis Piechota*

Exploration of the Anaximander Mountains: Mud Volcanoes, Cold-Seep Communities, and Cold Water Corals

By Nicole A. Raineault, Patricia A. Ramey-Balci, Timothy M. Shank, Eleanor Bors, Muhammet Duman, Derya Ürkmez, and Suna Tüzün

The Anaximander Mountains are located in a complex tectonic setting between the Hellenic subduction zone and the Cyprus arc in the Eastern Mediterranean Sea (Figure 1). The seafloor in this region records an active tectonic history of compression, extension, and strike-slip motion (Zitter et al., 2003). As the African plate moves north toward the Eurasian plate, the area in between, where the Anaximander Mountains are located, accommodates the relative motion of these plates.

The Anaximander Mountains are comprised of three seamounts: Anaximander, Anaximenes, and Anaxagoras. Both Anaximander, the westernmost seamount, with a summit at 1,250 m depth, and Anaximenes, the central seamount, with a shallower peak at 680 m depth, have similar morphologies, and trend northeast-southwest. Anaxagoras, the easternmost seamount, is less continuous, with many faults running through it, and has a much flatter summit at 930 m depth (Zitter et al., 2003). The origin of the seamounts is complex. Core, gravity, and magnetic, and seismic and other acoustic measurements suggest that Anaximander and Anaximenes Seamounts have a core of rocks from the southern Turkish microplate, possibly from the Taurus Mountains; however, the seamounts also contain blocks of completely different age, composition, and deformation stage, suggesting a

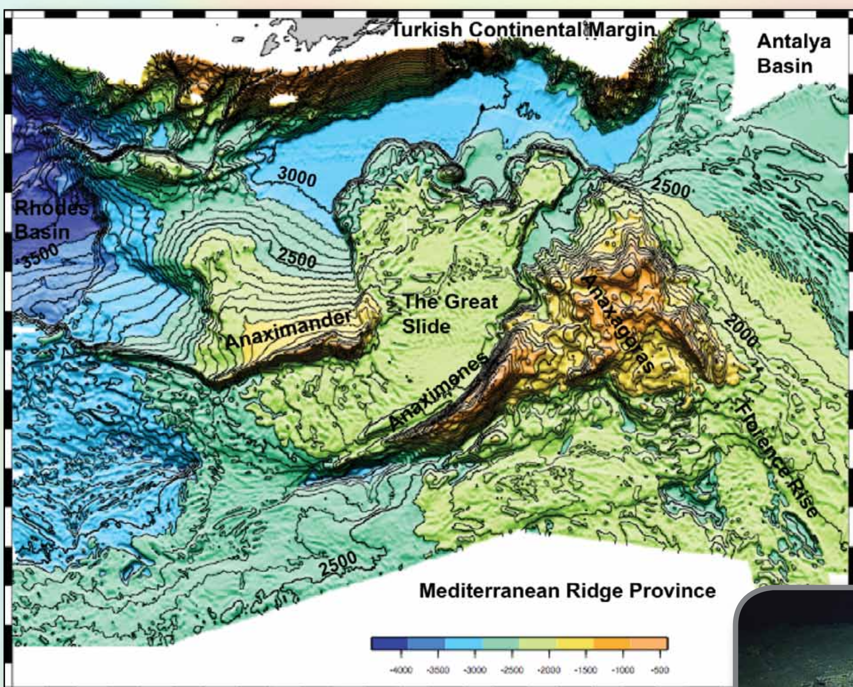


Figure 1. Bathymetric map of the Anaximander Mountain region in the Eastern Mediterranean Sea. Contour interval is 100 m. *Modified from Lykousis et al. (2009)*

Figure 2. A continuous release of methane bubbles from sediments beneath the fractured carbonate crusts at Athina mud volcano.

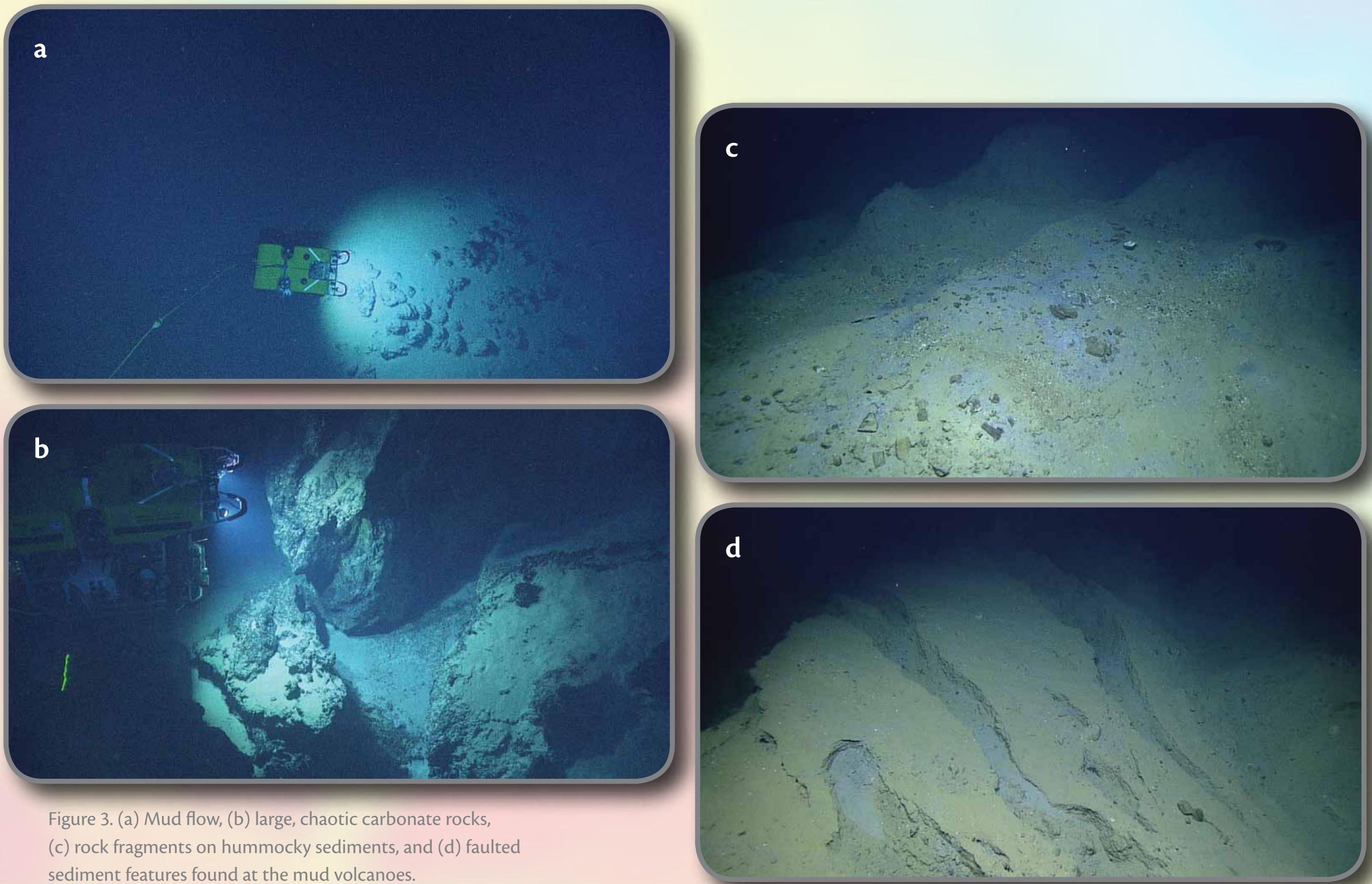


Figure 3. (a) Mud flow, (b) large, chaotic carbonate rocks, (c) rock fragments on hummocky sediments, and (d) faulted sediment features found at the mud volcanoes.

mixed origin (Zitter et al., 2003).

Local tectonic activity has resulted in the formation of seafloor features such as mud volcanoes and cold seeps. Mud volcanoes are conical mounds, typically ~ 100 m or less in height. Cold seeps are where slow, prolonged releases of fluids and methane occur that are often the result of degassing of mud volcanoes (Figure 2). Seismic activity can periodically trigger the release of deep, thermogenically produced, or shallower, microbially produced methane gases that are vented through mud volcanoes and cold seeps (Kopf et al., 1998; Olu-Le Roy et al., 2004).

Mud volcanoes go through periods of eruptive activity and inactivity. During active periods, mud, methane, and rock fragments are released explosively, blanketing the surrounding area in meters of poorly sorted sediment (Figure 3). The great volume of sediment forms mud flows. Recently erupted sediments in these settings are typically grey due to a lack of oxidation, while yellow-brown, oxidized, hemipelagic sediment accumulates slowly (2–5 cm per thousand years). Over time, methane-consuming microbes facilitate the formation of carbonate crusts up to tens of centimeters thick on top of erupted sediment (Olu-Le Roy et al., 2004). Thus, sediment cores taken at mud volcanoes can reveal the history of eruptive activity and inactivity (Figure 4). Sediment cores also reveal that gas hydrates are commonly associated with mud volcanoes (Lykousis et al., 2009).

Mud volcano activity can be gauged by examining the benthic macro- and megafauna as well as the surface sediment. Methane-oxidizing microbes form visible grey or white mats at methane seeps in the Mediterranean (e.g., Omoregie et al., 2009). On the microbial base, ecosystems often composed of bivalves, tubeworms, crabs, urchins, and other larger fauna can account for higher biodiversity of these seep sites in biologically depauperate deep-sea regions (Danovaro et al., 2010). When a seep is no longer active, inhabitants including bivalves die off, leaving large aggregations of shells and, sometimes, empty worm tubes in carbonate crusts. The communities at the Mediterranean mud volcanoes are thought to be different from those found in the Atlantic due to isolation following the Messinian salinity crisis 6.5–5.3 million years ago

Figure 4. ROV core sampling of the microbial mats for biological and sedimentological analyses.

(Danovaro et al., 2010). In the highly sedimented regions surrounding these mud volcanoes and on the summits of the neighboring seamounts, slow-growing cold-water corals are the predominant nonseep fauna.

Importance

The mud volcanoes of the Anaximander Mountains support diverse chemosynthetic communities rarely found in the Mediterranean Sea. E/V *Nautilus* exploration and sampling efforts have generated a series of data sets that include maps, samples, visual surveys, and ancillary data; they will help improve our understanding of the diversity and succession of species at these seeps and allow for the interdisciplinary study of the linkages between environmental variables and the differences in composition and distribution of fauna comprising these ecosystems. The high-resolution maps and imagery will also permit detailed analysis of mud volcano morphology.

Summary of 2010 *Nautilus* Cruise NA010

The *Nautilus* team carried out ROV and side-scan sonar surveys of the Anaxagoras and Anaximenes Seamounts in September 2010. Exploration of three mud volcanoes—Kazan, Amsterdam, and Thessaloniki—revealed chemosynthetic cold-seep communities at 1,300–2,000 m depth (Shank et al., 2011). Visual observations of the seabed in these areas revealed over two dozen localized seeps that, when combined with observations of bivalve aggregations and empty shells, can be useful in determining the extent and distribution of active and extinct cold seeps. An actively seeping area was observed at the northern side of the Kazan mud volcano, located on Anaxagoras. Mud volcano epibenthic communities (i.e., organisms living on the sediment surface) consisted mainly of siboglinid tubeworms (*Lamellibrachia sp.*), amphipods, brachyuran crabs, echinoid sea urchins, mussels, and clams (Figure 5; Shank et al., 2011). In contrast, the epibenthic communities on the seamount were characterized by cold water octocorals and scleractinian corals (Shank et al., 2011). One cruise highlight included observations of distinctive scars in seabed sediments on the Kazan and Amsterdam areas that Shank et al. (2011) say are consistent with hypothesized bottom-feeding activities of beaked whales (Woodside et al., 2006). Overall, the 2010 cruise provided the foundation for the 2012 expedition to the Anaximander region by identifying potential areas of interest for further exploration. Specifically, observations made during the 2010 cruise made clear the need for biological and geological samples to enable further study of these relatively unknown and important Mediterranean deep-sea habitats and associated communities.

Summary of 2012 *Nautilus* Cruise NA022

Nautilus returned to the Anaximander Mountains region July 28 to August 8, 2012, with a multinational, interdisciplinary exploration team from the United States, Turkey, Greece, Puerto Rico, the United Kingdom, Oman, and Australia. Several research institutions were involved, representing the fields of ecology, biology, geology, chemistry, and seafloor mapping. Broadly, the aim was to explore the biogeography of the Anaximander Mountains in an integrated way through visual surveys, detailed mapping, and physical sampling. The extensive 2012 exploration program permitted sampling of mega-, macro- and meiofaunal benthic communities at Amsterdam, Kula, Thessaloniki, Kazan, and Athina mud volcanoes, as well as at a single soft sediment nonseep site on the Anaximenes ridge. We gave priority to the most prominent mud volcano in the region, Amsterdam, where explorative video transects and sampling were conducted at multiple locations along the slope (i.e., base, middle, and summit). The data collected will aid in characterizing the biological assemblages and populations associated with mud volcanoes and cold seeps at a variety of geospatial scales.

Active seeping was evident at several mud volcanoes, including Amsterdam, Thessaloniki, and Athina, where bubbles, assumed to be methane, were observed escaping the seafloor, often through fractured carbonate crust that was host to abundant mussel and tubeworm populations. Where measured, the temperature of actively seeping fluid was the same as the ambient seawater (14°C). For two of the 10 dives, a mass spectrometer was mounted on *Hercules*, allowing for the measurement of methane concentration in seeping fluids (Wankel et al., 2011). The mass spectrometer detected methane at several of these active seeps, as well as at what is believed to be microbial-mat-covered sediment, which is commonly found in areas of active seeping.

Superficial microbial mats patchily distributed at all five mud volcanoes were among the most commonly observed microhabitats. Mats were highly variable in both size (up to several meters square) and color (white, orange, dark grey). The color of microbial mats is thought to be associated with the level of sulfide oxidation activity in the sediment (Nikolaus et al., 2003), with orange or reddish mats forming on sediments experiencing a higher flow of reduced fluids relative to areas with white mats (Levin, 2005). At the mid-slope region of Amsterdam, white mats were fluffy in appearance, compared to mats with a denser appearance sampled on the other mud volcanoes. The surface sediment surrounding the mats was light beige, indicating that it was oxidized. Microbial mats were often punctuated with hard substrates such as disjointed carbonate crusts (as observed at the Amsterdam mid-slope and summit sites) and/or with haphazardly distributed pebbles and rocks (as observed at the Amsterdam base site), resulting in the patchy distribution of mats. Extensive, dense aggregations of empty bivalve shells were observed at many sites, with the mid-slope site of Amsterdam having the highest density among sampled sites. Although microbial mats are associated with anomalous geochemical conditions such as high levels of sulfide, they can contain a diverse assemblage of meio- and macrofaunal organisms (e.g., Robinson et al., 2004).

