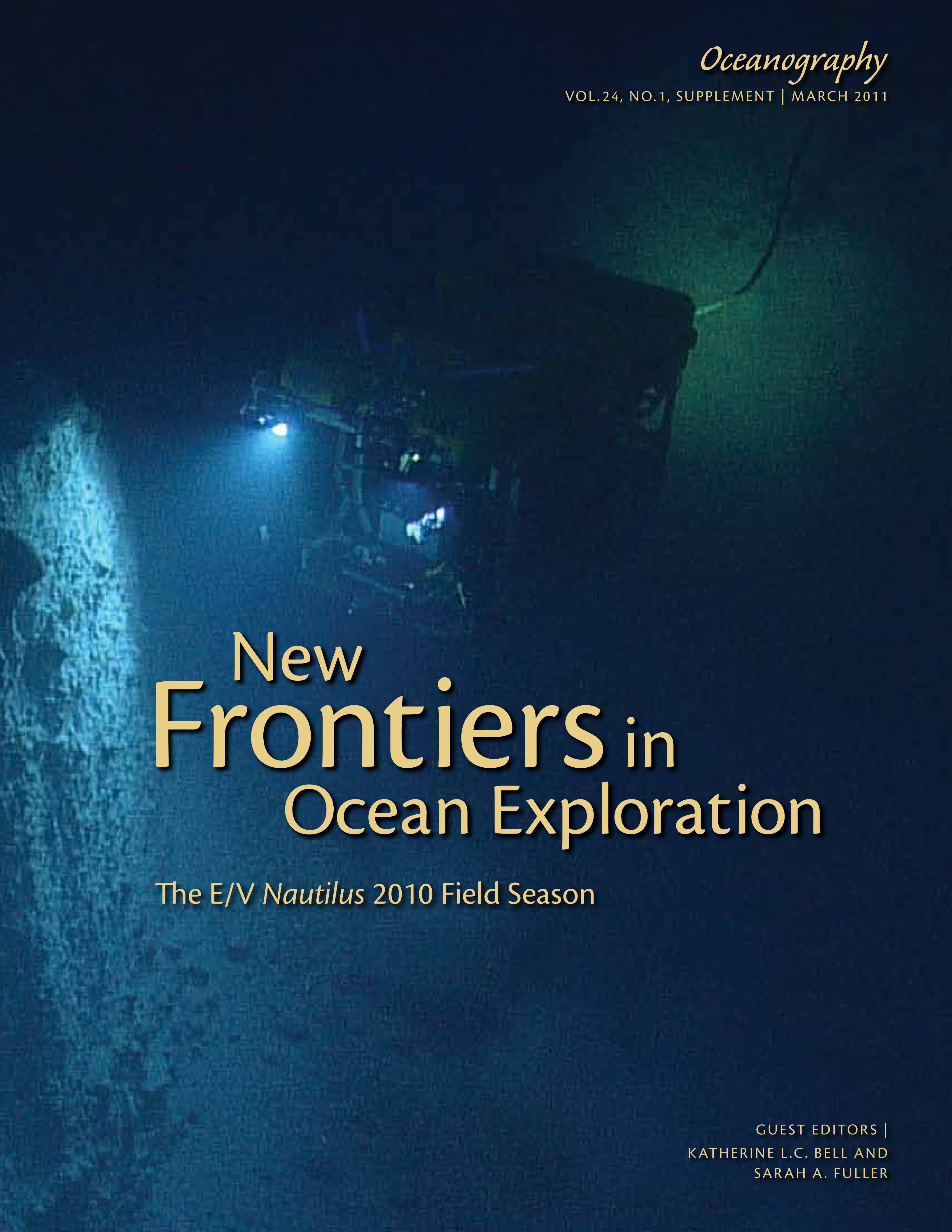

Oceanography

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New Frontiers in Ocean Exploration

The E/V *Nautilus* 2010 Field Season

GUEST EDITORS |
KATHERINE L.C. BELL AND
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FOREWORD | The Exploration Vessel *Nautilus*

By Robert D. Ballard

This supplement to the March 2011 issue of *Oceanography* is dedicated to the first series of missions conducted by the Exploration Vessel (E/V) *Nautilus* in 2009 and 2010. Our hope is to produce a similar summary report each year so that highlights of data collected by *Nautilus* will be available to the oceanographic community as soon as possible.

Nautilus is one of America's two ships of exploration supported by the US National Oceanic and Atmospheric Administration's (NOAA's) Office of Ocean Exploration and Research; the other is NOAA ship *Okeanos Explorer*. NOAA's program in ocean exploration evolved out of a recommendation in the 2001 report of President Clinton's Panel on Ocean Exploration entitled *Discovering Earth's Final Frontier: A US Strategy for Ocean Exploration*. The US Commission on Ocean Policy further endorsed the program in its 2004 report, *An Ocean Blueprint for the 21st Century*.

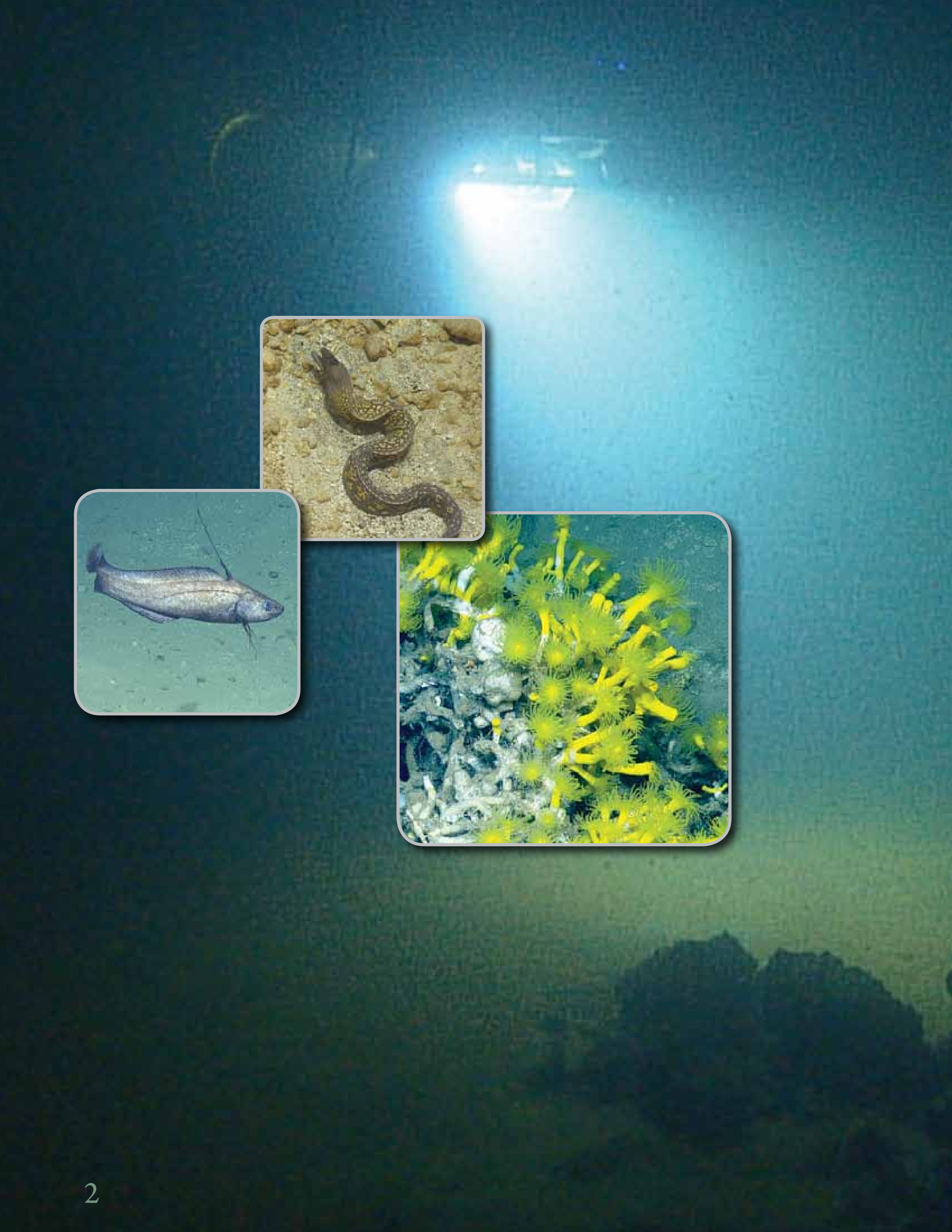
Both of these Presidential reports recommended that NOAA's newly formed Office of Ocean Exploration needed dedicated ships that would make it possible to conduct exploratory missions in remote areas of the world not routinely visited by America's existing academic research fleet.

Because the *Nautilus* program is exploratory in nature and represents the interests of the oceanographic community as a whole, it requires implementation of a new "telepresence" paradigm that makes it possible for experts from shore to assist in command of the undersea vehicle operations moments after a new discovery is made, no matter where or when that discovery occurs. The work carried out by E/V *Nautilus* and *Okeanos Explorer* is being executed with this paradigm in mind; both vessels are directed by advisory groups drawn from members of the oceanographic community.

As a result, both ships and the undersea vehicles they operate are equipped with control centers connected via a high-bandwidth satellite link to the Inner Space Center at the University of Rhode Island's Graduate School of Oceanography. Using Internet2, the images and data collected aboard E/V *Nautilus*, for example, are transmitted to a growing network of remote science consoles at various research centers across the United States and around the world, where scientists participating in this program are located. Referred to as the Doctors-on-Call network, these remote consoles make it possible for shore-based scientists to communicate with the operational team aboard ship in real time, and to help direct the ship's activities, vehicles, and shipboard team.

Telepresence technology also makes it possible for students, teachers, and the public to participate in the exploration being carried out aboard *Nautilus*. "Educators-at-Sea" are on every expedition, working with the shipboard team to transmit undersea video, along with the discussions being conducted by the at-sea team standing watch at that moment, to the Inner Space Center and then distributed on *www.NautlilusLive.org*. This Web site also makes it possible for people to ask questions of the shipboard team in real time.

Through this supplement, we hope to excite your interest in participating in our exploration and telepresence program by joining the Doctors-on-Call network and/or by using the preliminary results summarized here as the basis for more detailed investigation. At a minimum, we hope you will visit our Web site during the next exploration program and witness moments of discovery in real time.



INTRODUCTION | The 2009 and 2010 E/V *Nautilus* Field Seasons

By Katherine L. Croff Bell

The initial missions of E/V *Nautilus* focused on the eastern Mediterranean, Aegean, and Black Seas. Although a significant amount of research has been conducted in this region, our numerous discoveries over just two field seasons indicate that volumes of knowledge are still contained in these depths. While much data analysis remains to be carried out, we decided that it was critical to present the initial results as quickly as possible to make them available to the oceanographic community.

The Mediterranean region is one of the most tectonically complex regions in the world. Volcanoes, earthquakes, tsunamis, and fluid seeps are just a few of the area's surface expressions of our dynamic Earth. This geological activity creates a wide variety of habitats that are colonized by diverse biological communities—from the submerged continental shelves, to volatile hydrothermal vents, to fluid seeps. Likewise, humans have inhabited Mediterranean shores for thousands of years, trading, fishing, and fighting. All told, the eastern Mediterranean provides an area in which a diverse array of scientists—including geologists, biologists, chemists, physicists, archaeologists, anthropologists, and historians—can come together to explore the world around us. During its 2009 and 2010 field seasons, the *Nautilus* platform brought millions of people together, from the most learned expert to the curious child, to explore the ocean's depths.

This supplemental publication of *Oceanography* describes the technology used aboard *Nautilus* and preliminary results from the 2009 and 2010 field seasons. The first section details the capabilities of *Nautilus*, as well as the remotely operated vehicles *Hercules*, *Argus*, *Echo*, and *Diana*, systems specifically designed for deepwater exploration.

The second section focuses on our telepresence system, which is used for both science support and educational outreach. The ship-to-shore configuration allows us to send data, video, and audio from *Nautilus* to the Inner Space Center at the University of Rhode Island's Graduate School of Oceanography and on to the rest of the world. The shore-to-ship configuration brings hundreds of scientists and children "virtually" aboard *Nautilus*, allowing live interaction with on-board scientists and engineers throughout the field season.

The heart of this publication reports on months of exploration in the eastern Mediterranean, Aegean, and Black Seas. Our work off Turkey resulted in the discovery of 20 shipwrecks in the Aegean Sea and Sea of Marmara, as well as the biological and geological exploration of the Anaximander Mountains off the Mediterranean coast. Greek waters hold the Hellenic Volcanic Arc, in which Santorini, Kolumbo, and Nisyros volcanoes were the focus of exploration to reconstruct past and present volcanic activity and its impact on the environment. The Cypriot Eratosthenes Seamount provided an unexpectedly diverse array of discoveries, including sinkholes, fluid seeps, and shipwrecks. Newly discovered deepwater coral communities were found on Israel's continental margin, and as a result, this area may soon be designated as a marine sanctuary. Finally, although it was not carried out aboard *Nautilus*, we also include a description of our 2006–2008 archaeological surveys off Ukraine's Crimean coast that resulted in the discovery of 18 historical and archaeological sites.

I hope that this supplement to *Oceanography* and our ongoing exploration aboard *Nautilus* will contribute to our understanding of the underwater world, provide data for the oceanography community at large, and inspire future explorers around the globe. Whether at sea, on shore at a remote console, or via the Internet, we invite you to be a part of our exploration aboard *Nautilus*.