Sediment core sampling for sedimentological, macrofaunal (organisms retained on a 500 µm mesh screen), and meiofaunal (organisms retained on a 63 µm mesh screen) analyses were concentrated in these microbial mats. Degassing of the core samples on ascent to the surface, in addition to the strong methane and hydrogen sulfide odor coming from the sediment during processing, was evidence of the high gas concentration. While the degassing of the gray, fine mud disturbed the core stratigraphy, an oxidized surface layer (top several centimeters) and anoxic subsurface were preserved in many cores.

Figure 5. Common epibenthic fauna at cold seep sites included (a) tubeworms, (b) small mussels and gastropods, and (c) crabs.

This cruise marked the first occasion where the *Nautilus* team collected biological samples in the Anaximander region. Also, for the first time, quantitative community analysis and DNA barcoding of core samples will be used to describe and characterize the macrofaunal community structure (i.e., species composition, diversity, and abundance) within microbial-mat-covered sediments on mud volcanoes of the Anaximander Mountains. Preliminary examination of samples indicates that two species of spionid polychaetes dominate microbial mat sediments taken at the mid-slope region of the Amsterdam mud volcano at 2,216 m depth. We also observed small bivalves and gastropods.

Complementary high-resolution BlueView multibeam was used to map the sampling locations, producing a seafloor bathymetry grid at 0.05 m (Figure 6a). Stereo-imaging also produced photomosaics of the sampling locations that facilitated identification of megafauna and larger-scale geologic features as well as description of small-scale habitat features important for fauna (Figure 6b). Common epibenthic communities at the seep sites include tubeworms, mussels, gastropods, galatheid and other crabs, and urchins on more established or extinct sites. Nektonic fauna included leopard sharks, tripod fish, snipe and sawtooth eels, and shrimp (Figure 7).

The mud volcanoes exhibited a range of activity. Some were covered in gray (assumed unoxidized) mud with high amounts of angular rock clasts from recent volcanic events. Mudflow features, terraced or channeled, were evident on Kula and Kazan. There were long, linear or sinuous faults in the sediment-covered terrain. Other locations had hummocky terrain, where gas trapped in sediment bubbles to the surface. Carbonate crusts, sometimes laterally extensive and thick, were indicative of mud volcanoes with an older history of methane seeping, because it takes time for the microbes to produce crusts. The porous carbonate crusts host abundant organisms, including small (1–2 cm) bivalves and gastropods and siboglinid worms. Athina mud volcano has large, chaotic carbonate crusts that appear to

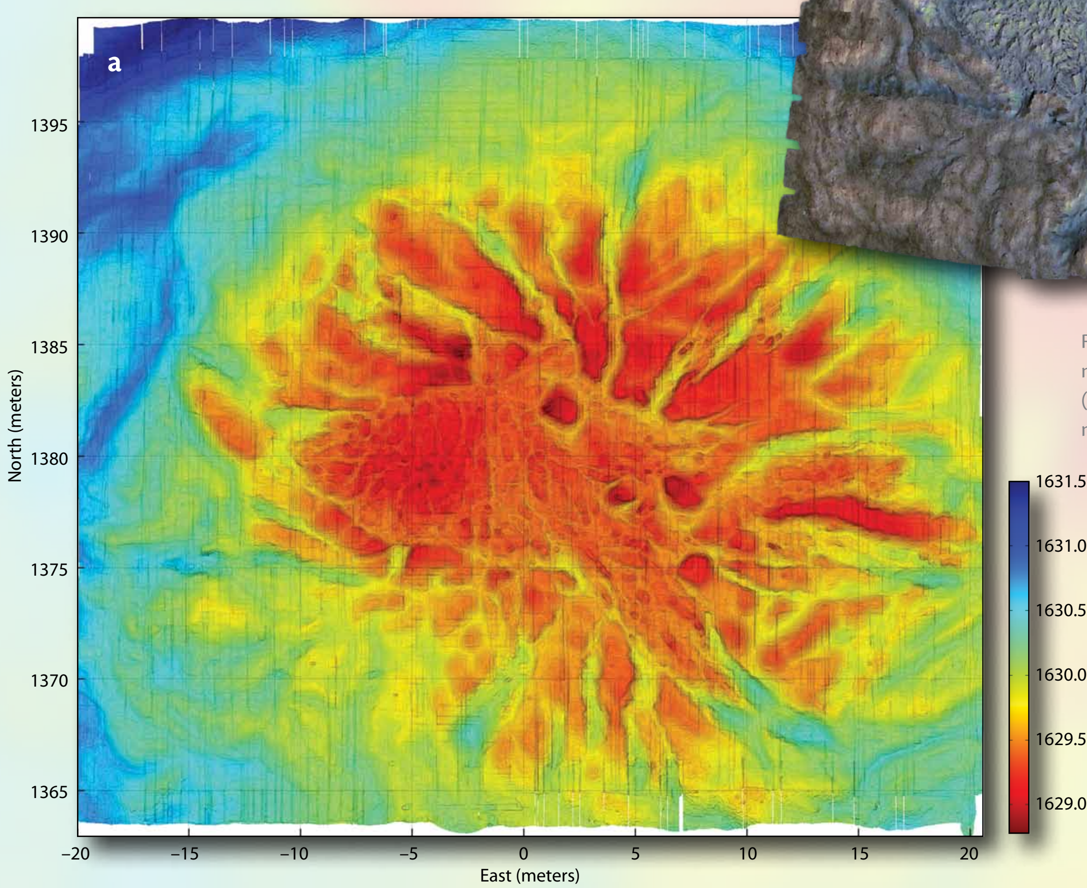


Figure 6. (a) High-resolution multibeam image and (b) photomosaic of the Kula mud volcano summit.

be moved from their original positions, likely by a combination of tectonics and mud volcano activity.

We recovered three small pieces (ranging from 10–30 cm) of wood during dives to Kula, Kazan, and Thessaloniki mud volcanoes. Two of these pieces were of natural origin (e.g., tree branches) and one was considered processed lumber. We recovered many (> 200) specimens of a boring clam species belonging to the genus *Xylophaga* from these wood samples (identification based on descriptions in Voight and Segonzac, 2012). Extremely large numbers (> 300) of an unidentified amphipod dominated the sample of processed wood with indications of previous colonization (i.e., burrows and bore holes) by boring clams.

Exploration of nonseep areas showed that cold-water corals and associated amphipods and shrimp are the main faunal constituents of the sediment-covered seamount ridges (Figure 8). Along the Anaximenes ridge summit, we observed black *Antipathes* coral and occasional *Desmophyllum* coral. Abundant fossilized cup corals occurred on large boulders along the slope of Athina mud volcano away from the cold-seep areas. Scour patterns in the mud assumed to be formed by beaked whales were observed on Kula and the Anaximenes ridge. The density and distribution of the scour marks in acoustic and video data sets from 2010 and 2012 on Eratosthenes Seamount are being compared to those found here. Finally, we found seafloor evidence of ancient mariners through our frequent discovery of amphorae, some identified as of probable late Roman provenance.

Further data analyses will reveal the differences in mud volcano morphologies and associated seep communities that will help address questions about methane seepage, deep-sea diversity, and local carbonate production.

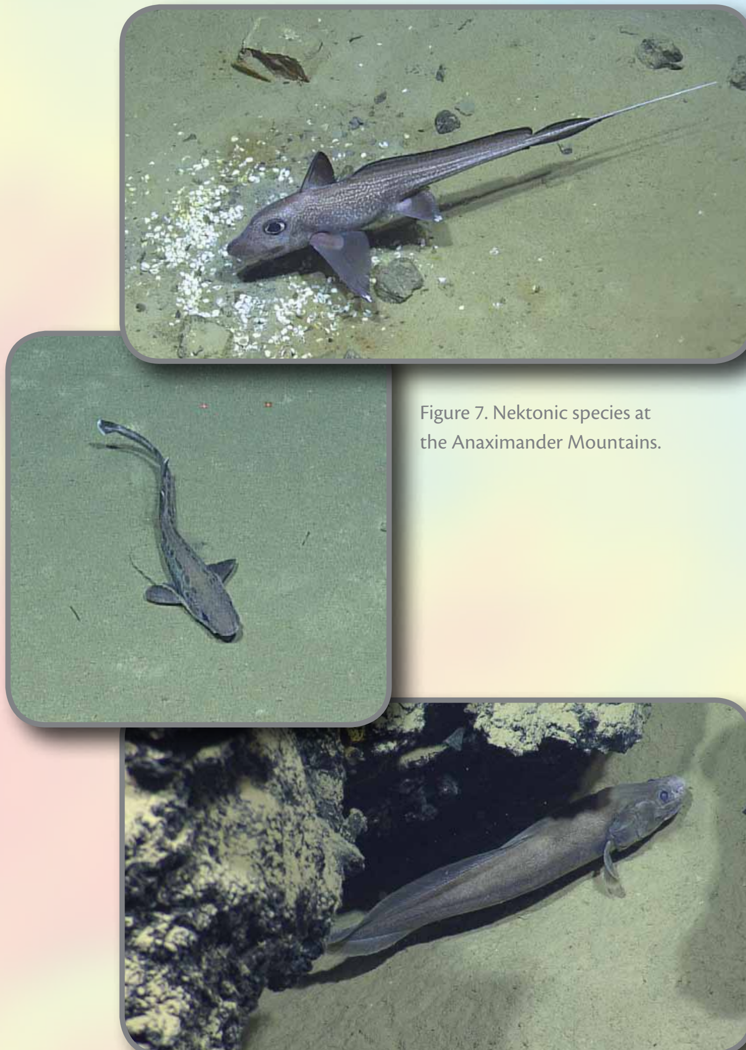


Figure 7. Nektonic species at the Anaximander Mountains.

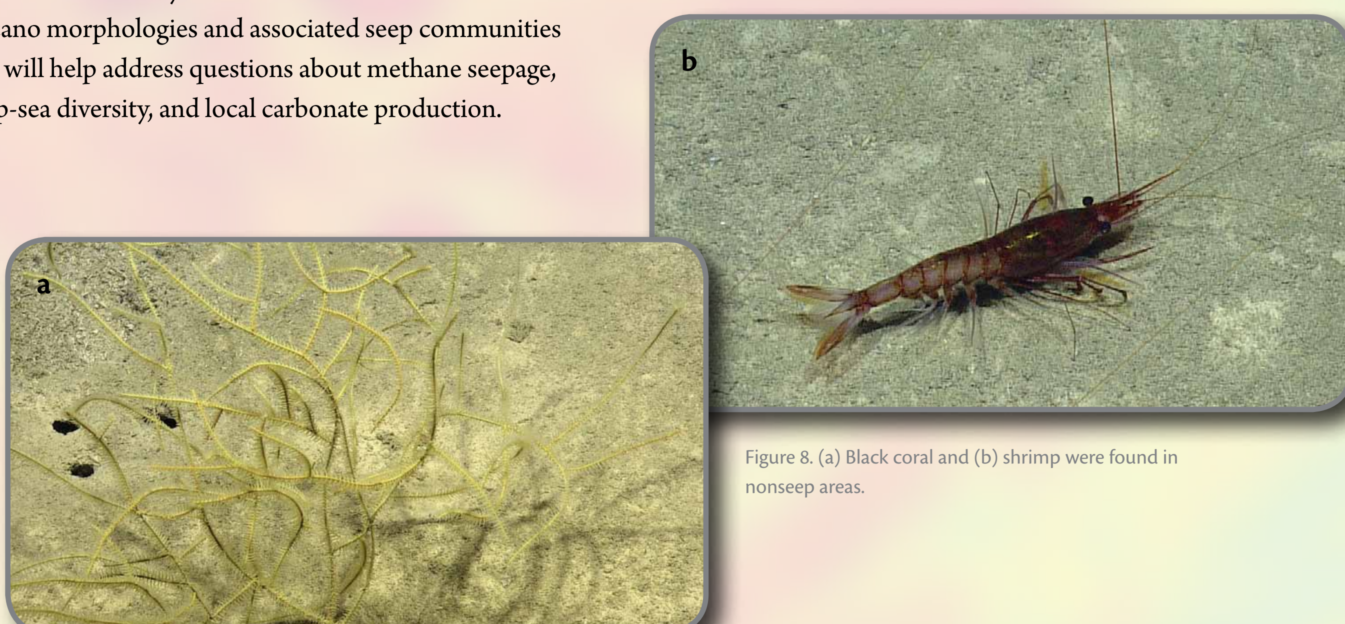


Figure 8. (a) Black coral and (b) shrimp were found in nonseep areas.

Exploration of Eratosthenes Seamount—A Continental Fragment Being Forced Down an Oceanic Trench

By Garrett Mitchell, Larry Mayer, Katherine L.C. Bell, Robert D. Ballard, Nicole A. Raineault, Chris Roman, W. Benjamin A. Ballard, Kelsey Cornwell, Al Hine, Eugene Shinn, Iordanis Dimitriadis, and Onac Bogdan

Eratosthenes Seamount is located in the Eastern Mediterranean Sea, approximately halfway between the island of Cyprus to its north and the Nile Delta cone to its south (Figure 1). One of the largest submarine geologic features in the Eastern Mediterranean, Eratosthenes Seamount rises over 2,000 m above the surrounding Eratosthenes Abyssal Plain, where its flat summit reaches a minimum depth of approximately 690 m (Figure 2). This large (120 km × 80 km) elliptically shaped seamount is thought to be a continental fragment rifted from the northern margin of the African plate in the early Mesozoic (Robertson, 1998) that is currently being subducted beneath the Cyprus trench.

The morphology and geology of Eratosthenes Seamount reveal its complex history. Deeper-water pelagic carbonates were deposited on top of shallow-water carbonates after the Eastern Mediterranean basin subsided in the early Cretaceous (Mart and Robertson, 1998; Robertson, 1998). Later tectonic activity resulting from Red Sea rifting uplifted the seamount, which was subaerially exposed during the Messinian salinity crisis 6.5–5.3 million years ago when the Mediterranean all but dried up (Mascle et al., 2000). During its geologically brief subaerial exposure, the seamount was severely eroded and chemically weathered, which contributed to its present-day flat top that is perforated by karst geomorphology (Mascle et al., 2000).

Ongoing subduction is flexing the less dense continental crust of Eratosthenes Seamount as it resists underthrusting at the Cyprus trench (Robertson, 1998). The result is both uplift of the seamount (Mascle et al., 2000, 2006) and a summit that is crosscut by a series of east-west trending normal faults that form a series of downward-stepping grabens with offsets up to 250 m (Robertson,

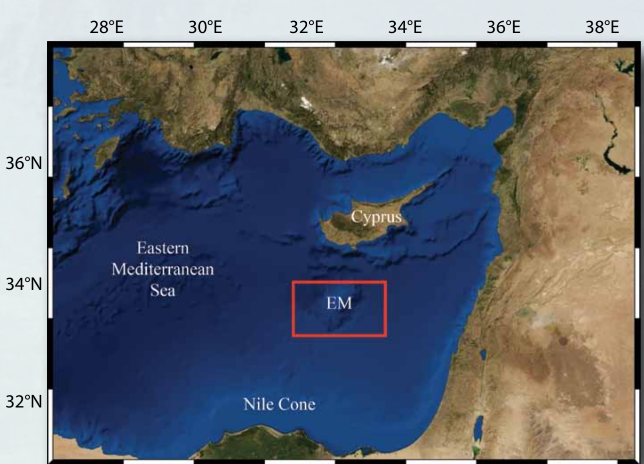


Figure 1. Geographic setting of Eratosthenes Seamount (EM) in the Eastern Mediterranean Sea, south of Cyprus.

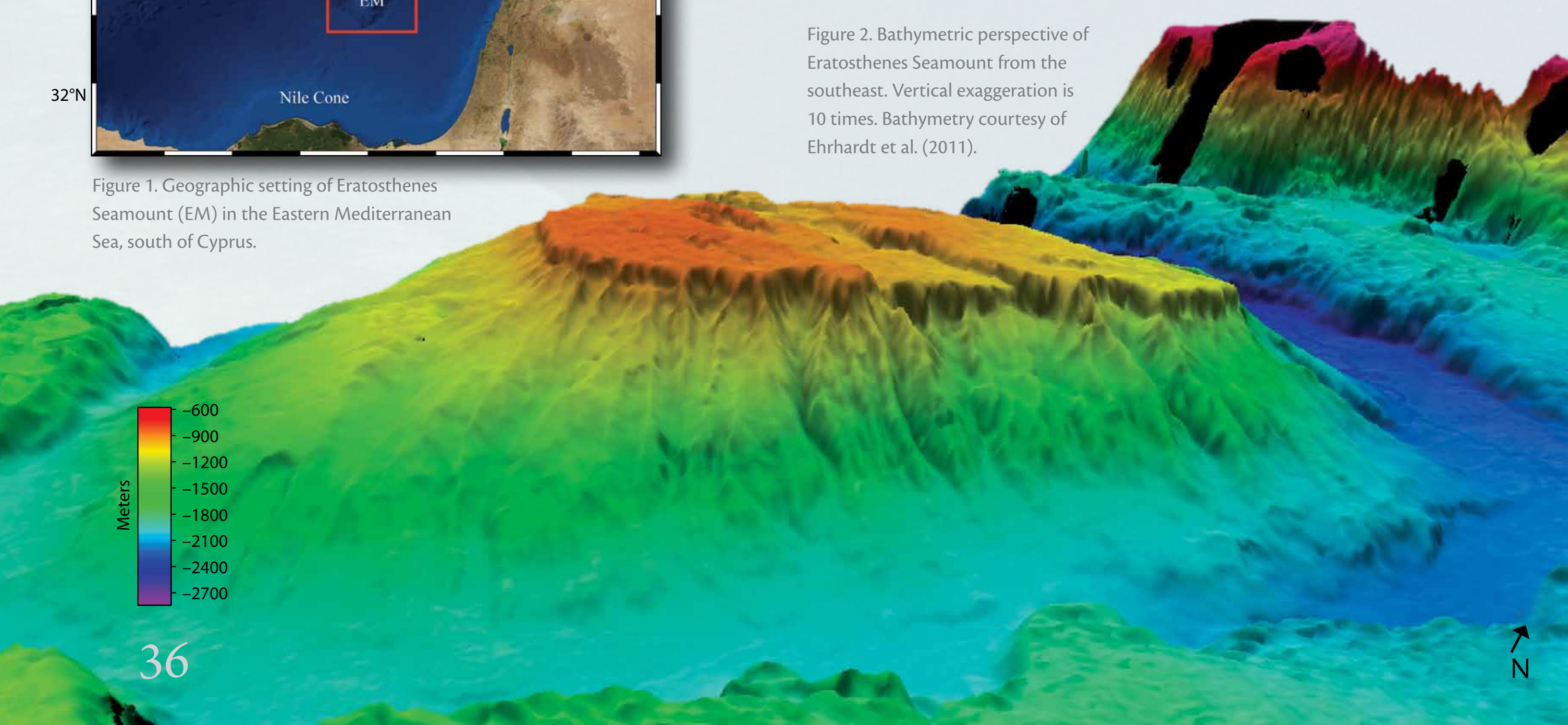


Figure 2. Bathymetric perspective of Eratosthenes Seamount from the southeast. Vertical exaggeration is 10 times. Bathymetry courtesy of Ehrhardt et al. (2011).

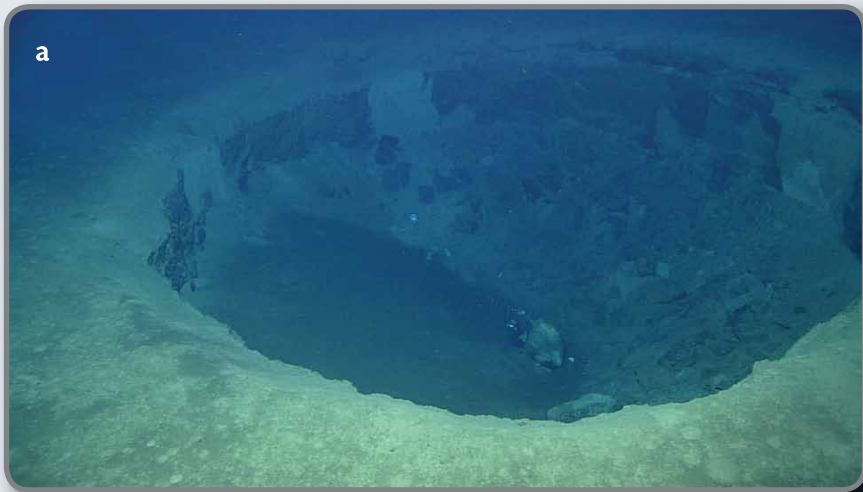


Figure 3. (a) One of the many circular sinkholes scattered on the summit of Eratosthenes Seamount. These sinkholes had diameters up to 40 m with depths to 10 m. Almost every one had trash accumulated in the bottom. (b) Outcrop of carbonate layers on rim of sinkhole.

1998; Galindo-Zaldívar et al., 2001; Dimitrov and Woodside, 2003). The eastern flank of Eratosthenes Seamount contains high gradient incisions formed by gravity-controlled slides, slumps, and other mass-wasting processes (Ehrhardt et al., 2011). Rapid sea level rise associated with refilling of the Mediterranean basin with Atlantic Ocean waters after the Messinian desiccation submerged Eratosthenes Seamount to its present-day bathyal depths.

We chose to explore Eratosthenes Seamount in 2010 with E/V *Nautilus* not only because of its tectonic environment and resulting morphology but also because earlier interpretation of mapping with a MAK-1 100 kHz side-scan sonar imaging system (Beijdorff et al., 1994; Dimitrov and Woodside, 2003) described numerous pockmarks on the summit as well as the deepest reported occurrence of living scleractinian corals in the Mediterranean (Galil and Zibrowius, 1998). The exciting discoveries made during the 2010 expedition and the proximity of the seamount to other intended areas of exploration led to additional exploration of Eratosthenes Seamount in 2012. In 2010, *Nautilus* primarily explored the seamount in a reconnaissance-type survey mode where *Argus* served as a deep-tow sled to acquire long-range side-scan images. During the 2012 expedition, the *Hercules-Argus* tandem ROV system was used to explore, in more detail, features of interest (sinkholes, cold seep venting communities, and exposed fault walls). We describe results from both expeditions below.

2010 E/V *Nautilus* Cruise NA008

One of the most significant discoveries of the 2010 expedition was that the circular structures common on the summit of the seamount were not pockmarks resulting from gas and fluid discharge as previously interpreted from side-scan sonar data by several groups (Beijdorff et al., 1994; Dimitrov and Woodside, 2003). Instead, the larger features were sinkholes formed by carbonate dissolution and the smaller features were erosional scour pits formed by current erosion around small rocks (Figure 3a). Both types of circular depressions observed during the ROV investigations lack the expected stratigraphic and morphological relationships associated with fluid and gas expulsion that commonly form seafloor pockmarks (Figure 3b; Mayer et al., 2011).

Just as surprisingly, the southeast flanks of Eratosthenes Seamount were found to contain focused regions of fluids actively seeping through a porous outcrop apparently confined to water depths between 900 and 1,000 m. Numerous chemosynthetic vent communities consisting of small clams, tubeworms (*Siboglinidae* sp.), urchins, and crabs were discovered in these cold seep zones where the measured in situ temperature of 14°C was approximately 1°C above the ambient seawater (Figure 4). The vent communities are associated with a reddish-brown staining that is possibly related to an oxidation reaction. Large regions of clam shells were also observed in the vicinity of the cold seeps and vent communities (Figure 5).

Another interesting discovery was made in 2010 on the steep, 70 m high southern inner wall of the largest fissure on the top of the seamount. This wall had a smooth limestone face with striations, called slickensides, and a sharp sediment-outcrop contact at its base (Figure 6). The slickensides were formed by near vertical movement between sides of a fault and may provide further clues about the faulting history of the seamount in response to subduction. Archaeologically, the 2010 expedition mapped numerous individual amphorae on the seamount's summit as well as at two Ottoman-era shipwreck sites (Wachsman et al., 2011). These discoveries formed the framework for planning the 2012 expedition.

2012 E/V *Nautilus* Cruise NA023

EXPLORATION OF THE SUMMIT

The 2012 survey began at the southern end of the seamount where numerous sinkholes were discovered in 2010. The seamount's southern summit area contains abundant sediment, with scattered circular sinkholes ranging in diameter from 10 to 40 m and in depth up to 10 m. *Hercules* explored inside these sinkholes and found numerous cup corals living on the carbonate walls. The seafloor in this area of the seamount is featureless mud, with traces of biological activity, but the ubiquitous presence of trash in the sinkholes implies that there is sufficient current activity to transport garbage; once in the sinkhole, the trash is trapped. The featureless sediment on the summit of Eratosthenes also contains numerous scours first observed in 2010 that are thought to result from the feeding behavior of Cuvier's beaked whales *Ziphius cavirostris* (Woodside et al., 2006; Bell et al., 2011). This initial 2012 summit

Figure 5. Kilometers of clam shells were found along the base of the outcrop containing the cold seeps. Live clams were found by digging beneath the shells in proximity to the vent sites.

Figure 4. The southeast flank of the seamount hosted numerous chemosynthetic vent communities consisting of tubeworms, clams, urchins, and crabs located around cracks with chemical staining.

Figure 6. A 70 m vertical limestone wall first discovered in 2010 contained slickensides that were later mapped with stereo-imaging cameras and a laser line scanner.

survey also further documented many individual amphorae and one ancient shipwreck, which were photographed with *Hercules'* high definition cameras.

EXPLORATION OF THE SOUTHEAST FLANK

After transiting eastward across the southern summit, *Hercules* descended the steep southeast flanks of Eratosthenes Seamount, confirming the 2010 discovery of a zone in the limestone outcrop where stained cracks were seeping fluids that were approximately 1°C higher than the ambient seawater (Figures 5 and 6). In 2012, live clams were sampled by digging beneath the unoccupied clam shells in the vicinity of fluid seeps. Continued exploration of the remarkable karst topography of the southeast flank revealed walls of manganese-encrusted fossilized horn corals (Figure 7) as well as an unusual columnar formation whose appearance was very similar to that of columnar basalts. Additionally, a very unusual feature was discovered that was quickly identified by our shore-based Doctors on Call to be phosphorized whale ribs (Eugene Shinn, USGS retired, *pers. comm.*, 2012; Figure 8).

HIGH-RESOLUTION MAPPING OF SHIPWRECKS, KARREN KARST, AND SLICKENSIDES

In preparation for the 2012 cruise, work was done to assign ages to the various individual amphorae discovered on the top of the seamount in 2010. This work continued during the 2012 cruise as new amphorae were discovered and documented (see pages 42–43). Amphorae were identified and then plotted geospatially by age, revealing a distribution of artifacts over the millennia across the seamount. Literature suggests that ancient mariners tended to use seaways near coasts for safety, yet the spatial distribution of the discarded amphorae suggests these mariners also relied on open water seaways that provided a more direct route between trading ports (Wachsmann et al., 2011). During the surveys here, a side-scan target was investigated by *Hercules*, which turned out to be a large (~ 45 m) undocumented shipwreck estimated to be a 4th to 5th century BCE ship (see pages 42–43). This wreck was surveyed with the high-resolution multibeam and stereo-imaging cameras (Roman et al., 2010; see pages 10–15).

Figure 7. Manganese-encrusted fossilized horn corals found in a vertical limestone wall.