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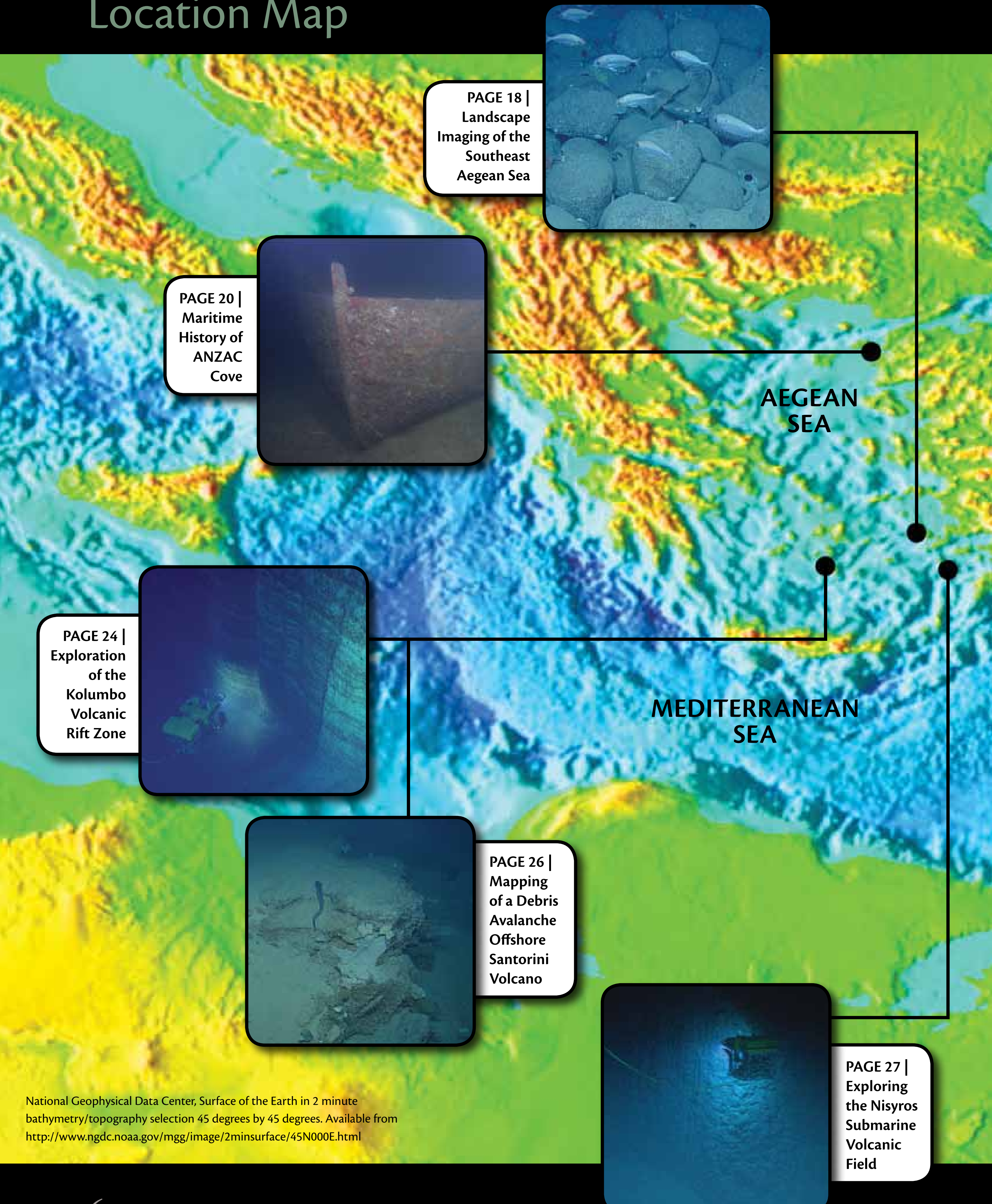
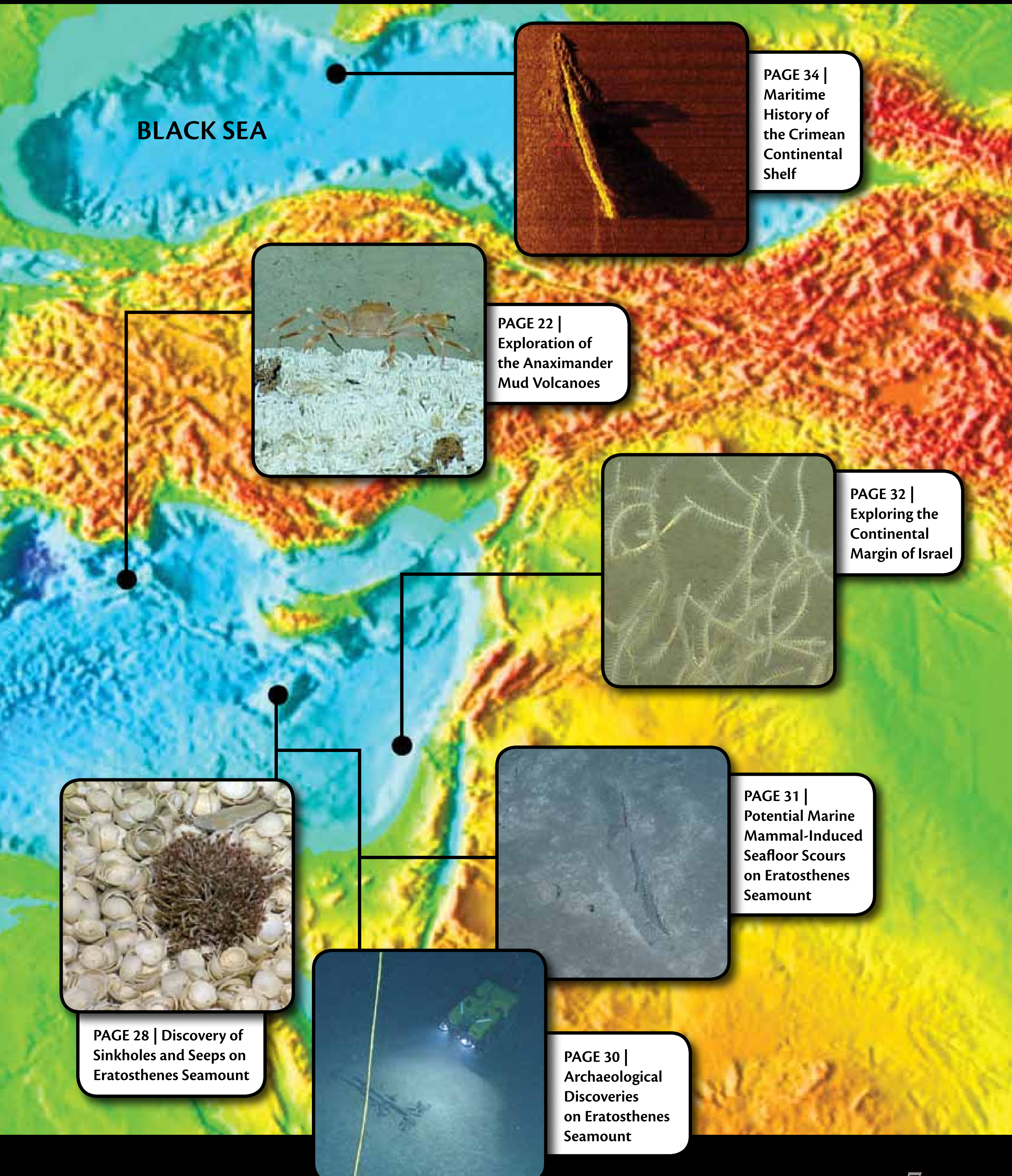
Location Map



National Geophysical Data Center, Surface of the Earth in 2 minute bathymetry/topography selection 45 degrees by 45 degrees. Available from http://www.ngdc.noaa.gov/mgg/image/2minsurface/45N000E.html


BLACK SEA
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Exploration Vessel (E/V) *Nautilus*

By Ian Kulin, Todd Gregory, and James Newman

FORMERLY: *Alexander von Humboldt*

LENGTH: 64.23 meters (211 feet)

BEAM: 10.5 meters (34.5 feet)

DRAFT: 4.9 meters (14.75 feet)

TONNAGE: 1249 gross, 374 net

MAIN PROPULSION: Single 1286 kw (1700 HP) controllable pitch

SPEED: 10 knots service, 12 knots maximum

DYNAMIC POSITIONING

CLASSIFICATION: Germanischer Lloyd (GL) 100 A5 E1 (Ice Strengthened)

BUILT: 1967, Rostock, Germany

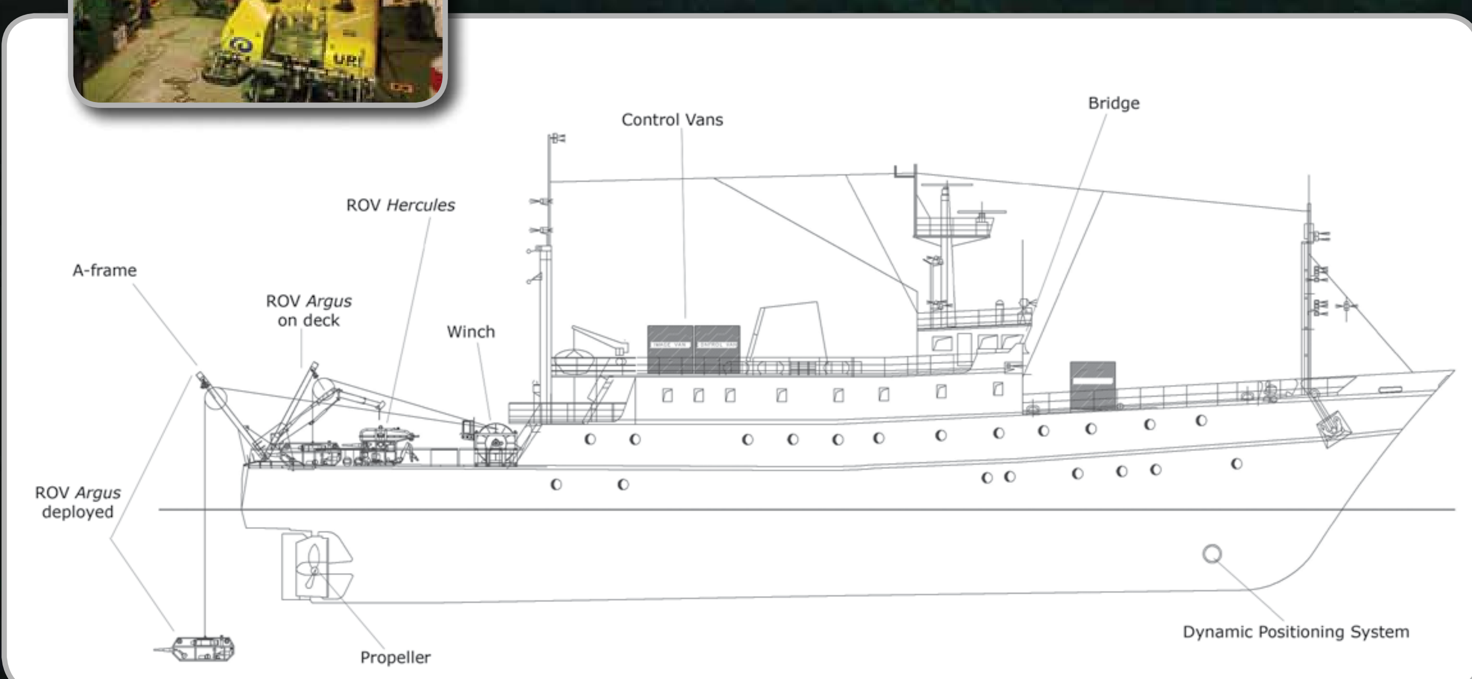
BERTHING: 36 bunks in single/double cabins and eight bunks in four-person cabins

CREW: 17

SCIENCE PARTY: 27

FLAG: St. Vincent and the Grenadines

HOME BASE: Yalikavak, Turkey



Capable of working as a stand-alone system, ***Argus*** becomes a towed-body instrument for large-scale deepwater survey missions. Side-scan sonar looks out on either side of the vehicle up to 400 m away, identifying features as small as a brick. Powerful 1200-watt lamps provide light miles below where sunlight is absorbed by seawater.

A 20-hp electric/hydraulic pump powers the mechanical functions on ***Hercules***. Two manipulator arms, one dexterous and the other strong, work together to sample and move equipment around on the seafloor. High-definition video cameras provide a clear, precise window to the world below…and create dazzling images.

E/V *Nautilus* Vehicles

By Brennan Phillips, Jim Newman, and Todd Gregory

Hercules and *Argus* are state-of-the-art deep-sea robotic vehicle systems capable of exploring depths up to 4000 m. Each remotely operated vehicle (ROV) has its own suite of cameras and sensors that receive electrical power from the surface through a fiber-optic cable, which also transmits data and video. Engineers and scientists command the vehicles from a control room aboard *Nautilus*, with some dives lasting more than three days.

Argus was first launched in 2000 and was soon followed by *Hercules* in 2003. The systems are versatile, capable of supporting a wide range of oceanographic instrumentation and sampling equipment. They have surveyed ancient shipwrecks, discovered hydrothermal vents, and recovered lost equipment in oceans and seas around the world.

Several smaller remote systems complement *Hercules* and *Argus* for various exploration objectives.

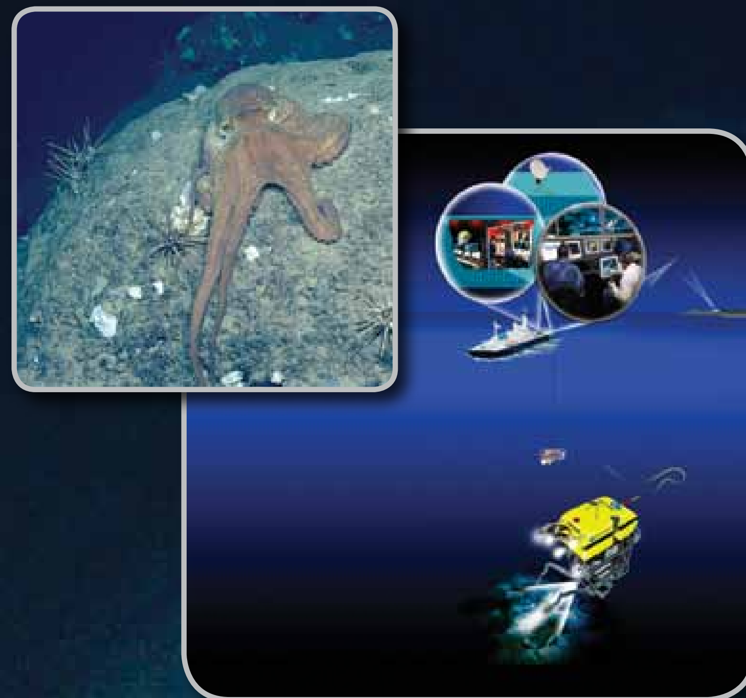
Echo is a side-scan and subbottom sonar towfish (100/400 kHz) capable of working at depths of up to 3000 m.

Little Hercules is a 4000-m-rated inspection-class ROV that features the same high-definition video system as Hercules, along with several other oceanographic sensors.

Diana is a side-scan sonar towfish capable of working as deep as 2000 m. The primary advantage of this 300/600 kHz system is the quality of data that is produced. ***Diana*** surveys create accurate, high-resolution maps of the ocean floor.

The Development of Telepresence Technology for Remote Exploration and Education

By Dwight Coleman and Robert Ballard



The Inner Space Center (ISC) at the University of Rhode Island Graduate School of Oceanography is the hub for remote telepresence-enabled expeditions where teams of scientists, students, and educators participate in the exploration cruises remotely. The facility uses advanced telepresence technologies, including video production and broadcast systems, ship-to-shore telecommunication equipment, and real-time data processing and visualization systems to enable remote, shore-based ocean exploration operations. Using this technology, teams of scientists, students, and educators based at the ISC communicate with their counterparts on board the research vessels to support live shipboard operations, remotely operated vehicle dives, data processing and analysis, and educational outreach activities. The ISC supports two primary ships of exploration: the Ocean Exploration Trust's E/V *Nautilus* and NOAA's *Okeanos Explorer*. The mission control facility within the ISC is equipped for 24-hours-per-day operations where teams of remote participants stand watch to support the shipboard scientific investigations. The facility's layout mirrors the mission control spaces on board the ships of exploration, and the functionality of the telecommunication, video, and data systems are nearly identical to those onboard the ships. During the 2010 field season, the ISC was staffed to support both ships, the Doctors-on-Call program, and the Educators-at-Sea and Ashore programs.

The ISC supports a growing network of Remote Science Consoles for the Doctors-on-Call program that are nodes off the ISC hub, connected via Internet2 to the ISC and the ships of exploration. These consoles are equipped with video decoding systems, intercom telecommunication equipment, and data visualization systems. Presently, permanent Remote Science Consoles are installed at NOAA headquarters in Silver Spring, MD, the NOAA Pacific Marine Environmental Lab in Seattle, WA, the University of New Hampshire, the University of Haifa, the Institute for Exploration at Mystic Aquarium, and the University of Delaware, with one in development at Syracuse University. In addition, "mini-consoles" were installed at the Woods Hole Oceanographic Institution, the University of Washington, and Texas A&M University. The ISC supported the technical aspects of their installation and configuration on Internet2, and helped manage their operation.

Immediately adjacent to the mission control space is a video production studio and control room to support the creation and delivery of live educational broadcasts. During 2010, the live streaming video feeds from E/V *Nautilus* were converted and combined at the ISC into a multi-screen video feed that was viewable at *www.NautilusLive.org*. In addition, the ISC supports a data center with online video and data servers and archival systems. All streaming audio, data, and video from the ships are captured in real time and made accessible to remote users. The ISC facilitates and manages access to the live and recorded information through the ongoing development and maintenance of an online data portal, video data archive, content management system, and a collaborative Web-based gateway. This data portal hosts the raw, unprocessed versions of all video and data collected by the ships and represents a short-term archive until the final data sets are transferred to the national data archives. Finally, the mission control space at ISC can be used as an education and hands-on training facility for all users of the ships' data and cruise participants.

The Doctors-on-Call Program: Maximizing the Interpretive Power of Telepresence

By James A. Austin Jr., Robert Ballard, and Katherine L. Croff Bell

During the 2010 *Nautilus* expeditions, telepresence was used to team up scientific expertise ashore with the shipboard scientific parties studying the biology, geology, and archaeology of the eastern Mediterranean. Because the ship offers a limited number of bunks, many of which are taken by the technical team operating the ROVs *Argus* and *Hercules*, experts ashore—known as Doctors on Call (DOC)—could be called on, often at short notice, to help those on *Nautilus* interpret and understand the video images streaming continuously from the seafloor.

Interactions from shore took a number of forms. For example, some scientists at URI's Inner Space Center literally stood watch right along with members of the shipboard parties studying Eratosthenes Seamount and the Santorini volcanic edifice. Other scientists and graduate students interacted using their own Remote Science Consoles (RSC). For example, personnel manning the RSC at Woods Hole Oceanographic Institution were fundamental to interpretations of biology encountered during the Anaximander Mountains expedition, while Israeli scientific personnel manning an RSC set up at the University of Haifa played a crucial role in interpreting videos collected along Israel's continental margin. At times, because *Nautilus* had direct phone and e-mail contact with shore-based institutions, diverse scientific expertise could be called upon at very short notice to collaborate with shipboard staff. One archaeological expert called upon by the University of Haifa used their RSC to judge the provenance (Roman) and age (3rd century CE) of an amphora in deep water off Israel, even as *Hercules* pilots were turning it gently for better views of its morphology. In more than one case, input from shore-based experts directly influenced how ROV dives were planned and conducted. Furthermore, interactions with such experts was continuously showcased on the *www.NautilusLive.org* Web site through emailed questions and verbal discussions between DOCs and members of the scientific and technical staff in the *Nautilus* control room.

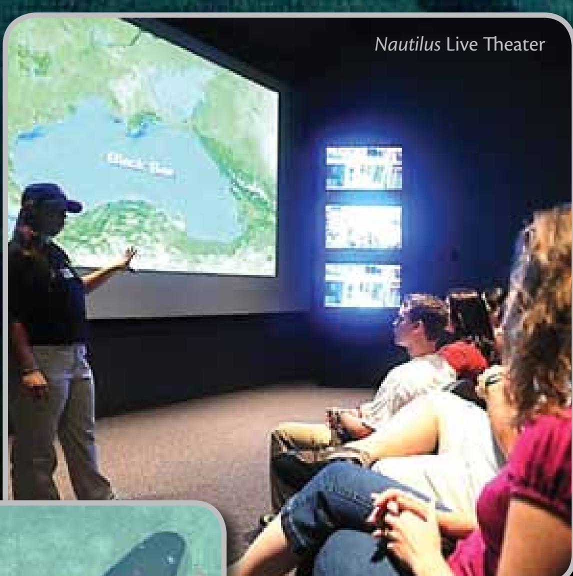
Everyone agreed that while such ship-shore collaborations enhanced the value of interpretive information flowing out over the Internet, "situational awareness"—knowing exactly what the ship and ROVs were doing all the time and where—could be improved. That will be done in 2011 by displaying maps on a DOC Web site that show each day's game plan and real-time visualizations (i.e., navigation outputs) of vehicles in the water, superimposed on up-to-date maps of seafloor bathymetry. Furthermore, verbal communications between members of the shipboard parties and shore-based experts will be made clearer so that all who visit the Web site will be able to appreciate fully the power of telepresence to put technical and scientific expertise from various land-based locations at the immediate disposal of *Nautilus* shipboard teams.

Education and Outreach Activities Enabled by Telepresence Technology

By Alexandra Witten and Amy O'Neal

Our goal for the 2010 telepresence-enabled education and outreach aboard *Nautilus* was to use the excitement generated by ocean exploration discoveries to open a path that children could follow to become scientists or engineers. To accomplish this goal, our objective was to determine the best content to deliver to on-shore educators and educational programs that would capture children's attention. Once engaged, the students would be directed to formal and informal education programs designed to expand upon that initial interest.

In addition to engaging and attracting students, we wanted to provide outreach opportunities for the general public to encourage broader support for ocean exploration and to make it a national priority. To accomplish all of these goals, the partner organizations established and embarked upon a set of education and outreach programs.



Nautilus Live Theater

Educator Program

Every leg of the 2010 *Nautilus* field program included an educator embedded in the sea-going team to ensure that the world could follow the explorations 24/7. The goal of the *Nautilus* Educator Program, comprised of both Educators-at-Sea and Educators-Ashore, is to get the best information for education and outreach from ship to shore. The role of the Educators-at-Sea is to serve as facilitators between the ship and shore-based educators and programs. The Educators-at-Sea are coached by a team of Educators-Ashore, who provide valuable input from a variety of locations and perspectives.

The 2010 Educators-at-Sea and Educators-Ashore were critical first filters of raw information, and they helped to shape the content that was displayed on Web sites, such as the Sea Research Foundation's *www.NautilusLive.org*, which was the public "face" of the ship for live daily information. They also contributed content and updates to Facebook and Twitter and worked with interpreters in a hosted theater presentation. Following the expedition, the educators continued to develop activities and lessons to bring the *Nautilus* experience to their students.

During the 2010 expedition, 12 Educators-at-Sea stood watch along with the exploration team while providing "live" commentary, posting photos and video clips, and conducting interviews with the team at sea. Our Educators-at-Sea came from across the United States, including Boys & Girls Clubs of America in Florida, Arizona, Illinois, California, Vermont, and Virginia, and public and private schools in Rhode Island, Texas, Connecticut, New Hampshire, and West Virginia.

Twenty Educators-Ashore stood watches at key exploration command consoles that linked directly to the Inner Space Center and *Nautilus*. These consoles were located at Mystic Aquarium, CT, and the University of Rhode Island, as well as at the Boys & Girls Club of Greater Scottsdale, AZ, the University of New Hampshire, and Smithfield High School in Rhode Island. Educators-Ashore came from local schools and Boys & Girls Clubs from Rhode Island, Connecticut, New Hampshire, Arizona, and New York.

NautilusLive Web Site

The Sea Research Foundation's (SRF) Digital Media Group created the NautilusLive Web site to provide public access to the ongoing exploration aboard *Nautilus*. The site includes four video displays, typically featuring underwater images from ROVs *Hercules* and *Argus*, the data being collected by those vehicles, and the voices of the team on watch aboard ship. In addition, the site included team member profiles, blogs, photos, video clips, and status updates from the Educator-at-Sea, as well as opportunities for live interactions with expedition scientists and engineers.

An important feature of the Web site was the opportunity for Web viewers to send in questions to the expedition team. During the four-and-a-half-month *Nautilus* deployment, 18,000 questions were answered via the NautilusLive Web site, which had 232,094 visits from 115 countries and territories around the world. US viewers logged the largest number of visits—166,208.

The NautilusLive Web site provided multiple paths for further educational exploration through links to Immersion Learning for after school programs, and the JASON Project for formal middle school curricula.

Immersion Learning is a STEM-based after-school program for the Boys & Girls Clubs of America and informal educational sites, such as museums, science centers, and aquariums. The Immersion Learning Web site at *www.immersionlearning.org/Nautiluslive* supported the *Nautilus* expedition with a kid-friendly expedition overview, interactive games, puzzles, hands-on activities, and videos covering topics such as marine archaeology, underwater geology, deep-sea biology, ocean exploration tools, and careers in ocean exploration. New content was added throughout the expedition. Immersion's "Meet a Scientist!" webcast series during the 2010–2011 academic year includes members of the *Nautilus* expedition team.

The JASON Project (*www.jasonproject.org*) brings together students and scientists in field research programs, and develops Internet-based core curriculum modules and exciting games and activities for the classroom. Prior to the expedition, JASON Project staff met with key expedition members to develop ocean-related content for its most recently produced geology curriculum entitled "Tectonic Fury." In 2011, the JASON Project will develop a robust live and curriculum-based program around *Nautilus*.

NautilusLive Web page during the Anaximander Mountain leg.

Theater Program

The 50-seat "*Nautilus* Live" Theater constructed at SRF's Mystic Aquarium & Institute for Exploration facility in Mystic, CT, further enhanced outreach within the United States. A team of interpreters hosted four live shows per day. The theater was equipped with a remote console connected to Internet2, a large high-resolution screen, and an audio board, enabling the interpreters to talk to the team at sea and the Educators-Ashore. By the end of the season, over 10,000 visitors participated in a theater presentation, representing 81% of the theater's capacity throughout the project.

Television Programming

In 2009 and 2010, several film crews participated in three separate projects highlighting *Nautilus*, its team, and telepresence technology. The first project was related to the production of two National Geographic television specials dealing with the Battle of Gallipoli. The second was a 40-minute segment of "60 Minutes," while the third was a multipart National Geographic television series on the ocean.

Outreach/Media Opportunities

The 24/7-telepresence capability during the expedition allowed us to host multiple large- and small-scale live events from *Nautilus* to venues across the United States and in partnering countries. These events were important opportunities to make connections with academia; industry; media; federal, state, and local partners; schools; Boys & Girls Clubs; and informal educational sites.

Development of High-Resolution Underwater Mapping Techniques

By Christopher N. Roman, Gabrielle Inglis, J. Ian Vaughn, Stefan Williams, Oscar Pizarro, Ariell Friedman, and Daniel Steinberg

Detailed photographic and bathymetric maps of the seafloor with resolutions better than 5 cm are broadly applicable for studies in marine geology, biology, and archaeology. Developing the tools and techniques to produce these data products is a central focus of the *Nautilus* program, enabled by a collaborative effort among several robotics groups. The overall goal of this work is to digitally document the seafloor and to determine which suite of sensors provide the most effective means for creating scale-accurate renderings with resolutions meaningful for archaeological and scientific diagnostics.

Hercules is equipped with a suite of mapping instruments that allow detailed visual and acoustic seafloor surveys. During the 2009 and 2010 field seasons, we used a 2250-kHz BlueView Technologies multibeam, a 240-kHz Imagenex multibeam, a verged stereo pair using color and black and white 12-bit 1360 x 1024 Prosilica cameras, and a 100-mW, 532-nm green laser sheet. The sonar, camera, and laser geometry were optimized for surveys between 2- and 4-m altitude off the bottom. We navigated the vehicle using an RDI Doppler Velocity Log (DVL), an IXSEA OCTANS fiber-optic gyroscope, and a Paroscientific depth sensor, and we used an ultra-short baseline system to georeference the surveys.

Our data-processing and map-making techniques are based on the Simultaneous Localization and Mapping (SLAM) concept, which is an active research area in both marine and land robotics (Singh et al., 2007). SLAM techniques combine direct navigation information with mapping sensor data to concurrently improve the direct navigation estimates and produce maps with resolutions consistent with the mapping sensors themselves. This type of approach is necessary to achieve centimeter-level resolution in the face of navigation uncertainly that quickly becomes the leading source of error.