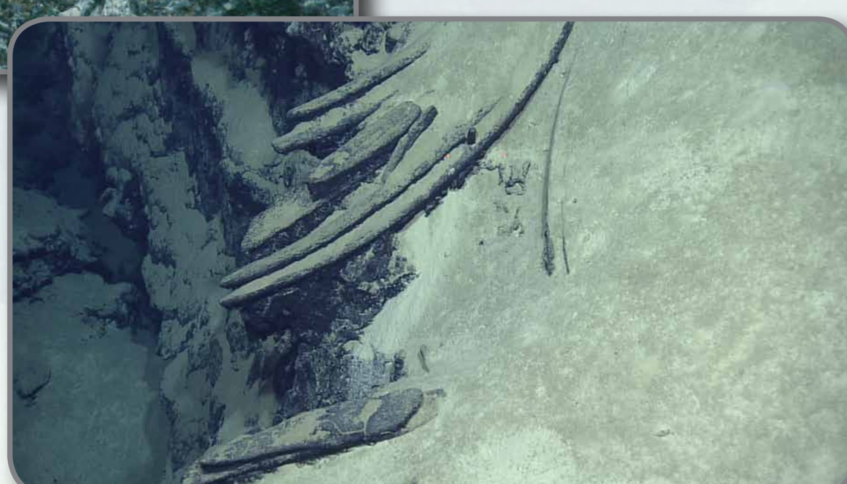


Figure 8. Phosphorized whale ribs discovered while exploring Eratosthenes and identified by the shore-based Doctors on Call.

Figure 9. High-resolution photomosaic of a vent region where clams are clustered.

After exploring and mapping this wreck, *Hercules* traversed to the southeast to perform a detailed high-resolution survey of the vent fields, in particular, to document that clam shell deposits continued on for many kilometers. *Hercules* also collected vent fauna samples, including tubeworms and clams. After conducting a high-resolution survey using the laser line scanner, stereo-imaging, and the BlueView multibeam sonar (Figure 9), *Hercules* continued north along the eastern flank to investigate and map the columnar features discovered previously (Figure 10). While these features looked very much like columnar basalts, the network of Doctors on Call identified them as a relatively obscure form of karst morphology known as karren (Ogdan Bonac, University of South Florida, *pers. comm.*, 2012). Karren develop subaerially when groundwater runs down a steep limestone cliff to erode regularly spaced grooves in the limestone wall (Ford and Williams, 2007; Ginés et al., 2009). *Hercules* mapped these features with the forward-mounted stereo cameras and collected a column sample that was coated with manganese and contained white unweathered limestone in its interior (Figure 11).

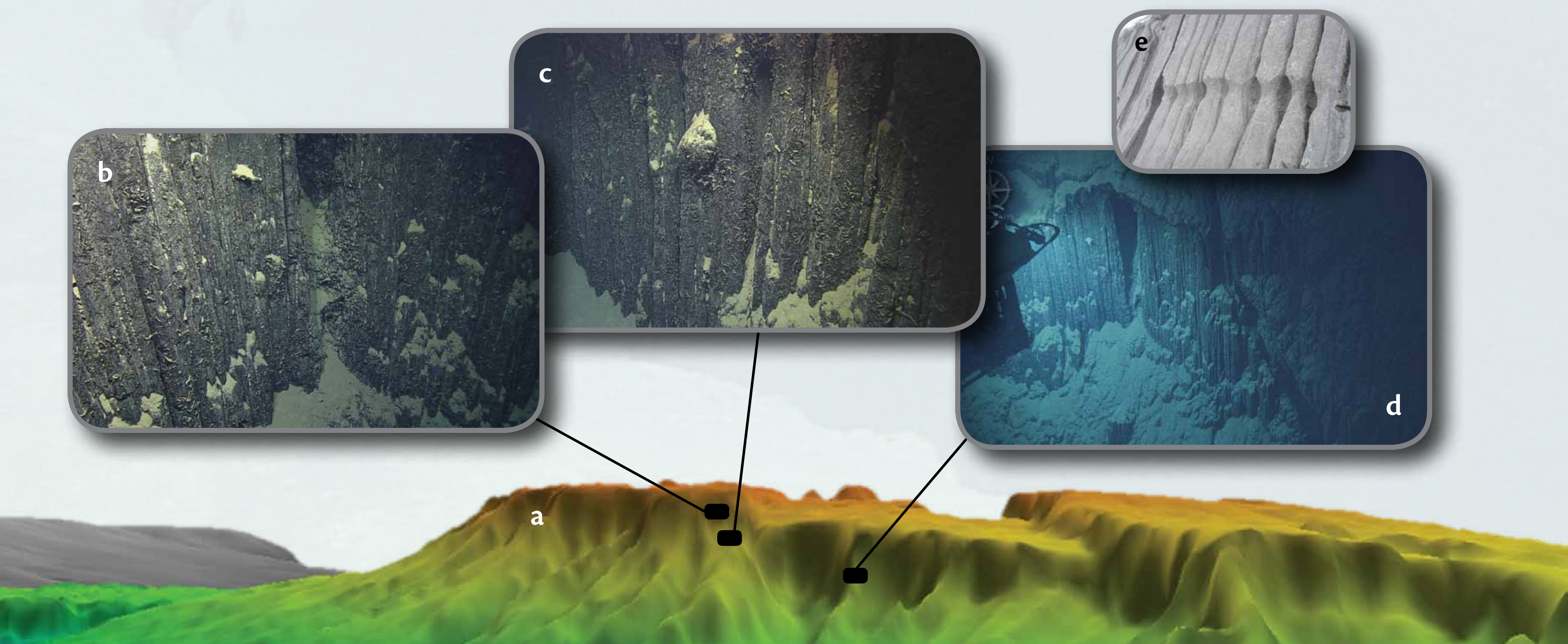


Figure 10. (a) Location of the karren karst morphology found along the steep gradient of the southeast flank of Eratosthenes Seamount. (b–d) Various images of observed karren on the seamount. (e) A terrestrial analogy. Image from http://www.geographie.unistuttgart.de/exkursionsseiten/Alpen2007/index.php?page=32

Finally, we reconfigured the mapping sensors on *Hercules* to survey the vertical fault wall where slickensides had been found in 2010. This fine-scale, high-resolution survey detailed the orientation of the slickenside grooves in the face of the outcrop; the results will be used to make a micromosaic for later tectonic analysis (Figure 12). Given that Eratosthenes Seamount is the only known continental fragment currently being subducted, mapping the observed faults and slickensides may provide new insights into continental accretion (Galindo-Zaldívar et al., 2001).

Summary

Exploration of Eratosthenes Seamount has provided a detailed view of remarkable submerged karst landscape containing fossilized corals, phosphorized whale bones, and numerous circular carbonate dissolution features. We found a far-ranging, depth-restricted zone of cold seeps associated with chemosynthetic communities on the southeastern flank that probably represents the escape of fluids along a porous layer as the seamount is being subducted at the Cyprus trench. Slickensides on the wall of a fault-bounded fissure on the top of the seamount demonstrate that Eratosthenes Seamount is in an active tectonic environment. The seamount also contains a rich marine archeological record due in large part to its strategic location between Cyprus and North Africa. Our efforts demonstrate how a combination of high-resolution exploration tools and a network of Doctors on Call can rapidly change our understanding of deep-sea features and processes, especially when unexpected discoveries are made. Our voyages are exploration missions—designed to make and document discoveries that warrant further investigation and study. Eratosthenes Seamount has certainly yielded its share of discoveries, and we hope that the community will use them to justify and promote the more detailed studies they demand.

Figure 11. ROV *Hercules* collecting a sample of manganese-coated karren column showing limestone interior.

Figure 12. Laser line image of slickensides on a scarp, indicating past fault movement.

Archaeological Discoveries on Eratosthenes Seamount

By Kelsey Cornwell, Andrei Opaiț, and W. Benjamin A. Ballard

In 2012, E/V *Nautilus* revisited Eratosthenes Seamount in the Eastern Mediterranean Sea. Although the primary motivations for returning to this submerged feature were biological and geological, the 2010 survey also indicated its potential for archaeological exploration (Wachsmann et al., 2011). In 2010, *Nautilus* came across 70 isolated amphorae, 38 of which have been securely identified and dated. Those that have not are either too fragmented or, in some cases, the images were not clear enough to define the vessel accurately. During the 2010 season, two early 19th century shipwrecks were also discovered at the top of the seamount.

Eratosthenes Seamount lies on a crossroads of maritime activity between Egypt and Cyprus (Wachsmann, 1986), the Levant and the Aegean Sea (Wachsmann, 2008), and the Near East and North Africa (Casson, 1994). Sometimes sailors would jettison cargo in a storm or lose some overboard during a crossing. When these amphorae fell into the sea, they sank to the bottom and stayed in place unless disturbed by strong currents or deep-sea trawling. The low sedimentation rate on Eratosthenes Seamount allowed us to find these amphorae hundreds to thousands of years later.

During the 2012 season, while using remotely operated vehicles to explore the geological and biological aspects of Eratosthenes Seamount, the *Nautilus* exploration team also discovered 149 new isolated artifacts and one 4th to 5th century BCE amphora shipwreck (Figure 1). Of the newly found amphorae and pottery, 91 artifacts have been identified, ranging from the mid second millennium BCE (Figure 2) to the 14th century CE (Figure 3). The set of artifacts consists primarily of amphorae, but several cooking pots and other wares were also found. The vessels also vary widely in origin, though, not surprisingly, the Levantine area of production dominates the assemblage (such as Persian, an abundance of Phoenician, possible Canaanite, and Gazan). We also identified vessels from the Aegean Sea (Rhodian, Chian, Koan, Knidian, Cretan) and Egypt, and there are many different Roman era amphorae (LRA 1, LRA 4, LRA 5/6). Other vessels were identified as Punic, and one was from Tripoli. The geochronology of these artifacts illustrates the range of maritime traffic that traversed this area over millennia.

We plotted the distribution of known isolated artifacts on a bathymetric map of Eratosthenes Seamount

Figure 1. Eratosthenes C shipwreck holds a diverse but scattered amphorae collection.

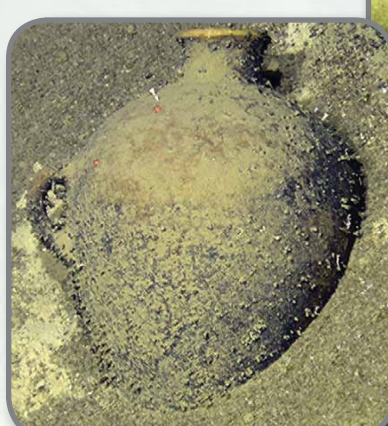


Figure 2. Possible Canaanite Jar (2000–1600 BCE). Red laser dots are 10 cm apart.

Figure 3. Byzantine amphora (ca. 14th century CE).

(Figure 4). The colors on the map signify the time period of the amphorae. The shapes denote the geographic region of origin for each amphora type. The cluster of eight green squares farthest to the west is Rhodian amphorae considered to be a single event, maybe a shipwreck, though no evidence of such a wreck was found in a thorough *Nautilus* survey of the area. Nonetheless, the high frequency of identical amphorae would indicate some sort of single event where the cargo was jettisoned quickly in one area. Green denotes the first time period (100 BCE–100 CE) when all three regions are represented (i.e., Near East, Greece, and Rome)—which is not surprising because it was during this period that traffic from the West began to traverse these waters.

It is interesting to note that green and blue are the only colors representing time periods (spanning 100 BCE–400 CE) that contain amphorae from Greece, Rome, and the Near East. Prior to that time period, we only encountered vessels from Greece and the Near East, and after 400 CE, the vessels are all Roman. The broad distribution of purple circles suggests that the Romans and Byzantines covered a wide area in this region by 400–800 CE. Again, while this was suspected, the data from the small area covered during these surveys support this hypothesis.

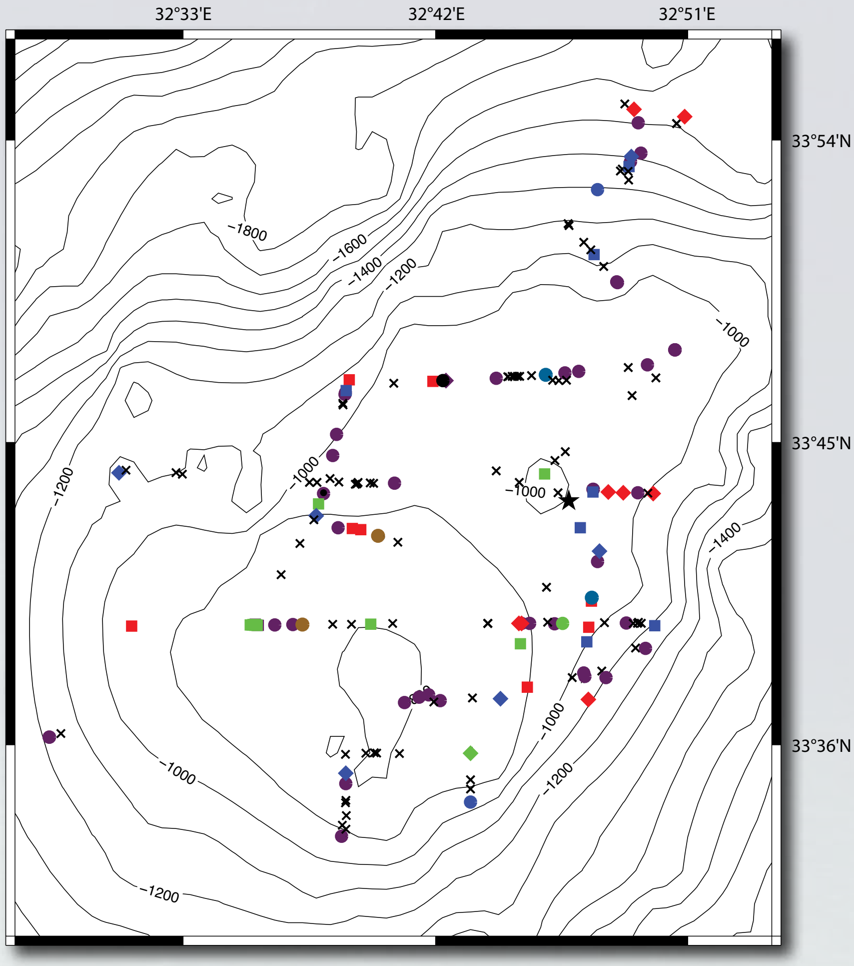


Figure 4. Bathymetric map of Eratosthenes Seamount with the distribution of isolated artifacts plotted. Shapes represent amphorae from different regions: circles = Roman, squares = Greek, diamonds = Near Eastern. Colors represent time periods: orange circles = Pre-1000 BCE, red = 800–100 BCE, green = 100 BCE to 100 CE, blue = 100–400 CE, purple = 400–800 CE, black circles = Byzantine, teal circles = post-1000 CE. The black star indicates the approximate location of the Eratosthenes C wreck, and black x's represent unidentified amphorae.