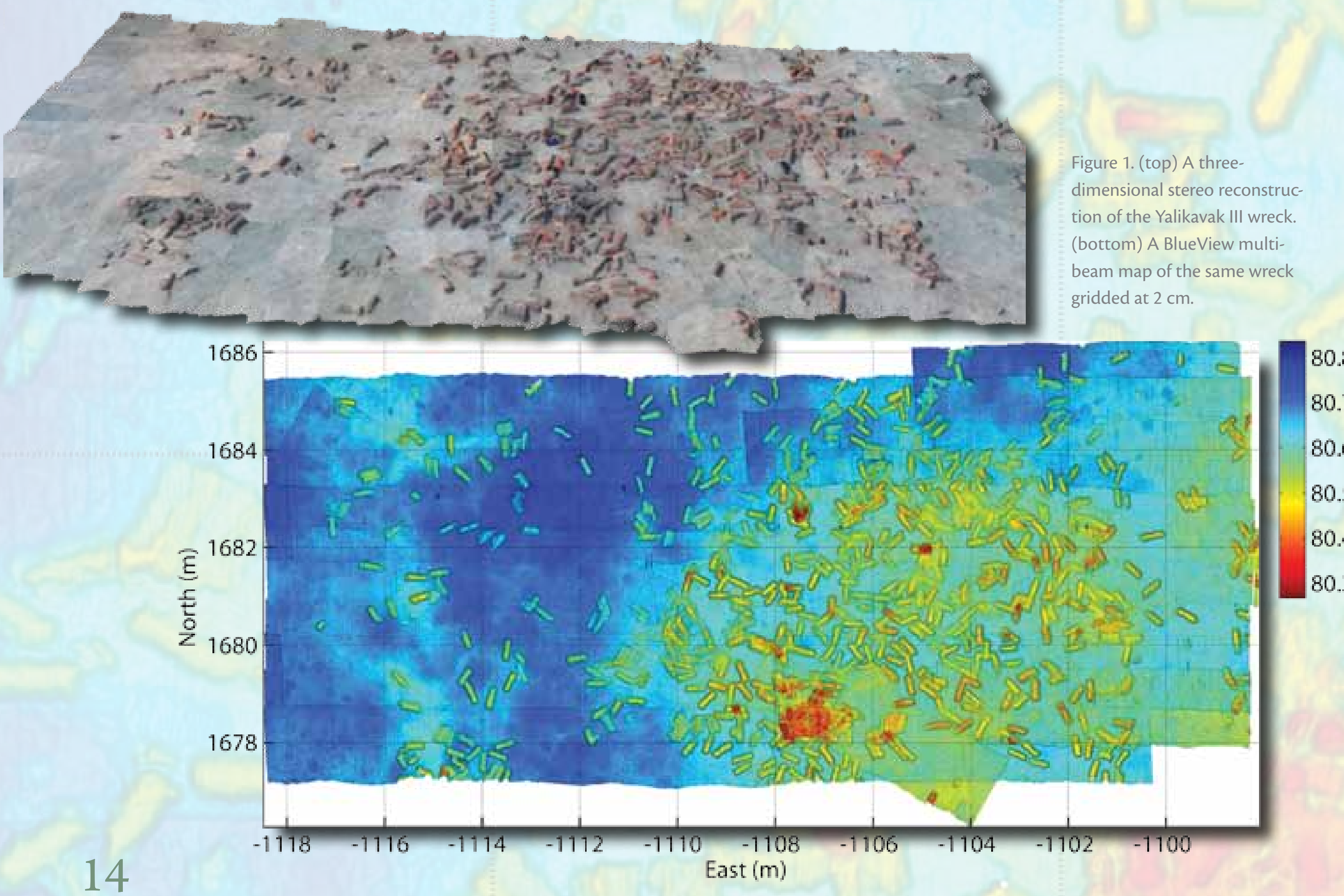


Figure 1. (top) A three-dimensional stereo reconstruction of the Yalikavak III wreck. (bottom) A BlueView multibeam map of the same wreck gridded at 2 cm.

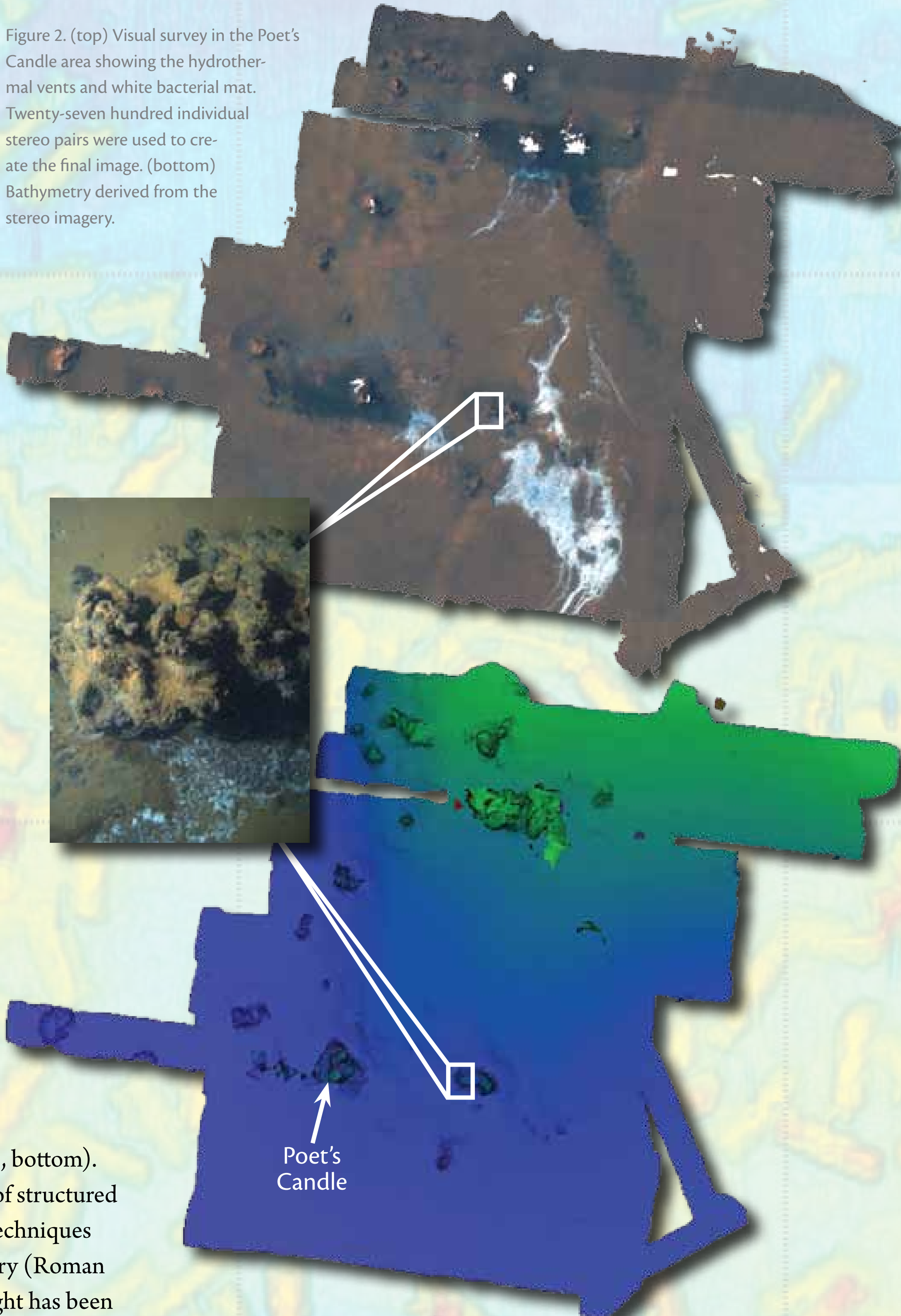


Figure 2. (top) Visual survey in the Poet's Candle area showing the hydrothermal vents and white bacterial mat. Twenty-seven hundred individual stereo pairs were used to create the final image. (bottom) Bathymetry derived from the stereo imagery.

During the eastern Aegean legs of the 2009 and 2010 seasons, we mapped 17 different wrecks in the Bodrum, Datcha, and Marmaris areas (see pages 18–19). Given the small size of the sites, typically 10 m x 20 m, the survey work was usually completed in just a few hours. Figure 1 shows example data for the Yalikavak III wreck. We produced the three-dimensional (3D) texture photographic mosaics using a stereo mapping and visual SLAM software pipeline (Mahon et al., 2008; Johnson-Roberson et al., 2010). The texture-mapped 3D models can be viewed in an interactive display that allows detailed investigation down to the pixel level of the original images (Figure 1, top). The high-frequency multibeam sonars were used at altitudes between 2 and 5 m to produce bathymetric maps (Figure 1, bottom).

We are also investigating the use of structured light laser imaging and developing techniques to obtain centimeter-level bathymetry (Roman et al., 2010). Although structured light has been a common machine vision technique in industrial applications for many years, it has had limited use underwater. By imaging a projected laser line, produced by shining the laser sheet on the bottom, it is possible to obtain a 3D profile of the seafloor with subcentimeter resolution. Our initial results using 2.5-mm gridding are encouraging (page 18, Figure 1). We are able to capture fine-scale features in the archaeological artifacts and subtle details in the shape of the seafloor. Data from the 2010 field season will be used in our research to expand the scale of the laser surveys while maintaining the 2.5 mm gridding using bathymetric SLAM techniques (Roman and Singh, 2007).

Our mapping capabilities were also used in the Kolumbo crater to document the hydrothermal vent field and steep pumice walls. We completed a large visual and bathymetric survey in the northern vicinity around the Poet's Candle vent (see page 25, Figure 3C) to map the distribution of nearby hydrothermal vents and bacterial growth on the seafloor (Figure 2). Over the main southern vent field, we performed detailed laser surveys to evaluate the resolution of the structured light mapping over the chimney features.

Our goal is to create a centimeter-level map of the features and obtain accurate estimates of their true shapes and volumes. A complicating factor in the active areas south of Poet's Candle was the hot water discharge and gas bubbling. The bubbles caused incidents of erroneous navigation drift by interfering with the DVL bottom tracking and the hot venting introduced blur and refraction in the green laser sheet. Looking forward, our future data processing

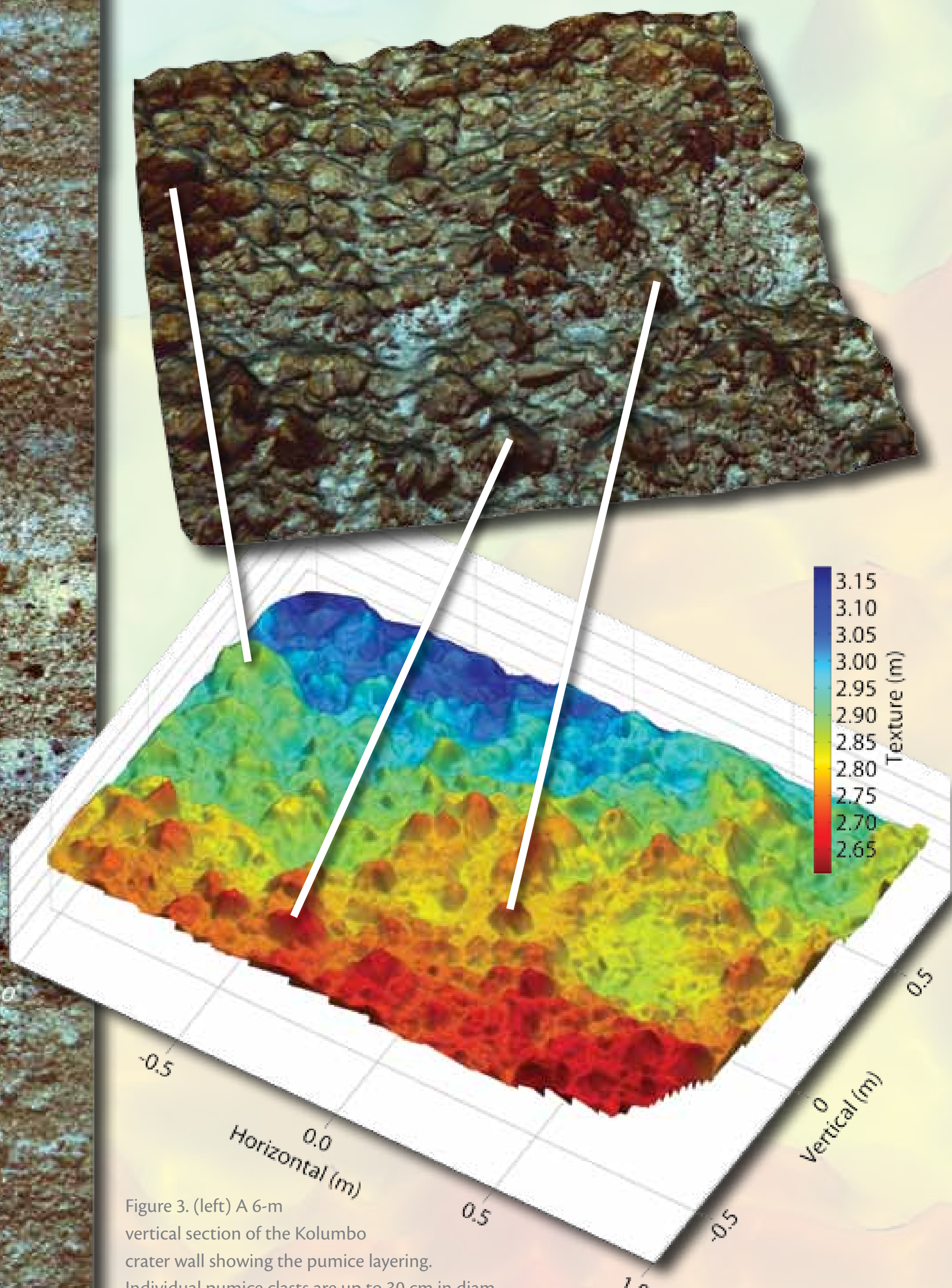


Figure 3. (left) A 6-m vertical section of the Kolumbo crater wall showing the pumice layering. Individual pumice clasts are up to 30 cm in diameter. (right) Small-scale textural maps of the vertical pumice outcrop made from the stereo cameras showing individual pumice clasts (top) and surface relief (bottom).

will need to contend with these distortions while also trying to exploit them as detectors of vent activity.

By mounting the cameras, sonar, and DVL on the front of *Hercules* to look forward, we were able to execute sequential "picket fence" vertical tracklines up and down the pumice wall from depths of 240–120 m (Figure 3 and page 25, Figure 2). We will use the collected data to construct a detailed, high-resolution record of grain size variations produced by submarine explosive eruptions.

At ANZAC cove, we were able to map a stone circle feature (pages 20–21) both acoustically and photographically (Figure 4). The maps enabled us to ground truth the apparent low relief of the site seen in the side-scan sonar data, and better understand the size distribution of the rocks comprising the circle. This survey will also be used in our research efforts to blend the camera and multibeam data into a single hybrid product.