Archaeologists and ceramists continue to examine the newly discovered shipwreck, whose initial dating to 4th to 5th century BCE is based on the artifact types found on this site. The wreck site is spread out over a large area, with roughly 100 artifacts visible on the surface scattered over an area of nearly two square kilometers. Where many ancient wrecks in the Mediterranean consist of a massive heap of amphorae that outlines the dimensions of the ship, this site consists of two smaller cargo piles at either end. The collection of artifacts is diverse, including cooking wares, bowls, multiple amphorae types, two large intact pithoi (wide-mouthed earthenware jars), little metal "teeth" sticking out of the seafloor, two T-shaped metal features, and an artifact that may be an iron chest.

This is not the first time that open water trade routes have been mapped through amphorae and shipwrecks found on the seafloor. Over 20 years ago, archaeologists observed trails of amphorae on Skerki Bank between Rome and Carthage, called "Amphora Alley I and II," which are now considered strong evidence for the presence of maritime trade routes north of Skerki Bank (Ballard et al., 2000; McCann and Oleson, 2004). It is possible that a comparable scenario is evident on Eratosthenes Seamount. Based on ancient literature and cultural remains, we know that ancient peoples navigated the entire Eastern Mediterranean. The recent discovery of these numerous isolated amphorae provides additional information about the routes those mariners may have sailed. Although more area of the seamount needs to be explored before any firm conclusions can be drawn, it is evident that ancient mariners braved the open waters of the Eastern Mediterranean far from shore.

Exploration of the Santorini Volcanic Group, South Aegean Sea, Greece

By Steven N. Carey, Paraskevi Nomikou, Katherine L.C. Bell, and Robert D. Ballard

Perhaps one of the best known volcanoes in the Mediterranean Sea, Santorini has been the site of numerous large-scale explosive eruptions during the last 360,000 years (Figure 1; Druitt et al., 1999). The Minoan eruption of Santorini (Thera) volcano in the Late Bronze Age, about 1600 BCE, is one of the largest volcanic eruptions in the historical age. This event has remained of great interest to geologists, historians, and archaeologists because of its possible impact on the Minoan civilization in Crete and on the Cycladic islands, which was at its peak at the time of the eruption and subsequently went into a steep decline. Recent interest in Santorini has focused on new GPS measurements collected within the caldera that indicate inflation and the possibility of renewed activity (Newman et al., 2012; Parks et al., 2012). The area is a popular tourist destination, with over 1 million people visiting the island every year. Consequently, a detailed understanding of Santorini volcano is essential for effective hazard evaluation and mitigation.

Santorini is part of a larger tectonic/volcanic complex that generally trends southwest-northeast over a distance of 45 km and includes the island of Christianna and numerous submarine volcanoes in the Northeast Anhydros basin (Figure 2; Nomikou et al., 2012b,c). *Nautilus* has conducted several expeditions throughout this complex that have led to important new insights into the volcanic hazards, eruptive processes, and hydrothermal mineralization within this active zone. These marine studies complement the extensive land-based research that has been carried out on Santorini and provide a more integrated view of this complicated geodynamic environment.

Santorini Caldera

The caldera of Santorini volcano formed as a result of a series of collapses associated with large explosive eruptions that drained shallow crustal magma chambers (Druitt et al., 1999). Currently, the central part of the caldera is occupied by two islands, Nea Kameni and Palea Kameni, built by repeated post-Minoan (3,600 years before present)

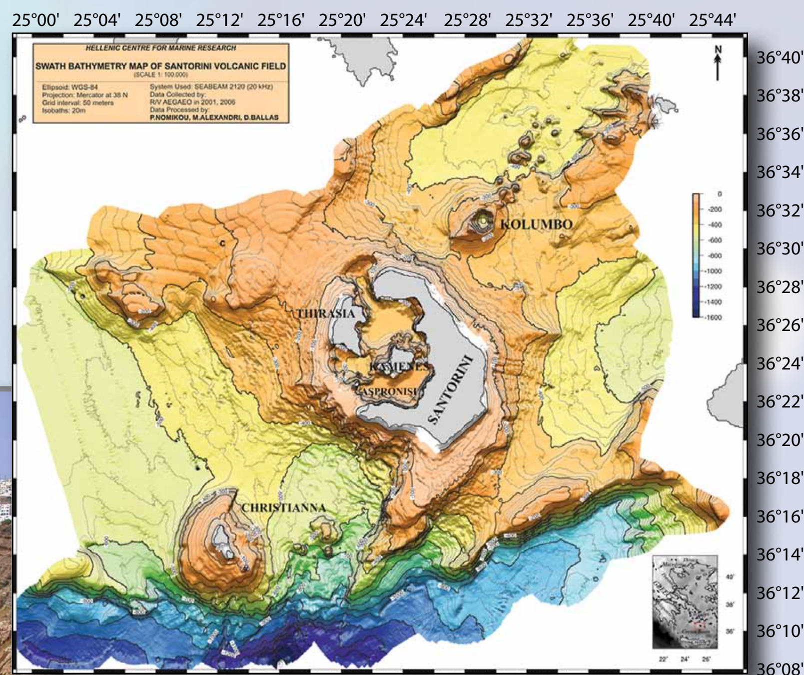


Figure 2. Swath bathymetric map of the Santorini volcanic field from Nomikou et al. (2012b).

Figure 1. View of Santorini's caldera wall showing layering produced by explosive volcanic eruptions.

lava flows and minor explosive activity (the last eruption was in 1950; Figure 3). We explored selected areas of the caldera during cruise NA014 to search for evidence of hydrothermal activity and to investigate the northern submarine portions of Nea Kameni Island where there is the possibility of new eruptive activity (Bell et al., 2012). Yellowish bacterial mounds up to one meter in height and a few meters in diameter spread over an area of about 200 to 300 m on the northern part of the caldera floor provided evidence of active hydrothermal venting (Figure 4; Sigurdsson et al., 2006a). Temperature measurements at the top of the vents indicate discharge of clear fluids up to 5°C above the ambient seawater. The position of this vent field, in line with a fault system that extends northeast from Santorini to the submarine volcano Kolumbo just offshore of Thera, is likely controlling the pathways of hydrothermal circulation within the caldera (Nomikou et al., 2012c).

ROV exploration near Nea Kameni Island revealed a rugged underwater terrain dominated by lava flows, dikes, and volcanic rock debris forming relatively steep slopes on the northern margin (Figure 5). A transect in the area between the east side of Nea Kameni and the town of Fira, where increased seismicity was recorded in 2012, encountered a hummocky region with a small flat-topped bathymetric rise. At its summit, the survey revealed a minor crater filled with shimmering water up to 25°C above ambient. We could not, however, precisely locate the source of venting. High-resolution mapping combined with ROV dives have enabled us to better define the extent of historic lava flow eruptions in the Santorini caldera and to more precisely determine their volumes.

Kolumbo Submarine Volcano

1650 AD ERUPTION

The largest of the submarine volcanic cones that extend into the Anhydros basin (Figure 2) is located northeast of Santorini. Lying only 7 km off the northeastern coast, Kolumbo is an elongated volcano with a 1.7 km diameter crater rising to within 18 m of the surface (Figure 6; Nomikou, 2003). In 1650 CE, the volcano erupted explosively, breaking the surface and causing about 70 fatalities on Santorini from toxic gases. Destructive tsunamis were also produced during the eruption, carrying away livestock, destroying buildings, and eroding roadways and 500 acres (2 km^2) of the eastern Santorini coastline (Fouqué, 1879; Dominey-Howes et al., 2000; Nomikou et al., 2012a).

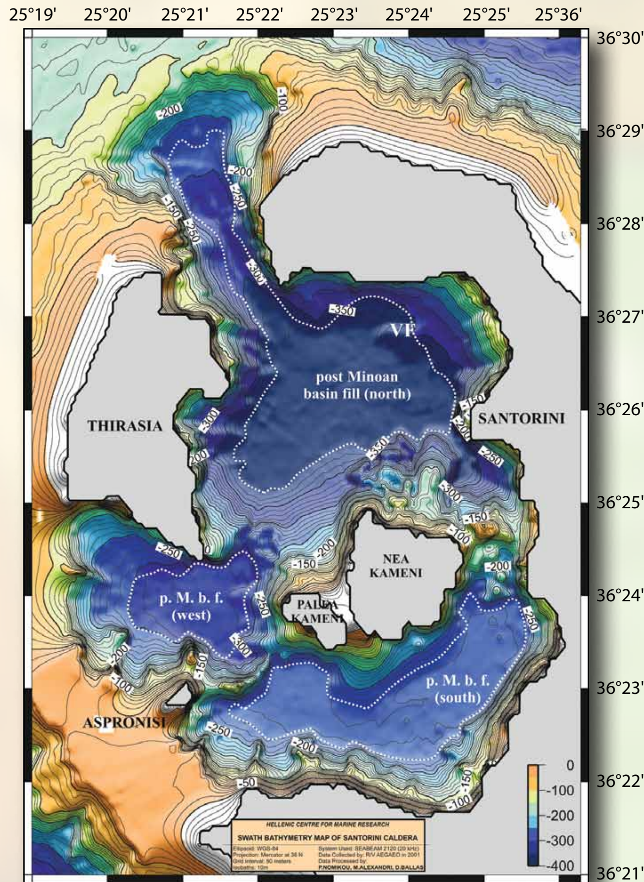


Figure 3. Swath bathymetric map of Santorini caldera using 10 m isobaths. Three post-Minoan caldera subbasins are indicated (bordered with dotted lines with varying depths: 350 m in the north, 280 m in the south, and 320 m in the west; Nomikou et al., 2012c). VF corresponds to the location of the low temperature vent field discovered in the northern part of the caldera.

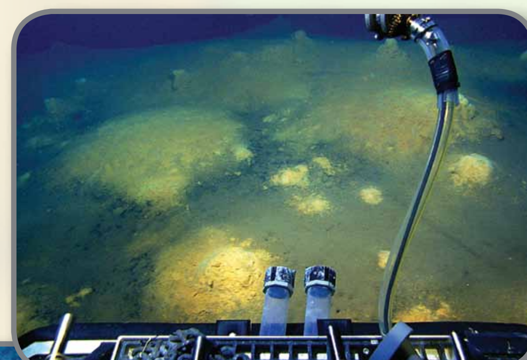


Figure 4. Field of low temperature bacterial mounds on the northern floor of the Santorini caldera at 340 m depth.

Figure 5. ROV sampling of lava flow outcrop on the northeast side of Nea Kameni Island inside Santorini's caldera.

ROV explorations of the crater wall during cruise NA007 revealed a remarkable undersea landscape composed of stratified pumice deposits created during the 1650 CE eruption. Transects down the crater wall showed that at least 200 m of loose pumice and ash form vertical outcrops that are similar to the subaerial cliffs exposed in the caldera wall of Santorini (Figure 7). Geochemical analyses of pumice samples indicate that the event produced relatively uniform gas-rich rhyolite magma that was erupted at a temperature of ~ 750°C (Cantner, 2011).

Kolumbo's undersea pumice cliffs are the first places where the deposits from a historical, well-documented submarine explosive eruption could be studied in situ. Details of the layering were observed using the high definition video camera on *Hercules*, providing data for interpreting the sequence of the underwater phase of the eruption (Cantner, 2011). The explosive eruption began at a depth as great as 500 m and built layers of pumice that eventually formed an ephemeral island. During the later stages of the eruption, energetic plumes of hot gas, pumice, and ash were ejected into the atmosphere, leading to adverse effects on Santorini and neighboring islands. Recent estimates of the total erupted volume based on the great thickness of inferred Kolumbo submarine pyroclastic flow deposits in the Anhydros basin suggests a 5 km^3 bulk volume or about 2 km^3 dense rock equivalent (Nomikou et al., 2012a). Kolumbo remains a significant threat to the region as shown by the high concentration of recent seismicity in the area and the discovery of a potential magma chamber beneath the volcano at a depth of about 5 km (Bohnhoff et al., 2006; Dimitriadis et al., 2010).

HYDROTHERMAL VENT SYSTEM

In 2006, an extensive hydrothermal vent system was discovered on the crater floor of Kolumbo at 500–505 m depth (Sigurdsson et al., 2006a). The first indication of venting was the appearance of white bacterial-laden streams on the northeast floor of the crater (Figure 8). These streams led to numerous active and inactive chimneys that occupy an area approximately 200 m by 260 m. Additional ROV exploration of the vent field took place during cruises NA007, NA011, and NA014 (2010–2011). Mapping and photomosaicking of the vents revealed their detailed shape and distribution (Roman et al., 2012). The chimneys are generally of two different morphologies. The majority are irregularly shaped, rather lumpy or trunk-like, and usually several meters high and several meters across

Figure 7. Stratified pumice outcrop along the crater wall of Kolumbo submarine volcano (from Carey et al., 2011).

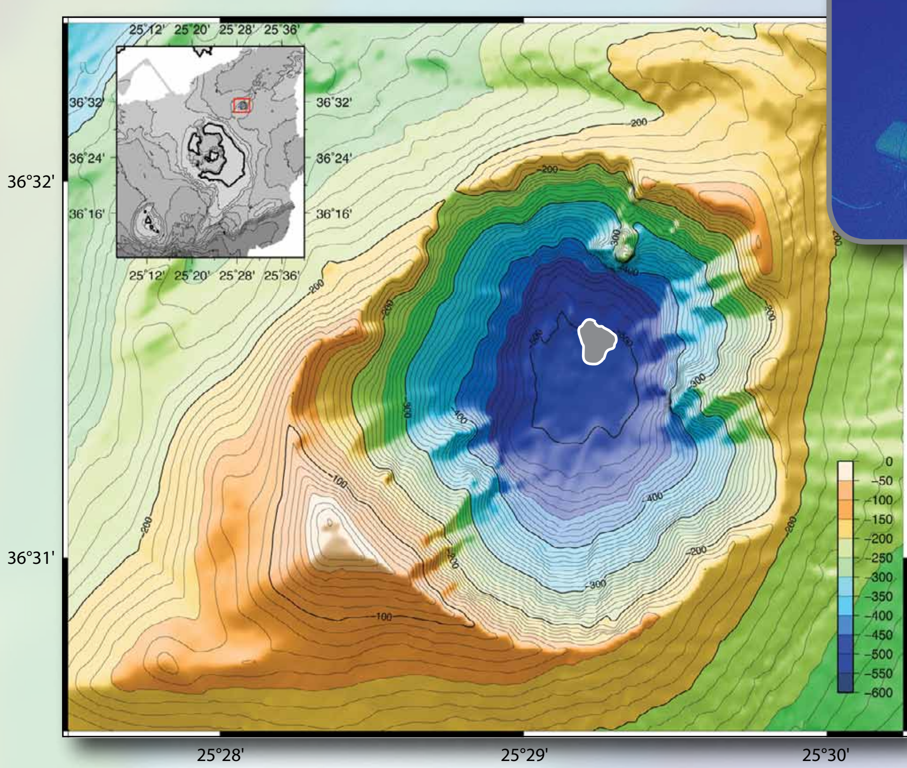


Figure 6. Swath bathymetric map of the Kolumbo submarine volcano, northeast of Santorini (after Nomikou, 2003). Location of the active hydrothermal vent field is shown by the gray shaded area in the northern part of the crater floor at 500 m depth.

at their bases (Figure 9). They can occur individually or in small groups. Their growth appears to have been highly irregular, with branches growing off both the tops and the sides. The maximum fluid temperatures recorded at these types of vents was 220°C. The second principal type of chimney consists of clusters of narrow, individual spires that are tall relative to their width. They are also a meter to several meters high but only tens of centimeters wide (Figure 10). The sides of these chimneys were covered with spectacular blue/gray, white, and yellow bacteria that gave the surface the appearance of velvet. In general, there was a surprising lack of macrofauna in the areas around the active and inactive vents or on their surfaces.