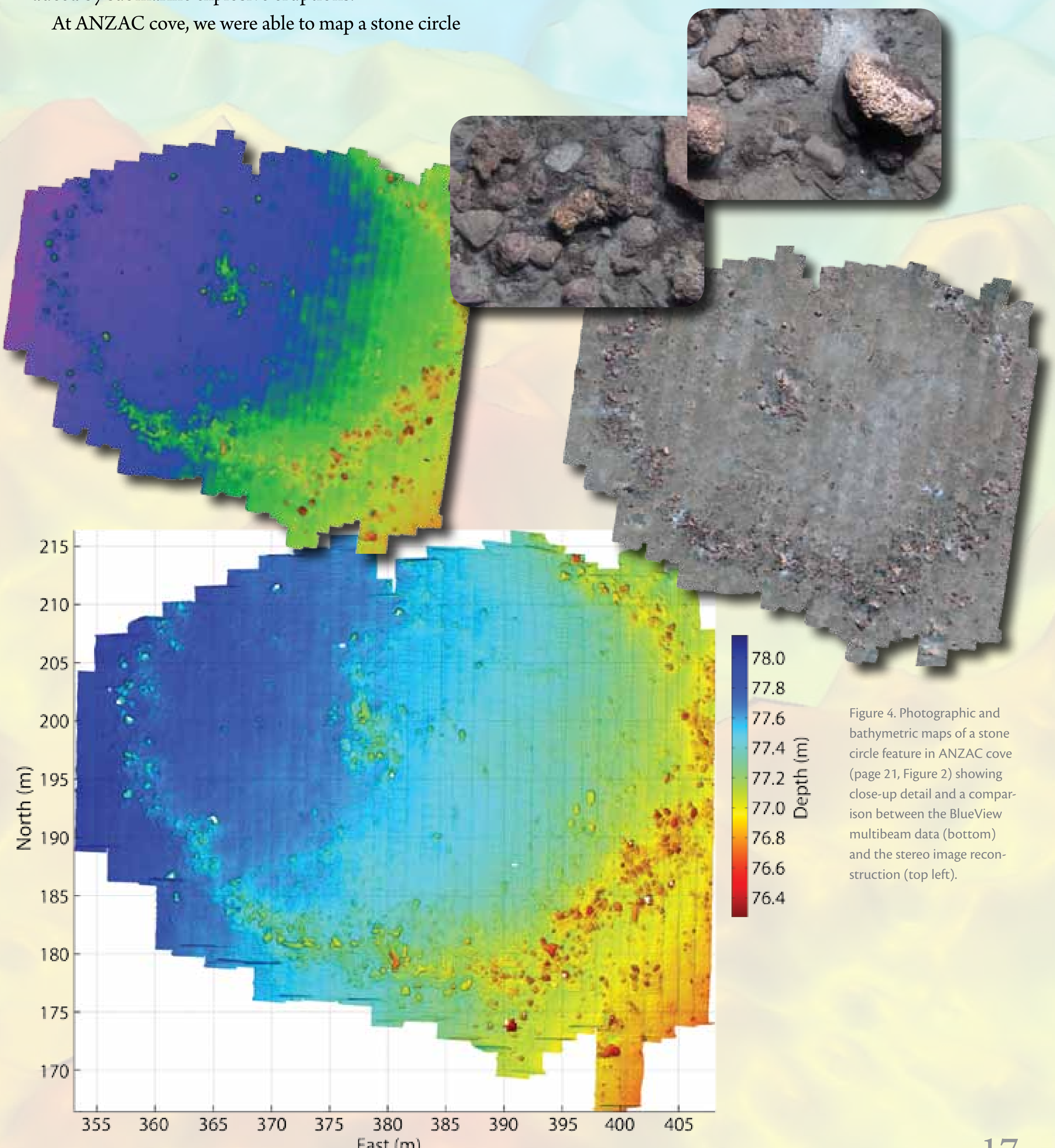


Figure 4. Photographic and bathymetric maps of a stone circle feature in ANZAC cove (page 21, Figure 2) showing close-up detail and a comparison between the BlueView multibeam data (bottom) and the stereo image reconstruction (top left).

Landscape Imaging of the Southeast Aegean Sea

By Michael L. Brennan, Tufan Turanli, Bridget Buxton, Katherine L. Croff Bell, Christopher N. Roman, Meko Kofahl, Orkan Koyagasioglu, Daniel Whitesell, Thomas Chamberlain, Richard Sullivan, and Robert Ballard

The waters of the Aegean Sea below depths accessible by recreational scuba divers are largely unexplored. The regions off the Bodrum and Datcha peninsulas, and in Marmaris Bay, have long been hubs of human activity, from ancient shipping to modern fishing. These areas are therefore important for understanding both the ancient and modern submarine landscapes.

Over the past three years, we have begun to document these areas of coastal deep water (50–600 m) with both acoustic and visual imaging systems. In 2008, we conducted a side-scan sonar survey from a small dive boat around the Bodrum peninsula with *Diana*, an EdgeTech 4200 MP towfish, coupled with the small ROV *Hylas* for visual identifications. The following year, *Nautilus* revisited some of the ancient shipwrecks located during this project with *Hercules* and *Argus*, and also began additional acoustic surveys off the Datcha peninsula to the south. A total of 11 ancient shipwrecks were located in 2008 and 2009, ranging in age from Archaic Greek to late Medieval (Brennan, 2010). In July of 2010, *Nautilus* continued this work south of Knidos and also began exploring the bay south of Marmaris to the east.

During the July 2010 survey, we mapped a total of 59 km^2 with side-scan sonar off Knidos, and 77 km^2 south of Marmaris. We found another nine ancient wrecks—five off of Knidos and four off Marmaris. These sites range in date roughly from Hellenistic to Byzantine (Cemal Pulak, Texas A&M University, *pers. comm.*, 2010). We imaged

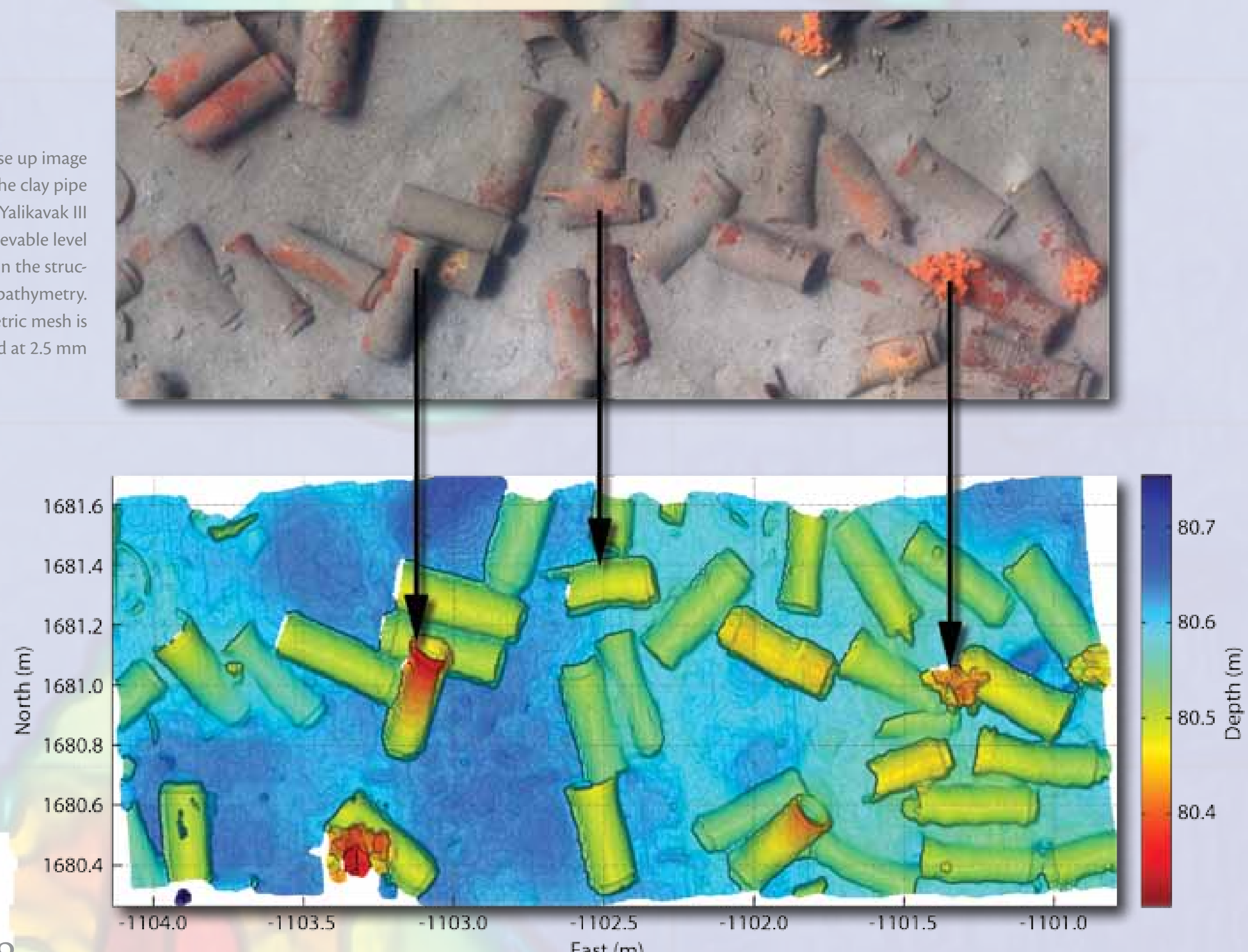
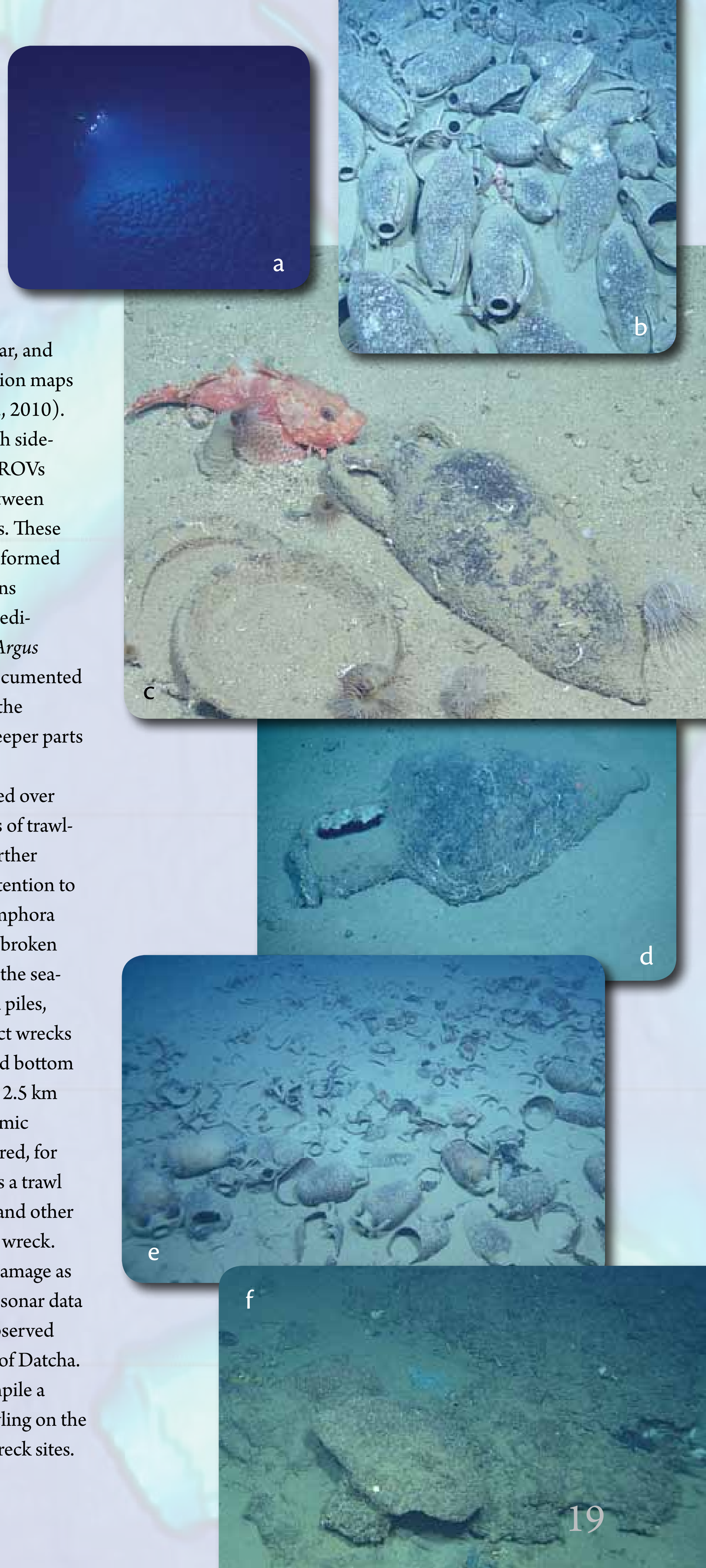


Figure 1. Close up image showing the clay pipe artifacts at Yalikavak III and the achievable level of detail in the structured light bathymetry. The bathymetric mesh is gridded at 2.5 mm

Figure 2. High-definition image captures of shipwreck sites: (a) Knidos F, (b) Knidos H, (c) Knidos I, (d) Knidos J, (e) Marmaris B, and (f) rock outcrop with carbonate crust.



each wreck site with high-definition video and then, time depending, surveyed with a combination of stereo cameras, multibeam sonar, and structured light systems for creating high-resolution maps (Figure 1; see also pages 14–17 and Roman et al., 2010). We also found a series of small rock outcrops with side-scan sonar and visually identified them with the ROVs (Figure 2f). They were found along the slope between 200–300-m depth off both Knidos and Marmaris. These outcrops appear to be carbonate crusts probably formed from methane gas seeps, and further investigations and sampling may be conducted during later expeditions. We also explored the Antalya Basin using *Argus* equipped with the *Diana* side-scan sonar, and documented a series of submarine landslides near the base of the Anaximander Mountains and bedforms in the deeper parts of the basin at 2600 m.

The 20 ancient shipwrecks observed and imaged over the past three years illustrate the damaging effects of trawling and other fishing operations on these sites, further documenting what others have begun drawing attention to in the area (e.g., Royal, 2008; Brennan, 2010). Amphora cargo shipwrecks exhibit this damage best, as the broken artifacts remain visible longer than trawl scars on the seabed. Some of the wrecks are fairly intact amphora piles, such as Knidos F and H (Figure 2a,b). These intact wrecks tend to be in close proximity to areas of prohibited bottom trawling, such as near submarine cables or within 2.5 km of shore (KKGM, 2006). Other wrecks have ceramic cargos that have been heavily damaged and scattered, for example, Marmaris B (Figure 2e). Knidos J shows a trawl scar that ripped through the center of the wreck, and other trawl scars were observed on the seabed near this wreck. Nonamphora cargo wrecks do not exhibit trawl damage as well, due to fewer artifacts (Figure 2c). Side-scan sonar data also show trawl scars, the heaviest of which we observed north of Yalikavak, and parallel to isobaths south of Datcha. Future acoustic imaging in this area will help compile a more comprehensive picture of the extent of trawling on the seabed and its damaging effects on ancient shipwreck sites.

Maritime History of ANZAC Cove

By Michael L. Brennan, Dwight Coleman, Christopher N. Roman, Tufan Turanli, Dan Davis, Alexis Catsambis, James Moore, Maureen Merrigan, Brennan Bajdek, Daniel Whitesell, and Robert Ballard

The entrance to Dardanelles Strait in the North Aegean Sea was the site of one of the greatest maritime battles of World War I. Mines sank a large number of warships during the Allied fleet's attempt to storm through to Istanbul in March 1915, and U-boats sank others a few months later during the ANZAC (Australian and New Zealand Army Corps) landing on the Gallipoli peninsula (Rudenno, 2008). In 2009, the first expedition of *Nautilus* filmed and documented some of these wrecks for a National Geographic documentary. *Hercules* and *Argus* dived on HMS *Irresistible* inside Canakkale Strait, the submarine *AE2* in the Sea of Marmara (Figure 1a), SMS *Breslau* outside the Dardanelles (Figure 1b), and HMS *Triumph* off Anzac Cove, where a landing craft from the battle was also filmed (Figure 1c). Battleships *Irresistible* and *Triumph* lie capsized on the seabed, while *Breslau* is upright with portions of its superstructure and guns still visible (Figure 1b). We also located and filmed a landing craft near Anzac Beach.

During the side-scan sonar imaging survey of the World War I battle area, we found a circular feature on the seabed in close proximity to the *Triumph* wreck (Figure 2; page 17, Figure 4). *Hercules* explored this feature, which is made up of a ring of various-sized rocks with a small pile in the middle, visible in the lower right corner of Figure 2. The rocks are well rounded and partially encrusted by a muddy matrix, indicative of an erosional shoreface environment. While the exact nature and origin of this feature is unclear, the North Aegean Sea is an area where ancient settlements could be preserved, having been inundated by post-glacial sea level rise (Kraft et al., 1983).

In July 2010, *Nautilus* returned to Anzac Cove and conducted a more comprehensive acoustic survey of this area. Approximately 30 of these stone features were found with side-scan sonar. Each varied in morphology, but all were roughly circular and measure about 40 m in diameter. In addition, we found all of these features at depths from 55 to 70 m within a 1-km radius of the *Triumph* shipwreck (Figure 3). This area of the Dardanelles and the Aegean shelf to the south was exposed subaerially during

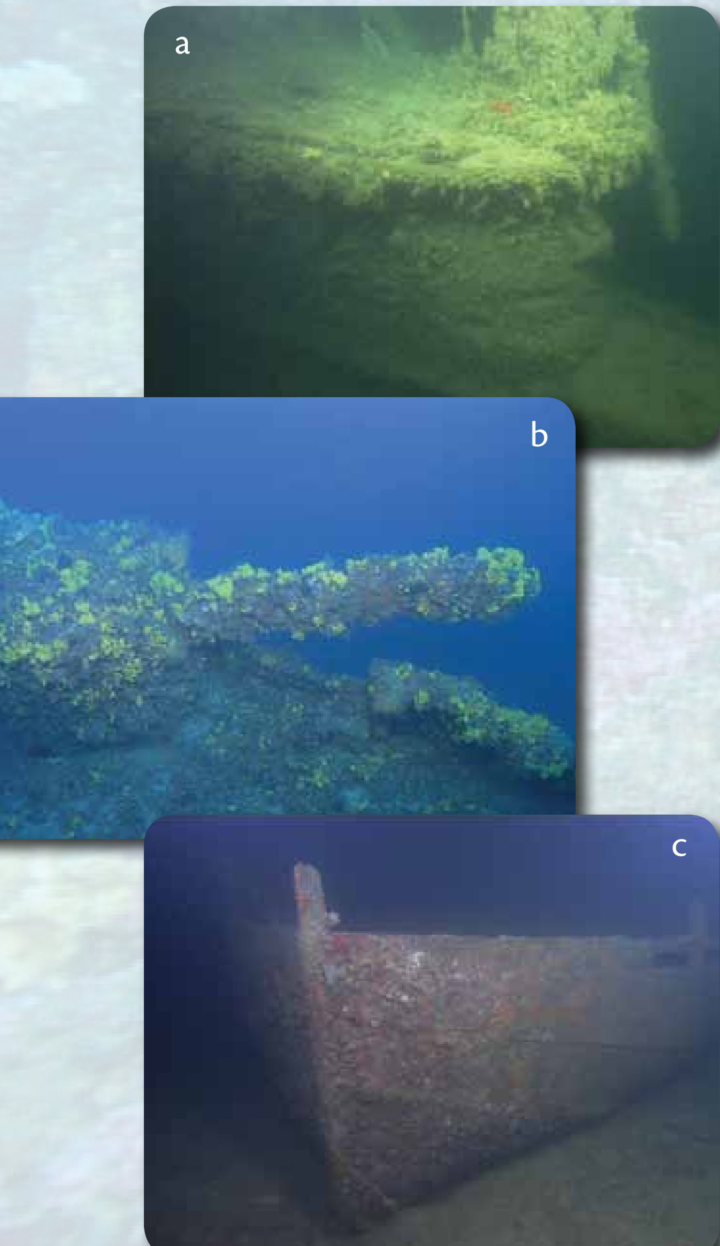


Figure 1. High-definition image captures of warship wreck sites: (a) Australian submarine, *AE2*, (b) light cruiser, *Breslau*, and (c) landing craft.

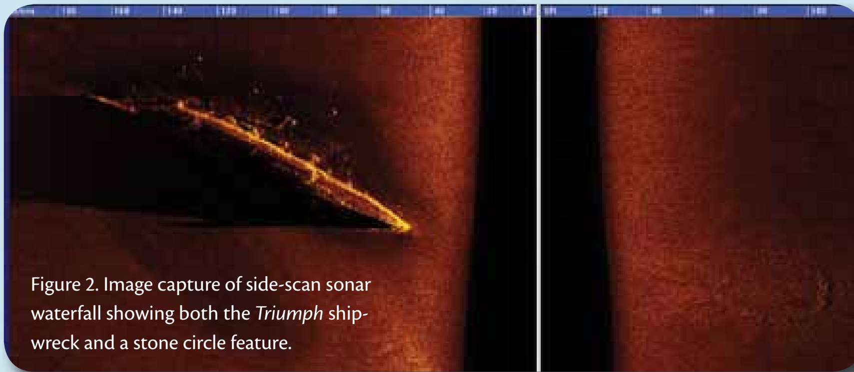


Figure 2. Image capture of side-scan sonar waterfall showing both the *Triumph* shipwreck and a stone circle feature.

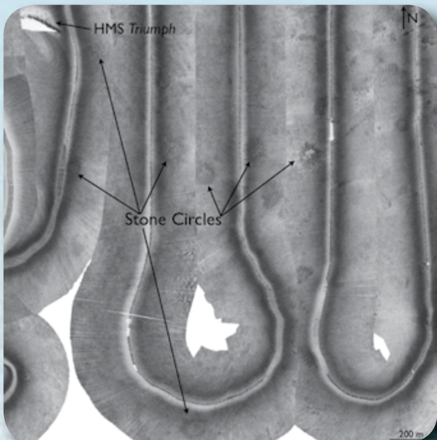


Figure 3 (above). Section of side-scan sonar mosaic showing *Triumph* shipwreck and positions of stone circle features to the southeast.

Figure 4. High-definition image capture of ancient shipwreck, *Gallipoli A*. Handles and mouths of amphoras are visible beneath the encrustations.

the Quaternary. The present-day seafloor represents an erosional surface created as the water level in the Aegean Sea rose (Gokasan et al., 2010). Anzac Cove's substrate lies stratigraphically above the bedrock sill, which was eroded during the evolution of Çanakkale Strait; little sediment has built up here due to the swift currents associated with the strait. *U-21* sank *Triumph* in May 1915. The U-boat's captain, Otto Hersing, wrote in his log that his submarine was damaged by depth charges dropped by the destroyers protecting the battleship during the attack (Hersing, 1932). Such explosions on or above the seabed could have displaced the beach rocks that form the erosional surface and redeposited them, thus accounting for the multitude of features in the vicinity of the battleship wreck. Further investigations will include a closer examination with divers, as well as processing of subbottom profile data to image any geological structures of these features that may lie beneath the surface.

During the survey of the cove, we observed and recorded an ancient shipwreck, dubbed *Gallipoli A*, south of *Triumph*. The wreck site consisted of a large mound of heavily concreted amphoras of Thasian or North Aegean type roughly dating to the Hellenistic period. The stacks of amphoras appear in part to remain in their original orientation, possibly held in place by the encrustations. The wreck was in good condition compared to other similar wreck sites in the Aegean (see page 15). *Gallipoli A* lies within 2.5 km of shore in an area where bottom trawling is prohibited. This location, as well as the designated no-dive zone around the wreck of *Triumph*, have protected the ancient wreck from damage. Trawl scars were observed with side-scan sonar farther out from shore during the survey, but this wreck's fortunate location in close proximity to both the battle site and the coast illustrate the tangible benefits of such fishing restrictions on submerged cultural resources.

Exploration of the Anaximander Mud Volcanoes

By Timothy M. Shank, Santiago Herrera, Walter Cho, Christopher N. Roman, and Katherine L. Croff Bell

The Anaximander Mountains—Anaximander, Anaximenes, and Anaxagoras—located in the Mediterranean Sea between the Hellenic and Cyprus arcs (Figure 1) were formed in large part due to the ongoing convergence of the African and Anatolian plates (Zitter et al., 2006). As a result, it is a region of active mud volcanism and gas hydrate formation (Lykousis et al., 2009) that hosts (little known) chemosynthetic fauna, largely endemic to the Mediterranean. Previous expeditions observed methane seepage through these volcanoes and thriving chemosynthetic communities of megafaunal invertebrates. These communities stand in stark contrast to the low faunal biodiversity of the nonchemosynthetic surrounding deep Mediterranean seafloor (Danovaro et al., 2010).

In September 2010, we explored the summits and flanks of three mud volcanoes, Kazan, Amsterdam, and Thessaloniki, between 1300-m and 2000-m depth and two volcanic seamounts, Anaximenes and Anaxagoras (Figure 2). We discovered chemosynthetic cold-seep communities in previously unexplored areas of the mud volcanoes. These communities, consisting of siboglinid tubeworms and thyasirid clams, were similar, yet more widely distributed as small, localized patches compared to ones documented in the past (Olu-Le Roy et al., 2004).

Exploration of the three mud volcanoes documented diverse seep habitats in more than two dozen localized seep areas. We observed extinct and active seep sites with an abundance and richness of fauna rivaling those of previously known seep communities in the Mediterranean (Figure 3; Olu-Le Roy et al., 2004). The dominant and most abundant community members were siboglinid tubeworms (*Lamellabrachia* sp.), amphipods, brachyuran crabs, echinoid sea urchins, galatheid squat lobsters, mytilid mussels, and lucinid, vesicomyid, and thyasirid clams. Active seepage on the northern side of Kazan mud volcano's summit near ~1720-m depth fueled aggregations of tubeworms and bivalves in an area more than a 300 m^2. Amsterdam mud volcano (summit near 2050-m depth) hosted tubeworms and bivalves, and abundant crabs. In both of these areas, observations of numerous sediment scars were consistent with hypothesized bottom feeding of beaked whales (Woodside et al., 2006). Our observations of active and extinct seepage areas (as evidenced by the extent of bivalve shell aggregations) add significantly to our ability to determine the present and historical sizes and distributions of the seepage fields and their possible contribution to the ecology and chemistry of the Mediterranean Sea.

The seafloor of Anaximenes and Anaxagoras seamounts was generally sediment covered, even on steep razorback ridges and summits. In contrast to the mud volcanoes, the dominant megafauna on Anaximenes and Anaxagoras

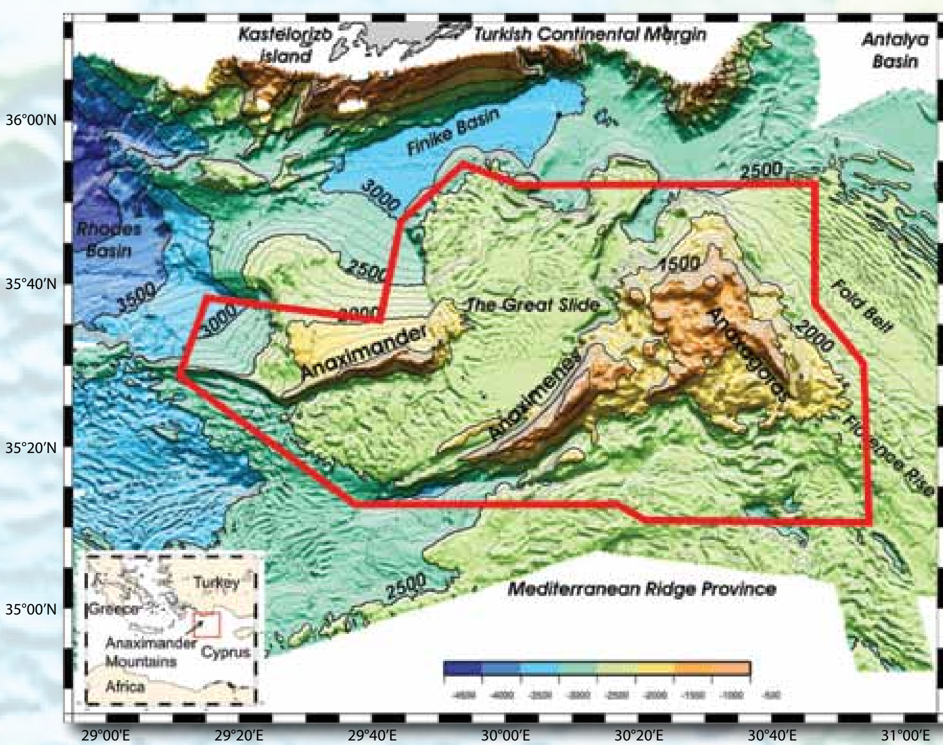


Figure 1. Bathymetric map of the Anaximander Mountain region and surrounding basins. Inset map shows location within the eastern Mediterranean Sea. Contour interval = 100 m (from Lykousis et al., 2009).