Samples of the vent chimneys show that they consist of a large variety of sulfate and sulfide minerals, including pyrite, galena, sphalerite, As-sulfides, anhydrite, and barite (Figure 11; Sigurdsson et al., 2006b; Kilias et al., 2011). The bulk chemistry is enriched in Au, Ag, As, Sb, and Pb relative to more common black smoker vents found at mid-ocean ridges. This chemistry reflects both their association with highly evolved rhyolite magma and their presence in an environment where continental crust is being subducted. It bears many similarities and differences to Kuroko-style volcanic-hosted massive sulfide deposits around the Pacific margin that have significant economic value (Glasby et al., 2008).

CARBON DIOXIDE

Many of the hydrothermal vents on the floor of Kolumbo's crater emit streams of gas bubbles (Figure 12). On cruise NA007, gases were sampled using pressure-tight containers. Shore-based analyses show that the gases are composed almost exclusively of CO_2 with only very minor amounts of methane. Carbon dioxide discharge is common at other submarine volcanoes and hydrothermal systems in subduction zone environments (e.g., Lupton et al., 2006, 2008). At Kolumbo, the water depth in the crater (500 m) and temperature of discharge fall in the range of CO_2 gas stability.

The bubble plumes rising from the vents were imaged using a BlueView multibeam system on *Hercules* (Roman et al., 2012). At about 10 m above the vents, the bubbles disappear and are likely dissolving into the surrounding seawater. Carbon dioxide dissolution increases the water density and lowers the pH. The crater of Kolumbo forms an isolated bowl, and thus it is likely that the CO_2 discharge is being sequestered in the deeper part and making

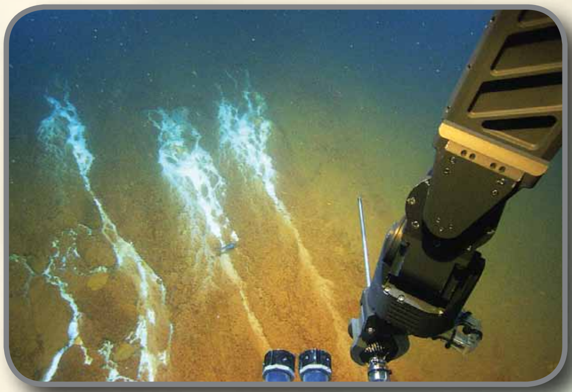


Figure 8. Streams of bacteria-rich fluid flowing along the crater floor of Kolumbo submarine volcano (water depth 500 m).

Figure 9. Massive sulfide hydrothermal vent on the floor of Kolumbo submarine volcano (water depth 500 m).

Figure 10. Spire-type hydrothermal vents on the crater floor of Kolumbo submarine volcano (water depth 500 m).

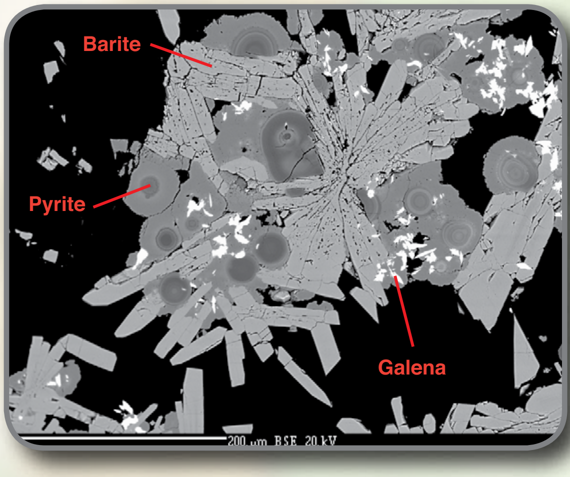


Figure 11. Scanning electron microscope photomicrograph of hydrothermal vent sample from Kolumbo submarine volcano.

conditions acidic (recent work of author Carey and colleagues). Evidence for this circumstance lies in the lack of macrofauna on the Kolumbo vents and the carbonate-poor nature of the bottom sediments collected by the ROV.

To further investigate the nature of the crater's water on cruise NA014, samples were collected in a vertical profile using Niskin bottles and pressure-tight containers. The profile indicates a pH of about 8 at 100 m depth, decreasing to a pH of below 5 near the bottom of the crater (Figure 13). Degassing of CO_2 at Kolumbo has thus produced a natural experiment in ocean acidification that provides opportunities to study the impacts on biological communities and seawater chemistry. In addition, water samples collected in pressure-tight containers discharged CO_2 at the surface when the pressure was reduced to atmospheric levels. This indicates the potential for surface gas release of CO_2 if the deep crater water overturns. Mechanisms that would cause overturning include saturation of the bottom water with CO_2, an increase in water temperature if Kolumbo enters a new phase of eruptive activity, or increased seismic activity. Currently, the CO_2 content of the bottom is well below saturation levels at 500 m water depth.

Northeast Submarine Cones

Further to the northeast of Kolumbo, there is a linear field of 19 other submarine cones that generally decrease in size away from Santorini (Figure 14). Many of these cones were explored during cruise NA007 to search for evidence of recent activity or hydrothermal mineralization. Seismic profiling data indicate that the linear distribution of the volcanic cones is controlled by strike-slip faults that run parallel to the long axis of the basin (Sakellariou et al., 2010; Nomikou et al., 2012c). This transtensional zone has provided pathways for subduction-generated magmas to reach the surface. ROV exploration of 11 cones in the northeast field found that in general there was a lack of fresh outcrops and that the majority of the centers were covered to varying degrees with several to tens of centimeters of brownish gray hemipelagic sediment (Carey et al., 2011; Nomikou et al., 2012b). Outcrops of volcanic rock were found in the crater walls and slopes of some of the cones, but they typically consisted of volcanic fragments of pumice and lava cemented together by biological activity, indicating a lack of recent eruptive activity. The sedimentary cover around most cones varies somewhat locally, with fine-grained material at the base of the slopes that typically becomes coarser with scattered lapilli, small pumice rocks, and talus toward the upper slopes and summits. We found evidence of low-temperature hydrothermal activity on two of the cones in the form of manganese oxide deposition on sediments and outcrops. One cone had several areas of black coloration, particularly where fracturing had exposed vertical outcrop faces. These areas were also associated with concentrations of bivalve shells, suggesting seepage of

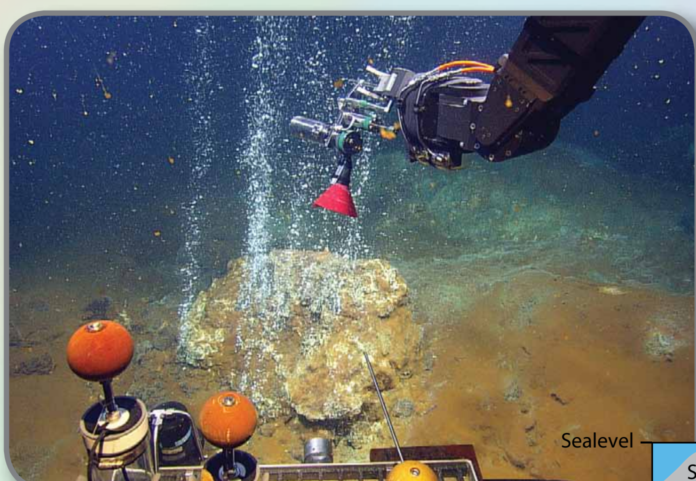


Figure 12. ROV sampling of gas bubbles from a hydrothermal vent on the crater floor of Kolumbo submarine volcano (water depth 500 m).

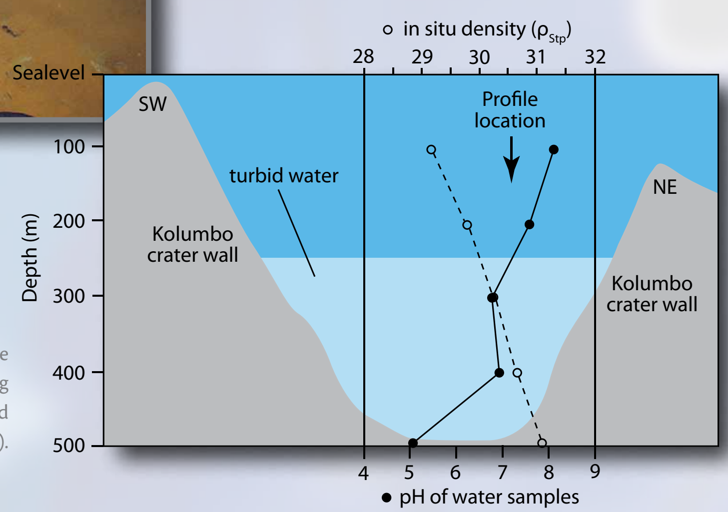


Figure 13. Water sampling profile in the Kolumbo crater showing gradients in pH (solid circles) and density (open circles).

fluids from depth in the sediment. More significant areas of black deposits were found on many parts of another cone in small depressions and along channels that were oriented perpendicular to the local bathymetry (Figure 15). Samples of the black sediment within the channels found biogenic and volcaniclastic sediments that were encrusted with manganese oxide overgrowths exhibiting concentric mineral zonation in small globular form (Figure 16). Research indicates that manganese oxide deposition in subduction zone volcanoes is related to low-temperature hydrothermal circulation (e.g., Usui et al., 1988; Frank et al., 2006).

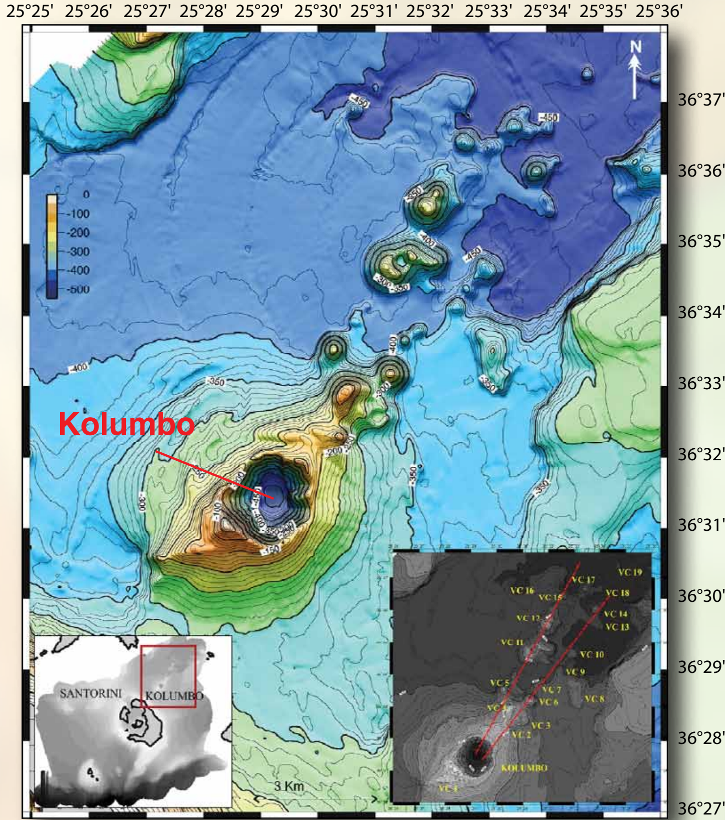


Figure 14. Swath bathymetric map of the submarine volcanoes northeast of Santorini. *After Nomikou et al. (2012b)*

Summary

The Santorini islands in the Aegean Sea have long been the focus of geological and archaeological interest based on their importance to the history of natural disasters and cultural evolution in the Eastern Mediterranean area. New explorations by E/V *Nautilus* of the marine environment surrounding the islands have added compelling new dimensions to the wealth of land-based studies. It is now known that an economically significant massive sulfide deposit lies in relatively shallow water in the crater of Kolumbo submarine volcano. Only a handful of these types of deposits have been documented throughout the world ocean. From a volcanic hazards perspective, the new explorations have also provided critical information about the potential location of future eruptive activity in Santorini caldera, the types and scales of hazardous processes associated with the Kolumbo submarine volcano, and the relative activity potential of the numerous submarine centers northeast of Santorini. All of these results combine to form a deeper understanding of this complex volcanic system and serve to better evaluate the environmental and societal impacts of future eruptions of Santorini and Kolumbo volcanoes.