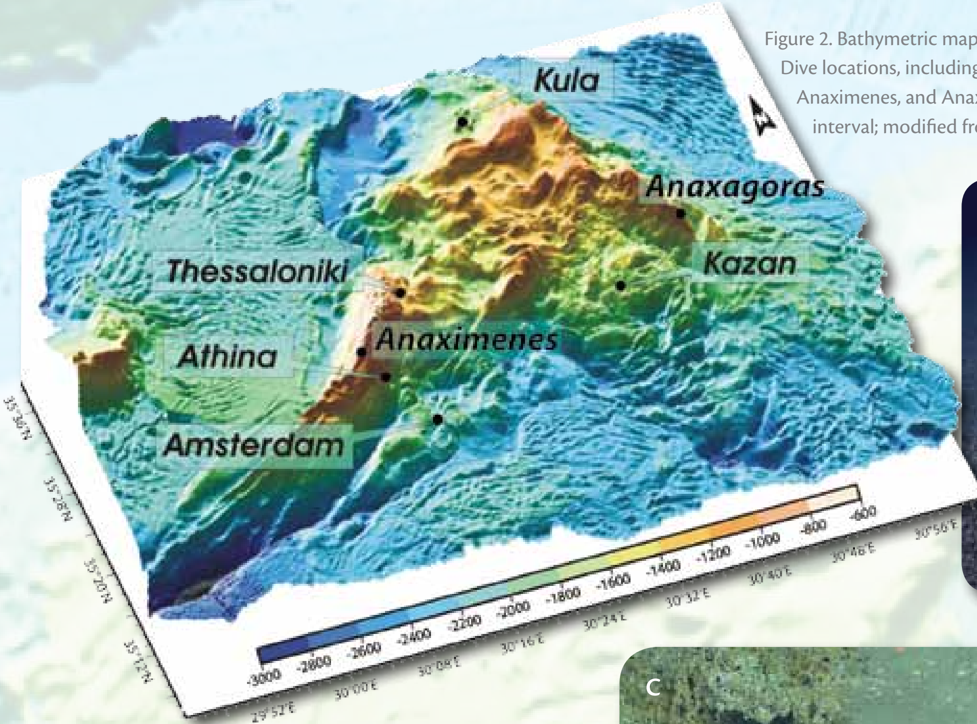


Figure 2. Bathymetric map of the region of exploration. Dive locations, including Kazan, Amsterdam, Thessaloniki, Anaximenes, and Anaxogoras are shown (20–50-m grid interval; modified from Lykousis et al., 2009).

were local patches of cold-water octocorals and scleractinian corals. Brittle stars, chirostylid crabs, shrimp, and polychaetes, typically observed living on deepwater corals on seamounts worldwide, were not observed on corals in the Anaximenes and Anaxagoras region. Other organisms observed thriving on these hard substrates included actinarians and solitary scleractinian (cup) corals. Remarkably, these cup corals were also observed on the exposed surfaces of (ancient) shipwrecked amphorae, suggesting that these anthropogenic artifacts could constitute important habitats for these organisms as well as providing information (through radiocarbon dating) about the currently unknown rates of colonization and growth of these developing coral ecosystems.

Future exploration and investigation of mud volcanoes and gas hydrate-related seeps in the Anaximander region will be key to understanding their important role in accessing global carbon budgets, nonconventional energy sources, marine geohazards, and the evolution and diversity of deep-sea life.

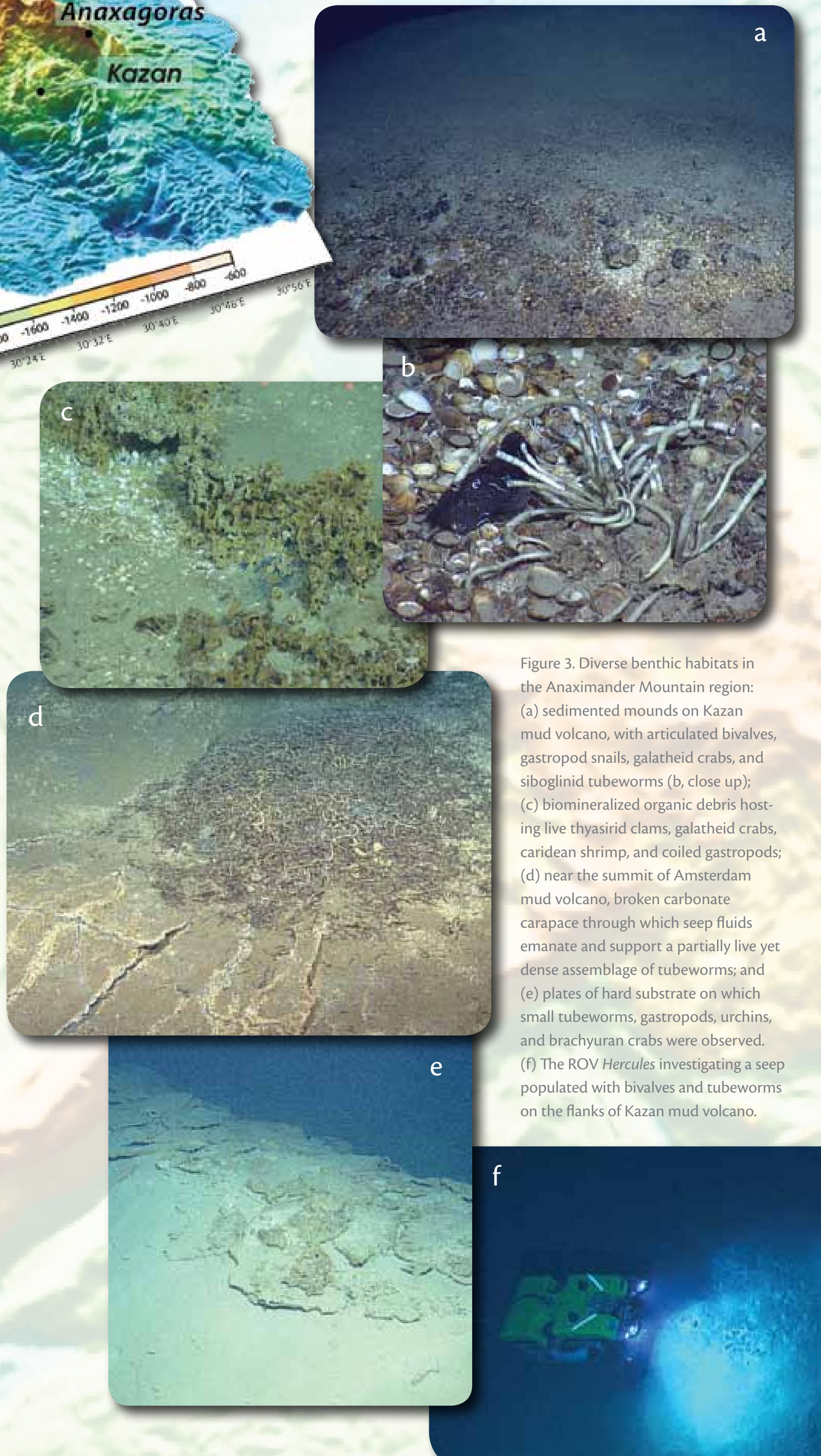


Figure 3. Diverse benthic habitats in the Anaximander Mountain region: (a) sedimented mounds on Kazan mud volcano, with articulated bivalves, gastropod snails, galatheid crabs, and siboglinid tubeworms (b, close up); (c) biomineralized organic debris hosting live thyasirid clams, galatheid crabs, caridean shrimp, and coiled gastropods; (d) near the summit of Amsterdam mud volcano, broken carbonate carapace through which seep fluids emanate and support a partially live yet dense assemblage of tubeworms; and (e) plates of hard substrate on which small tubeworms, gastropods, urchins, and brachyuran crabs were observed. (f) The ROV *Hercules* investigating a seep populated with bivalves and tubeworms on the flanks of Kazan mud volcano.

Exploration of the Kolumbo Volcanic Rift Zone

By Steven Carey, Katherine L. Croff Bell, Paraskevi Nomikou, Georges Vougioukalakis, Christopher N. Roman, Kathleen Cantner, Konstantina Bejelou, Maria Bourbouli, and Julie Fero Martin

The seafloor northeast of Santorini volcano in Greece consists of a small, elongated rifted basin that has been the site of recent submarine volcanism (Sakellariou et al., 2010). This area lies within the Cyclades back-arc region of the present Hellenic subduction zone where seafloor of the eastern Mediterranean Sea is descending beneath the Aegean microplate. The Cycladic region and the Aegean Sea as a whole are known to be locations of southeasterly back-arc extension and continental crust thinning. Nineteen submarine volcanic cones occur within this small rift zone (Figure 1).

Previous SeaBeam multibeam bathymetric mapping and seismic studies indicate that many of the smaller volcanic cones are built above the present seafloor, while others are partly buried, indicating a range of ages for activity along this volcanic line. None of the cones to the northeast of Kolumbo had been explored in detail prior to the 2010 E/V *Nautilus* cruise. The ROV *Hercules* explored the slopes, summits, and craters of 17 of the 19 volcanic centers identified on multibeam maps of the area. The submarine volcano's summits ranged from 18–450-m water depth. In general, the domes/craters northeast of Kolumbo were sediment covered and showed little evidence of recent volcanic activity. We found volcanic rock outcrops in the crater walls and slopes of some of the cones, but they typically consisted of pumice and lava fragments that had been cemented together by biological activity, indicative of the lack of recent eruptions. One cone, target 68 (Figure 1), showed evidence of low-temperature hydrothermal circulation on the summit and upper flanks in the form of stream-like manganese precipitates emanating from pits and fractures. Geochemical analysis of samples collected on the northeast cones will provide insights into the sources of magmas to these centers and their relationship to the nearby Santorini volcanic complex.

Unlike the smaller cones of the northeast rift zone, Kolumbo exhibits dramatic evidence of recent volcanic activity and the potential for future eruptions. Kolumbo is a 3-km-diameter cone with a 1500-m-wide crater, a crater rim as shallow as 15 m in the southwest, and a crater floor 500 m below sea level (Figure 1). ROV explorations of the crater walls revealed a fascinating underwater landscape of pumice deposits up to several hundred meters thick. These deposits formed as a result of the

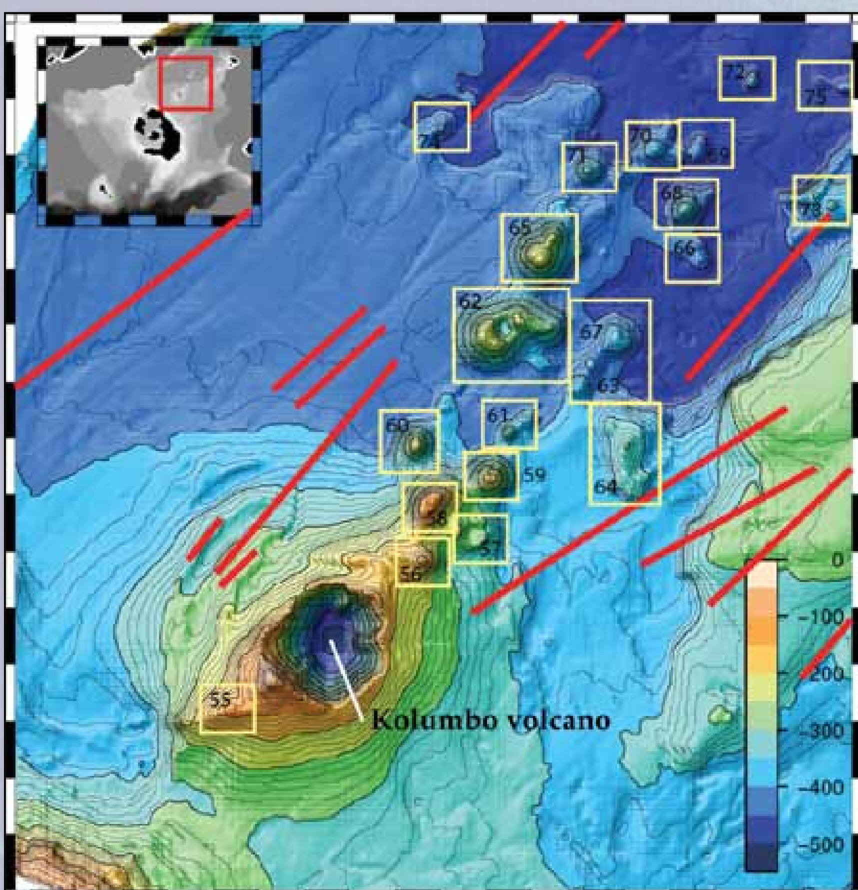


Figure 1. Bathymetric map of Kolumbo and other submarine cones in the Kolumbo volcanic rift zone northeast of the Santorini volcano, Greece. Inset map shows the main island of Santorini and location of study area. Solid red lines are northeast/southwest-trending faults in the rift basin. Unpublished swath bathymetric data collected in 2001 aboard R/V *Aegaeo* around Santorini, Greece, by S. Alexandri, P. Nomikou, and D. Ballas.

explosive 1650 CE eruption that caused significant damage and fatalities on nearby Santorini Island. Mass wasting since the eruption has sculptured complex scalloped outcrops with knife-edge promontories that extend outward from the crater walls (Figure 2; see page 16, Figure 3). Observations and samples from this sequence will provide important information about the processes of shallow-water explosive volcanism and the hazards that it poses to island and coastal communities.

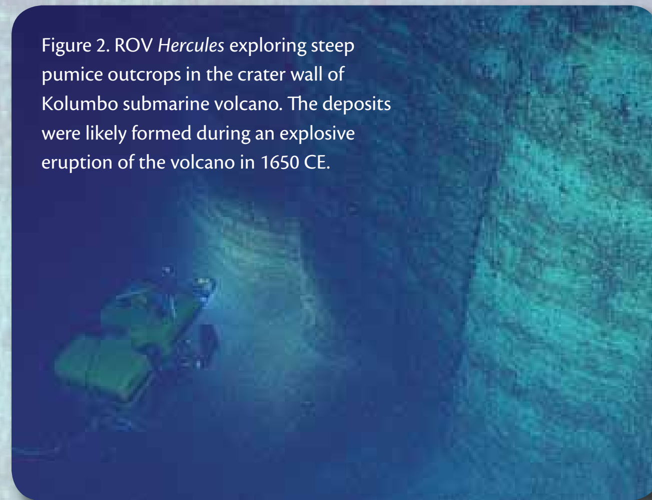


Figure 2. ROV *Hercules* exploring steep pumice outcrops in the crater wall of Kolumbo submarine volcano. The deposits were likely formed during an explosive eruption of the volcano in 1650 CE.

On the floor of Kolumbo's crater (500-m depth) is an active hydrothermal vent field, first discovered in 2006 (Sigurdsson et al., 2006), where a Kuroko-style massive sulfide deposit is currently forming (Figure 3a). Only a handful of such deposits have been identified in the world's ocean and they are of great interest because of their higher gold and silver contents compared with the well-known black smoker vents found along mid-ocean ridges (Tivey, 2007; Figure 3b). New ROV explorations of the Kolumbo hydrothermal field led to the discovery of the largest vent structure yet found at the volcano. In the northern part of the crater, a 6-m-high, bacteria-draped vent, nicknamed Poet's Candle, rises above the sediment-covered floor (Figure 3c). An interesting characteristic of Kolumbo's hydrothermal vents is the active discharge of gas bubbles together with high-temperature fluids. This feature is unique to relatively shallow-water volcanic centers in subduction zone environments. Samples of these gases were collected on cruise NA007 using special gas-tight sampling bottles (Figure 3d). Ongoing analyses of the samples by John Lupton (NOAA/PMEL) and Marv Lilley (University of Washington) will determine gas composition and enable interpretations to be made about its origin. In addition, detailed mapping of the hydrothermal field using photomosaics and multibeam data is the first attempt to construct an integrated, high-resolution image of this type of vent system at a subduction zone volcano (see page 15). Such a map will be valuable in assessing the complete distribution of vents and their sizes, as well as their contribution to the total mineral resources of the deposit.