Figure 15. Trails of low-temperature hydrothermal seeps with manganese oxide deposition on a submarine cone northeast of Kolumbo submarine volcano. *After Nomikou et al. (2012b)*

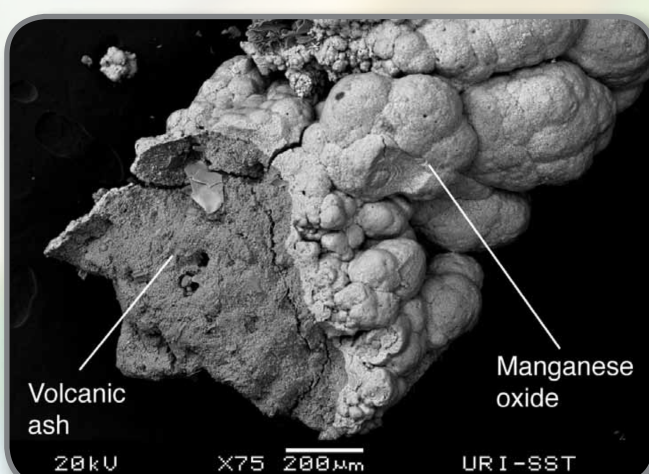


Figure 16. Scanning electron microscope photograph of manganese oxide deposition on volcanic ash particles from the Northeast Kolumbo volcanic chain of the Santorini volcanic field. *After Nomikou et al. (2012b)*

WORKSHOP ON TELEPRESENCE-ENABLED EXPLORATION OF THE CARIBBEAN REGION

By Katherine L.C. Bell, Michael L. Brennan, Peter Girguis, James A. Austin Jr., Steven N. Carey, Dwight F. Coleman, Larry Mayer, Robert D. Ballard, Catalina Martinez, and Craig Russell

In November 2012, the Ocean Exploration Trust, in partnership with the NOAA Office of Ocean Exploration and Research, hosted a workshop in Miami, Florida, where members of the scientific community identified and discussed potential targets for telepresence-enabled exploration in the Caribbean Region, including the southeastern Gulf of Mexico.

BACKGROUND

The Workshop on Telepresence-Enabled Exploration of the Caribbean Region is the fourth in a series of workshops that have been held in response to recommendations by four executive and congressional panels:

- *Discovering Earth's Final Frontier: A US Strategy for Ocean Exploration*, Ocean Exploration Panel, 2000
- *Exploration of the Seas: Voyage into the Unknown*, National Academy of Sciences, 2003
- *An Ocean Blueprint for the 21st Century*, US Commission on Ocean Policy, 2004
- *Final Recommendations of the Interagency Ocean Policy Task Force*, Interagency Ocean Policy Task Force, 2004

Photo Credit: NOAA *Okeanos Explorer* Program

A common recommendation throughout these reports is that the United States should be a leader in ocean exploration—striving to increase scientific understanding of the ocean and including public outreach and education as an integral component of a national ocean exploration program.

In response to these recommendations, the NOAA Ship *Okeanos Explorer* and Exploration Vessel *Nautilus* came online as two national platforms dedicated to ocean exploration. Since 2007, community input has been solicited to assist in shaping these budding national exploration programs by holding a series of workshops that so far include:

- Technological Requirements for *Okeanos Explorer*, Monterey Bay Aquarium Research Institute, 2007
- Priority Areas for Exploration in the Pacific Ocean, National Geographic Society Headquarters, 2007
- Priority Areas for Exploration in the Atlantic Ocean, University of Rhode Island Graduate School of Oceanography, 2011
- Priority Areas for Exploration in the Caribbean Region, Miami, 2012

Fifty scientists and program staff from nine countries and territories participated in the Caribbean workshop. Their goals were to:

- Identify key priority areas for exploration for *Nautilus* and *Okeanos Explorer*
- Engage scientists with a broad range of expertise through real-time interaction with the ships during field programs
- Develop education and outreach programs as integral parts of exploratory missions in this region

Telepresence capabilities will enable us to work with partner countries to foster real-time interaction by their research communities and stakeholders, and to open opportunities for engaging the next generation of regional scientists. Because of the possibility for live access to field programs, we expect that participating regional scientific communities will generate broader public support for and interest in exploration of the Caribbean region.

IDENTIFYING HIGH-PRIORITY TARGET AREAS

There were two breakout sessions in the Caribbean workshop. The first consisted of three disciplinary groups—biology, geology, and archaeology. The primary goal of the discipline-based discussions was to identify major Caribbean-wide questions that span multiple regions—for example, the biogeography of deep reefs, regional tectonics, trade routes—that can be answered through telepresence-enabled exploration. A secondary goal was to identify areas and transects that should be explored to answer key questions identified within the realms of biological, geological/physical, and archaeological oceanography that span the Caribbean region (Figure 1).

Workshop participants overlaid these areas/transects on a map of the Caribbean and identified six overlapping priority areas to be discussed in further detail (Figure 2). On the second day, participants regrouped according to geography—northwest, mid, and southeast Caribbean—to further narrow down exploration target areas in each of the six priority areas. The groups were asked to identify six to 10 high-priority target areas in each of their regions that address the key questions identified in the first breakout sessions, have high potential for discovery, apply available technologies appropriately, are multidisciplinary in nature, have high potential for education and outreach activities, and are politically feasible.

The final result is a list of 20 high-priority target areas that will be considered by the Ocean Exploration Trust and the NOAA Office of Ocean Exploration and Research when identifying areas to explore in the Caribbean region in the coming years.

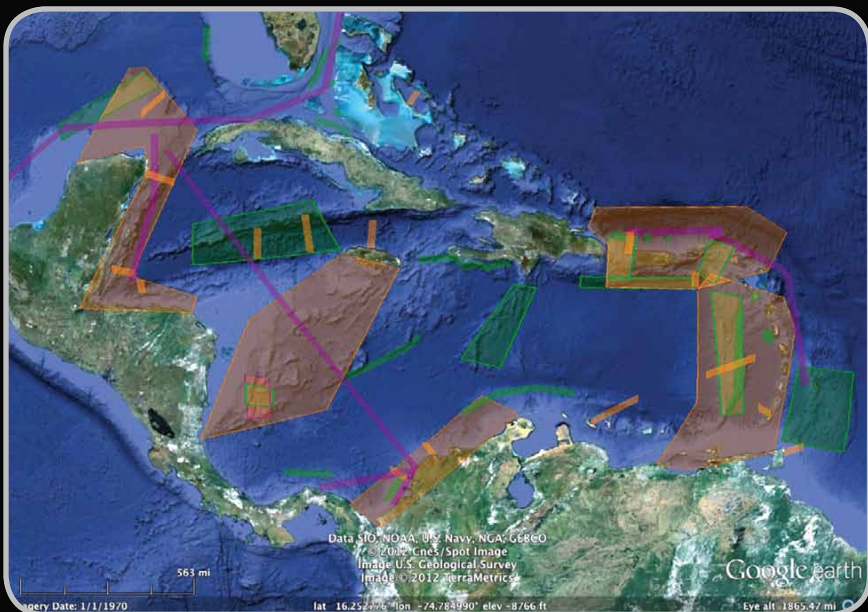


Figure 1. Composite map of the Caribbean region, including the southeastern Gulf of Mexico, showing the areas of interest identified by the biology (orange), geology (green), and archaeology (purple) breakout groups.

Figure 2. Priority areas identified for the region-based breakout sessions. The northwest group focused on the Yucatán Peninsula and Florida Straits to the Bahamas (yellow), the mid-Caribbean group on Cayman Rise and the Greater Antilles (red), and the southeast group on the Caribbean Basin and Lesser Antilles (blue).

GEOLOGY

The geology breakout group examined overarching geological and physical oceanographic questions in the Caribbean region that could be addressed by ocean exploration. The key geological and physical oceanographic questions for the Caribbean identified by the breakout group were:

- GQ-01: What are the routes and volumes of Atlantic inflow into the Caribbean, and how do they influence biodiversity?
- GQ-02: What is the relationship between Antarctic Bottom Water and North Atlantic Deep Water in the Puerto Rico trench?
- GQ-03: What is the origin and nature of the formation and erosion of steep escarpments in the Caribbean?
- GQ-04: What is the nature of slope failure of carbonates and volcaniclastics in the Caribbean, and what is the relationship of these failures to tsunamigenesis?
- GQ-05: What is the nature of faulting in the Caribbean, including offshore expression of onshore faults, activity, and relationship to degassing?
- GQ-06: What is the nature of active volcanism and venting in the Caribbean, including their relationships to natural hazards and benthic communities?
- GQ-07: What is the distribution of mud volcanoes, cold seeps, and vent communities in the Caribbean?
- GQ-08: What is the nature of deformation in the Caribbean?
- GQ-09: Where are the least studied, least known areas of the Caribbean that are prime targets for exploration?

The full report of the Caribbean workshop and a database of white papers and high-priority target areas can be accessed at:

http://www.oceanexplorationtrust.com/#!2012-caribbean-workshop/cg3o.

The Caribbean region is a complex geologic and physical oceanographic environment that contains numerous current and past plate boundaries juxtaposed in a small but highly productive geographic area. The intense tectonic activity has resulted in a combination of faulting and carbonate platform growth that has produced some of the steepest escarpments known in the world ocean. Associated with these escarpments are slope failure and the great potential for tsunamigenic events in a highly populated region. Additionally, the presence of active volcanism makes the existence of exotic vent communities likely and increases the potential for geohazards associated with volcanism. From a physical oceanographic perspective, the Caribbean is a region of very constrained inflow of Atlantic waters through mostly shallow passages as well as a region of confluence of North Atlantic Deep Water and Antarctic Bottom Water. The combination of these features all in a relatively small geographic area makes the Caribbean region ideal for an ocean exploration program.

BIOLOGY

Photo Credit: NOAA
Okeanos Explorer Program

The biology group set out to develop a list of key questions that represent issues relevant to many ecosystems. These questions naturally fell into four themes:

- BQ-01: What is the nature and extent of deep-sea soft-bottom, hard-bottom, coral, seep, and vent communities?
- BQ-02: What is the relationship between chemical, physical, and biological processes in the shallow and deep ocean?
- BQ-03: To what degree are these communities connected, and how do oceanographic processes and anthropogenic activities influence this connectivity?
- BQ-04: What are the kinds of data that we need to develop a better capacity to predict the location and apparent health of deep-sea ecosystems, including their responses to anthropogenic activities such as increasing atmospheric CO_2?

Participants noted that there remains a paucity of fundamental data in many regions of the Caribbean and southeastern Gulf of Mexico. They also noted that, in general, there is substantially more known about the central and northern Gulf of Mexico, largely due to the continued research activities of US-based scientists in academia, government, and industry. Data needs led participants to focus on the southeastern Gulf of Mexico and Caribbean regions, in particular, on how the Gulf of Mexico interacts with the Caribbean, and how that interaction ultimately influences the ecology and evolution of both mid-water and benthic communities. There was great interest in generating additional physical and geochemical information that will enable the broader community to develop predictive models on where benthic communities might be located.

ARCHAEOLOGY

The archaeology breakout group included members of both ship operations and science teams and archaeologists who specialize in research in this area. The Caribbean region holds great potential for discovery of archaeological sites, as it has been a highly active area for maritime traffic since the colonial period. Therefore, it is probable that shipwrecks will be encountered during exploration anywhere in the region, and explorations teams should be prepared to:

- Handle politics and permits with appropriate coastal states
- Have a team of archaeologists ashore linked to the ships via telepresence and prepared to document, characterize, and identify sites
- Develop a standard operating procedure to protect the locations of archaeological sites with potentially sensitive materials
- Tailor outreach efforts to the general public to enhance understanding of archaeological sites, history, methods, and ethics

To address the larger issue of how to respond to archaeological sites discovered during expeditions, the group turned to the example of the copper shipwreck located in the Gulf of Mexico and explored by *Okeanos Explorer* in the spring of 2012. Although this was a target effort on a suspected wreck site, the paradigm of having the science team ashore was an effective way of accommodating an archaeological team “on call” for unexpected finds.

Photo Credit: NOAA
Okeanos Explorer Program

HIGH-PRIORITY TARGET AREAS

Twenty high-priority target areas were identified by the region-based breakout discussions.

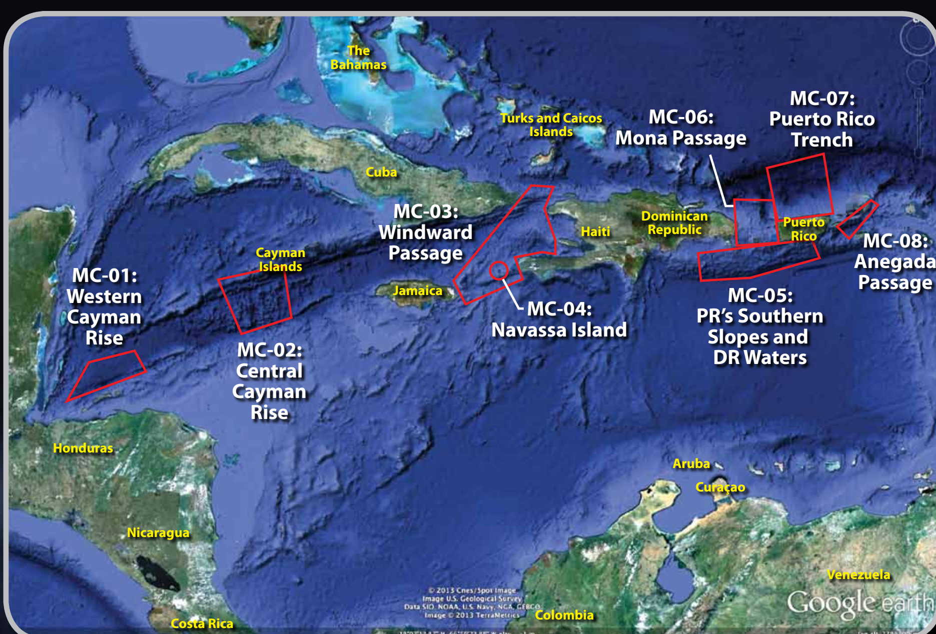
MID-CARIBBEAN

MC-01: WESTERN CAYMAN RISE has extremely steep walls associated with the Oriente Fracture Zone where very deep water rises to very shallow levels. It could be interesting to conduct biological and geological transects upslope to look at biodiversity and geologic structure.

MC-02: CENTRAL CAYMAN RISE expeditions have resulted in the recent discovery of the deepest known hydrothermal vent systems in the world with biological assemblages that resemble both Pacific and Atlantic Ocean vent communities.

MC-03: WINDWARD PASSAGE has deep faults, there is a high likelihood of discovering cultural material, and it is a location for deepwater exchange between the Atlantic Ocean and the Caribbean Sea.

MC-04: NAVASSA ISLAND is a US territory whose waters have never been explored. It lies within the US Exclusive Economic Zone in the Windward Passage. Strong currents exchange water between the Atlantic Ocean and Caribbean Sea here, and there is good potential for studies of deep habitats, cultural heritage, and deep plate boundary faulting.



MC-05: PUERTO RICO'S SOUTHERN SLOPES AND DOMINICAN REPUBLIC WATERS exhibit complex seafloor morphologies associated with active thrust faulting. The Muertos Trough region of Puerto Rico features microplate subduction, deformed and tilted carbonate platform rocks, and continental crust. Proximity to the Atlantic and Mona Passage offer potential for studying biological connectivity.

MC-06: MONA PASSAGE includes steep escarpments, major faults, and massive slope failures, as well as undiscovered archaeological sites ranging in age from the colonial period to World War II.

MC-07: PUERTO RICO TRENCH is the deepest point in the Atlantic Ocean, with an abundance of scientific problems to pursue, including hadal habitats, residence time of North Atlantic Deep Water, and geohazards related to deep faulting.

MC-08: ANEGADA PASSAGE is the epicenter of an earthquake that occurred in 1867. It is a major connection between Atlantic and Caribbean waters and the seafloor here may contain shipwrecks from the slave trade.

Photo Credit: NOAA *Okeanos Explorer* Program

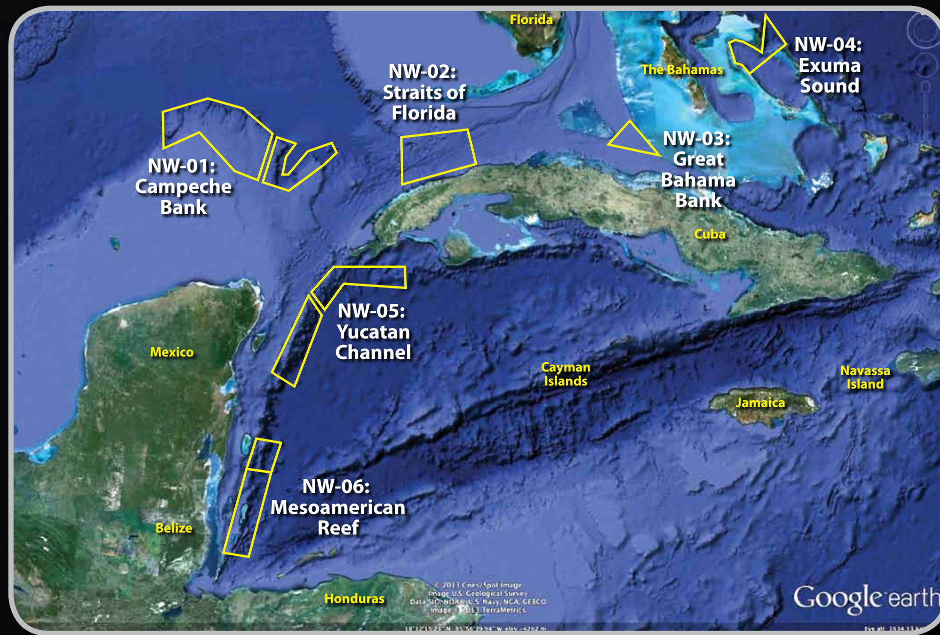
NORTHWEST CARIBBEAN

NW-01: CAMPECHE BANK is interesting for biological, geological, and archaeological reasons. The group proposes vertical transects for biological and geological exploration and horizontal surveys for archaeological exploration. There is particular interest in this region for tri-national collaboration between the United States, Mexico, and Cuba.

NW-02: THE STRAITS OF FLORIDA area includes the western approach to Cuba, one of the least explored regions in this area. The straits are known for powerful currents and are of particular interest for studies of species connectivity between the northern and southern straits, as well as for mass wasting and the potential for tsunamigenesis.

NW-03: GREAT BAHAMA BANK exhibits carbonate structures and multiple slope failures that could lead to tsunamigenesis.

NW-04: EXUMA SOUND hosts a large diversity of vertebrates in deep water, as does Bahama Escarpment, a major hub for British colonization of the islands and where deep water enters from the Atlantic Ocean.



NW-05: YUCATÁN CHANNEL has very strong currents and deep-sea corals that are possibly connected to Bahama Escarpment fauna.

NW-06: MESOAMERICAN REEF is of interest particularly for the study of drowned reefs, deepwater corals, and associated fauna; for possible trade routes along the Yucatán Peninsula; and for strong seasonal currents.

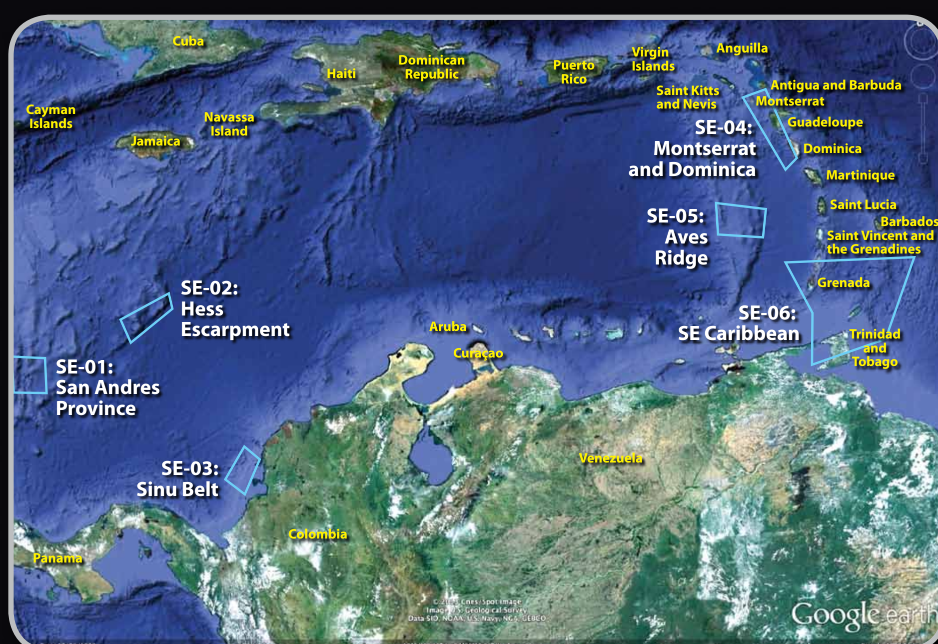
SOUTHEAST CARIBBEAN

SE-01: SAN ANDRES PROVINCE hosts the second longest barrier reef in all of the Caribbean, as well as atolls, inactive volcanoes, and possible shipwrecks from the colonial period.

SE-02: HESS ESCARPMENT is a steep cliff on the southeastern side of the Nicaraguan Rise that is very poorly surveyed.

SE-03: SINU BELT is composed of a compressional area with active mud volcanoes and evidence of chemosynthetic communities, and it may lie on a trade route from Cartagena, Colombia, to other locations in the Caribbean.

SE-04: MONTSERRAT AND DOMINICA are active volcanic islands in the Lesser Antilles that may pose geohazard threats for those living on land and whose volcaniclastic deposits and tectonic activity also impact the seafloor and biological communities.



SE-05: AVES RIDGE in the eastern Caribbean is an unexplored feature that is possibly an extinct volcanic edifice and that likely hosts biological communities related to both the Atlantic and Caribbean.

SE-06: THE SOUTHEAST CARIBBEAN contains Kick'em Jenny underwater volcano, mud volcanoes, and tar seeps, along with biological communities associated with these unique environments.

EPILOGUE

By Robert D. Ballard

The Foreword to this issue briefly recounted the initial four-year history of the Ocean Exploration Trust and its efforts to bring E/V *Nautilus* online as a fully outfitted ship of exploration capable of working in the unexplored regions of the world ocean. *Nautilus*, its Corps of Exploration, and its growing network of remote Exploration Centers across the country and around the world are now ready to meet that challenge.

In this issue, we have presented not only the results of *Nautilus'* 2012 field season but also a summary of its four years of exploration in the Black, Aegean, and Mediterranean Seas from 2009 to 2012.

Recently, the Ocean Exploration Trust, with funding from the Richard Lounsbery Foundation and in collaboration with the NOAA Office of Ocean Exploration and Research, conducted a workshop in Miami, Florida, attended by 50 scientists from nine countries invested in having *Nautilus* carry out a series of exploratory expeditions in the Gulf of Mexico and the Caribbean Sea. The *Nautilus* Science Advisory Board was so impressed with the results of this workshop that the decision was made to spend two to three years in this area before pushing through the Panama Canal to begin exploration of the Pacific Ocean Basin.

As *Nautilus* leaves the Mediterranean in late April 2013, it will begin a multiyear journey of exploration that will take it half way around the world to its eventual goal—exploration of the Western Pacific and Indian Ocean.

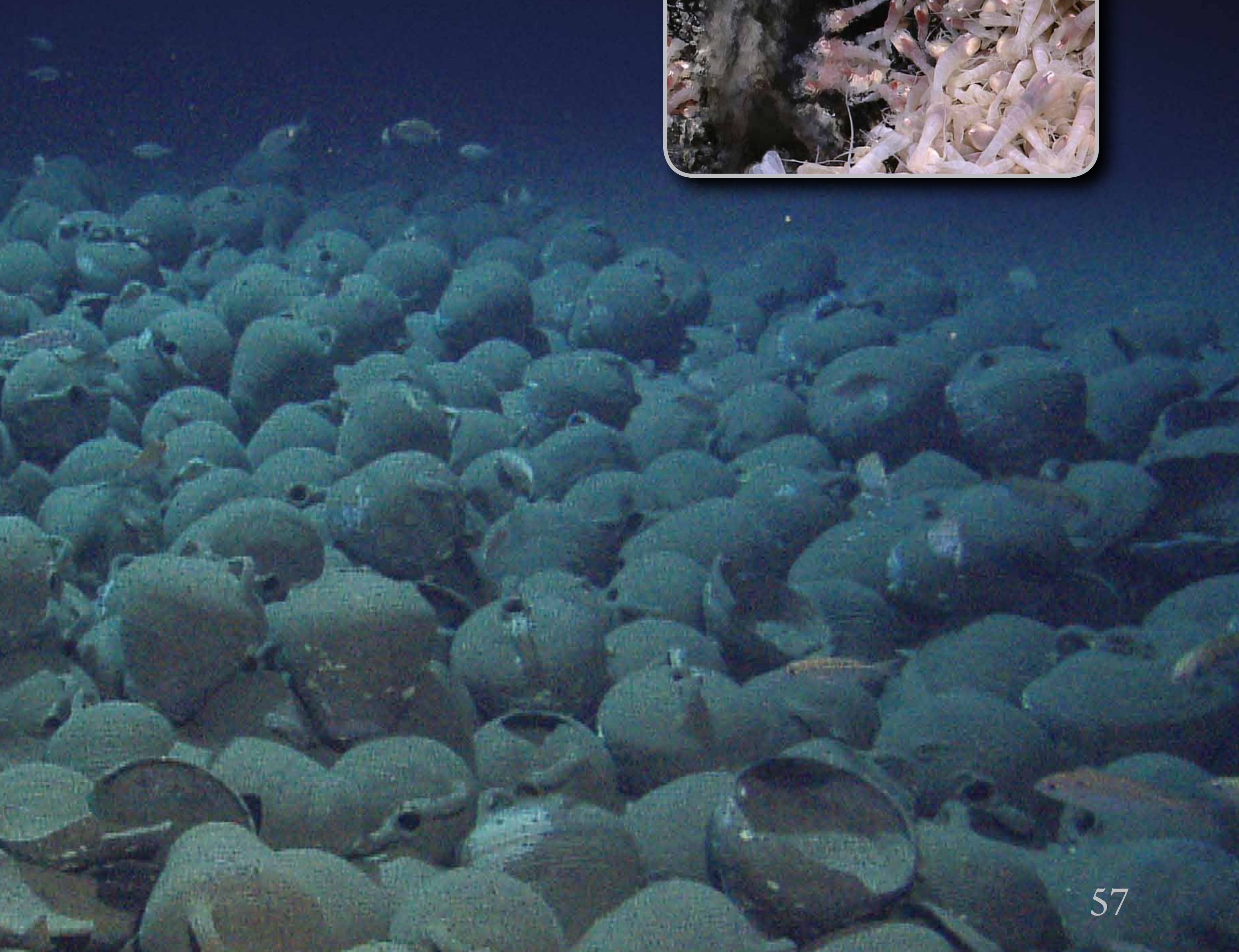


Photo Credits: NOAA
Okeanos Explorer Program

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65 Texas A&M University, College Station, TX
66 Thomas Jefferson High School for Science and Technology, Alexandria, VA
67 Titanic Belfast Museum, Belfast, Ireland
68 Traian National College, Romania
69 Tropical Discoveries, USVI
70 Troy High School, Troy, MI
71 U.S. Geological Survey, Reston, VA
72 Universidad de los Andes, Bogotá, Colombia
73 Universidad Simón Bolívar, Venezuela
74 University High School, Illinois State University, IL
75 University of Belize, Belmopan, Belize
76 University of Delaware, Newark, DE
77 University of Massachusetts, Boston, MA
78 University of Missouri, Columbia, MO
79 University of New Hampshire, Center for Coastal and Ocean Mapping, Durham, NH
80 University of Portsmouth, Portsmouth, UK
81 University of Puerto Rico, Mayagüez, PR
82 University of Rhode Island, Kingstown, RI
83 University of South Florida, St. Petersburg, FL
84 University of Texas, Austin, TX
85 University of the West Indies, St. Augustine, Trinidad & Tobago
86 University of Washington, Seattle, WA
87 Williams School, New London, CT
88 Woods Hole Oceanographic Institution, Woods Hole, MA

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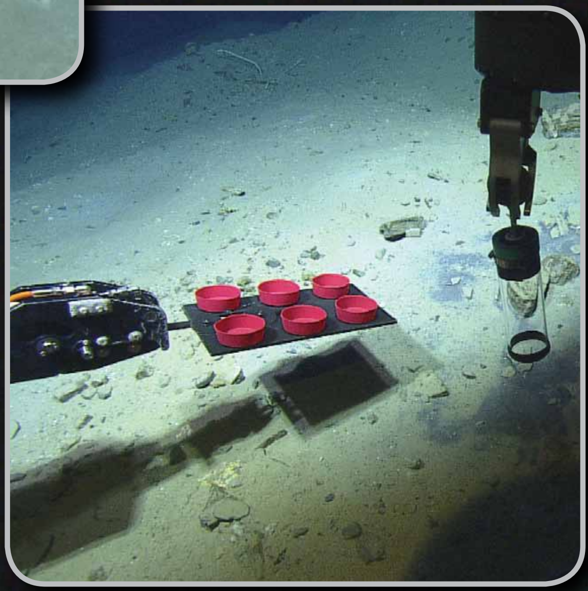

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