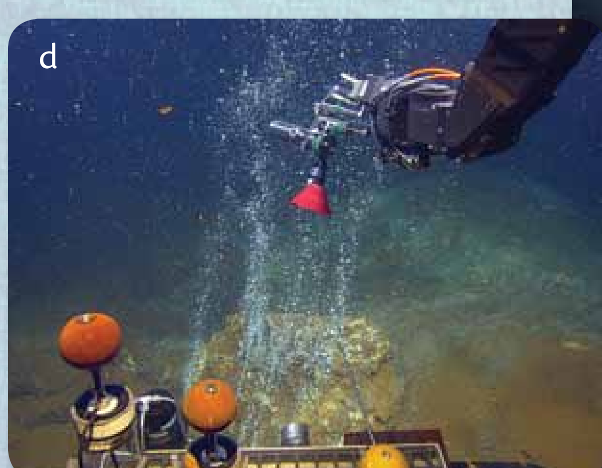


Figure 3. The northern part of the Kolumbo volcano's crater floor has an extensive hydrothermal vent field where massive sulfide chimneys are venting high-temperature fluids (> 200°C) and gases. (a) ROV sampling massive sulfide chimney. (b) Broken vent chimney revealing zonation of hydrothermal minerals. (c) Six-meter-high "Poet's Candle" hydrothermal vent with bacterial covering. (d) Sampling gases being given off by hydrothermal vent using a gas-tight container.

Mapping of a Debris Avalanche Offshore Santorini Volcano

By Katherine L. Croff Bell, Paraskevi Nomikou, Steven Carey, Julie Fero Martin, and Kathleen Cantner

We discovered hummocky deposits on the eastern submarine slope of Santorini using multibeam bathymetric mapping and seismic profiling aboard R/V *Aegaeo* in 2006 (Sigurdsson et al., 2006). The hummocks are similar in morphology to debris flows found in other volcanic environments, and their backscatter signature indicates that they are different in composition than the surrounding seafloor.

During the 2010 *Nautilus* field season, we carried out a side-scan sonar survey and visual exploration of the hummocks using the ROV *Hercules* to determine their depositional origin. A 40 km^2 area was covered using *Diana's* 300-kHz side-scan sonar transducers mounted on the sides of *Argus*. These data revealed many more hummocks than were previously known to exist. In the basin on the southeast side of Santorini, near Anafi Island, the seafloor consists of a large number of blocks that range from 5–200 m in diameter and stand approximately 5–40 m proud of the surrounding seafloor (Figure 1). The majority of the hummocks have flat tops with vertical sides and occur in clusters (Figure 2). The hummocky sequence extends more than 20 km from Santorini, and seismic profiles indicate a sediment thickness of the order 50 m for much of this area. Visual inspection with Hercules and sampling of the hummocks revealed that they are primarily composed of pyroclastic flow deposits, similar to those deposited on land by the Minoan eruption of Santorini 3600 years ago (Figure 3).

We propose that the deposit is the result of a multistage landslide event that was caused by the July 9, 1956, earthquake and/or aftershock that occurred near the islands of Amorgos and Santorini (Papadopoulos and Pavlides, 1992). The main shock or aftershock triggered a massive slump on the eastern shelf of Santorini, which evolved into a debris avalanche, depositing hummocky blocks at the base of the slope, and further transformed into a suspension flow that traveled over 20 km from the initial failure. This landslide event caused a tsunami that affected the islands across the entire southern Aegean Sea. Understanding of earthquake-landslide dynamics has important implications for hazard assessment in this seismically active, highly populated region of the world.

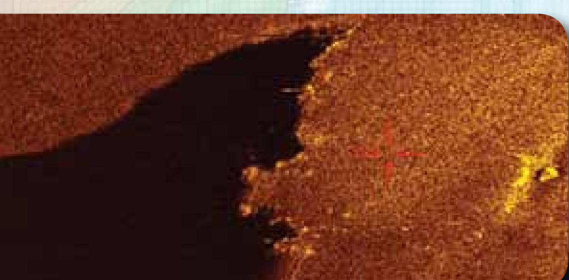


Figure 1. Side-scan sonar image (300 kHz) of one of the hummocky blocks found east of Santorini. The blocks were typically on the order of a few tens of meters in diameter and 1–10-m tall.

Figure 3. Underwater imagery of one of the hummocky deposits reveals that they are composed of pyroclastic flow material similar to sediment deposited on land during the Minoan eruption of Santorini. Black lithics and white pumice layers can be seen in the stratigraphy of this hummock.

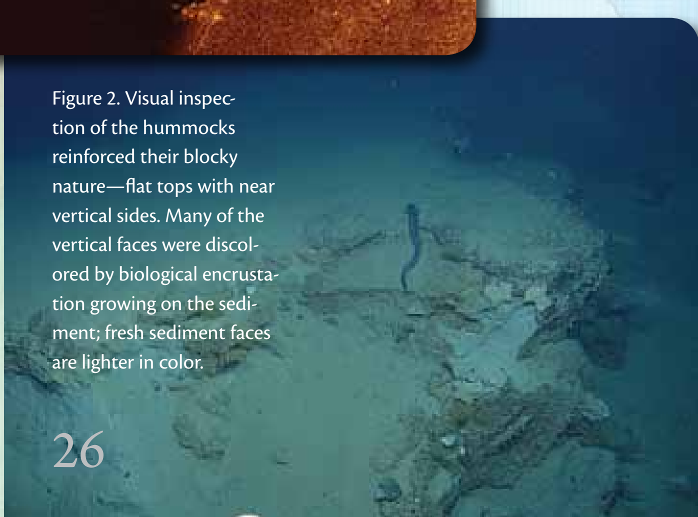


Figure 2. Visual inspection of the hummocks reinforced their blocky nature—flat tops with near vertical sides. Many of the vertical faces were discolored by biological encrustation growing on the sediment; fresh sediment faces are lighter in color.

Figure 4. An abundance of sea life was discovered on the hummocks, including sea urchins, fish, sponges, and corals.

Exploring the Nisyros Submarine Volcanic Field

By Paraskevi Nomikou, Katherine L. Croff Bell, Georges Vougioukalakis, Isidoros Livanos, and Julie Fero Martin

On the eastern extent of the Hellenic Volcanic Arc lies the volcanic centers of Kos, Yali, and Nisyros. Recent swath bathymetric surveys and seismic profiling led to the discovery of several submarine volcanic centers and massive underwater volcaniclastic deposits that were the focus of our fieldwork in this region (Papanikolaou and Nomikou, 2001).

Located northeast of Strongyli islet, Avyssos crater is believed to be the origin of a massive eruption of the Kos ignimbrite 160,000 years ago (Nomikou, 2004). Exploration of Avyssos showed that it is covered with fine-grained sediment full of bioturbation holes and mounds without any evidence of hydrothermal activity (Figure 1). Geochronological dating and geochemical analysis of samples will indicate their relation to the Kos ignimbrite.

Yali and Strongyli represent Late Pleistocene to Holocene volcanic islands that developed between the islands of Kos and Tilos. ROV exploration of the eastern flank of Yali revealed wave-type sediment structures, as well as linear fractures at various depths. We discovered craters on the northwest slopes of Strongyli (Figure 2), aligned with ENE-WSW trending fractures, without any sign of hydrothermal activity. Heavy biogenic encrustations cover the volcanic rock outcrops on the flanks of both Yali and Strongyli (Figure 3). Analysis of recovered samples will provide information about their relationship to deposits on the nearby islands.

Several volcanic domes are located northeast of Kondelioussa Island and southwest of Nisyros (Nomikou, 2004). In 2000, a submersible dive on one of these domes using *Thetis* of the Hellenic Center for Marine Research revealed an underwater crater, several meters in diameter, at 430-m depth (Papanikolaou and Nomikou, 2001). In 2010, the ROV *Hercules* explored this dome and others in the area (Figure 4). In many cases there were large fields of feather corals with elasmobranch egg cases on them, as well as patches of biogenic sediments with abundant sponges.

The hummocky topography southeast of Nisyros Volcano (Nomikou et al., 2009) is likely a debris avalanche deposit that originated onshore. A detailed side-scan survey of this area enabled evaluation of the surface morphology of the avalanche field and comparison with more recent examples of known debris avalanche deposits. Using *Argus*, we investigated the distribution, size, and lithology of selected hummocks.

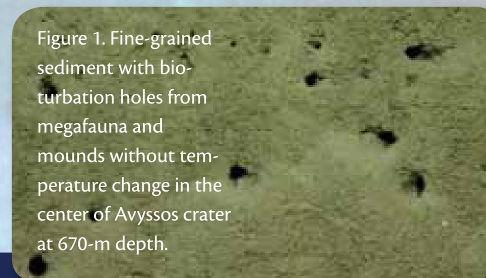


Figure 1. Fine-grained sediment with bioturbation holes from megafauna and mounds without temperature change in the center of Avyssos crater at 670-m depth.

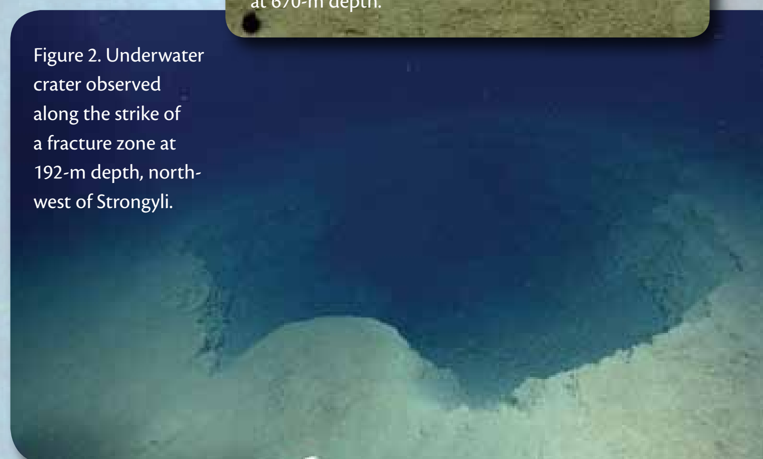


Figure 2. Underwater crater observed along the strike of a fracture zone at 192-m depth, northwest of Strongyli.

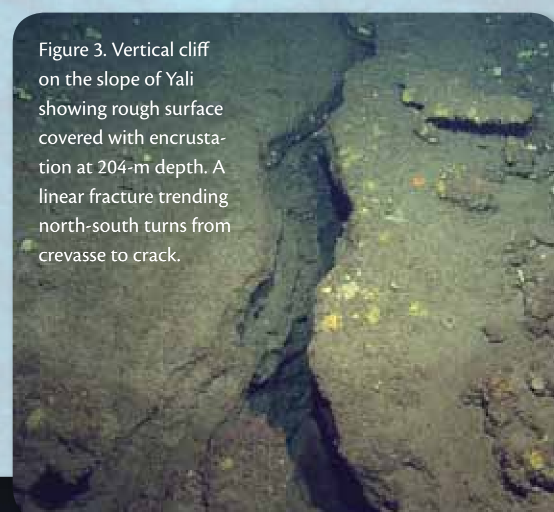


Figure 3. Vertical cliff on the slope of Yali showing rough surface covered with encrustation at 204-m depth. A linear fracture trending north-south turns from crevasse to crack.

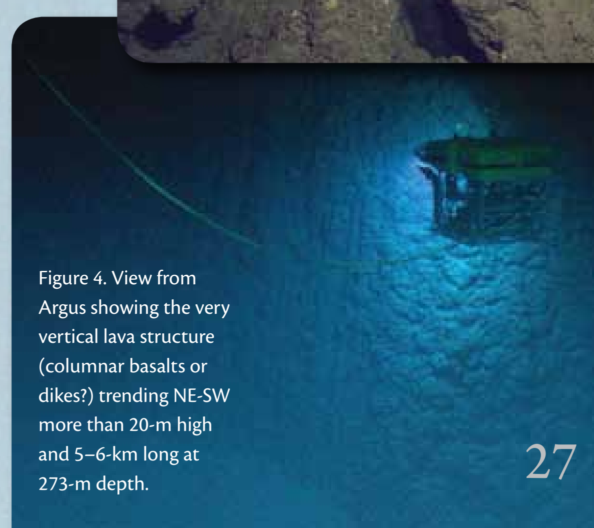


Figure 4. View from Argus showing the very vertical lava structure (columnar basalts or dikes?) trending NE-SW more than 20-m high and 5–6-km long at 273-m depth.

Discovery of Sinkholes and Seeps on Eratosthenes Seamount

By Larry Mayer, Katherine L. Croff Bell, Robert Ballard, Stelios Nicolaides, Kostas Konnaris, John Hall, Gideon Tibor, James A. Austin Jr., and Timothy Shank

Eratosthenes Seamount, located in the eastern Mediterranean between Cyprus and the Nile Cone, is one of the largest subsurface features of the region. The elliptically shaped seamount is 120-km long by 80-km wide and stands 2000-m proud above the surrounding Eratosthenes Abyssal Plain, reaching a depth of approximately 700 m at its shallowest (Figure 1). The seamount is thought to be a continental fragment that broke off the northern margin of the African Plate in the early Mesozoic period. By the early Cretaceous, Eratosthenes Seamount was a shallow-water carbonate platform that subsided and was overlain by deep-sea pelagic carbonates (Robertson, 1998). The feature was uplifted in the early to middle Miocene, and may still be uplifting now as it begins to collide with the Cyprus margin. During the Messinian dessication crisis (6.5–5.3 million years ago) Eratosthenes Seamount emerged several hundred meters above sea level and eroded intensely, leaving a very flat surface riddled by karst-like topography (Mascle et al., 2006). The seamount is also cut by a series of east-west trending normal faults thought to be associated with crustal flexure related to the collision of the seamount with the Cyprus active margin (Roberston, 1998). Dimitrov and Woodside (2003) reported numerous pockmarks on the surface of the seamount that are thought to represent extrusions of gaseous muddy sediments from the pre-Pliocene erosional surface.

We explored Eratosthenes Seamount in two phases. The initial phase used only the 300-kHz side-scan sonar on *Argus* and focused on the top of the seamount to identify potential targets. Particular attention was paid to the southern portion of the seamount where pockmarks had been previously described as well as the large east-west trending fault on the top of the seamount. These reconnaissance surveys were followed by closer examination of the most promising targets using the high-definition cameras mounted on *Argus* and *Hercules* as well sampling by *Hercules*.

The side-scan sonar on *Argus* imaged numerous large circular features (tens to a few hundreds of meters in diameter, 10–30-m deep) in the region where pockmarks had been reported. Closer examination of these features' characteristics led us to question their origin as gas or extrusion features (i.e., pockmarks). The walls were typically vertical or near vertical with outcropping limestone beds, there was no evidence of gas or water extrusion, and high-resolution subbottom profiles showed that sections were missing rather than material ejected. Closer examination with *Hercules* (Figure 2) revealed that all of

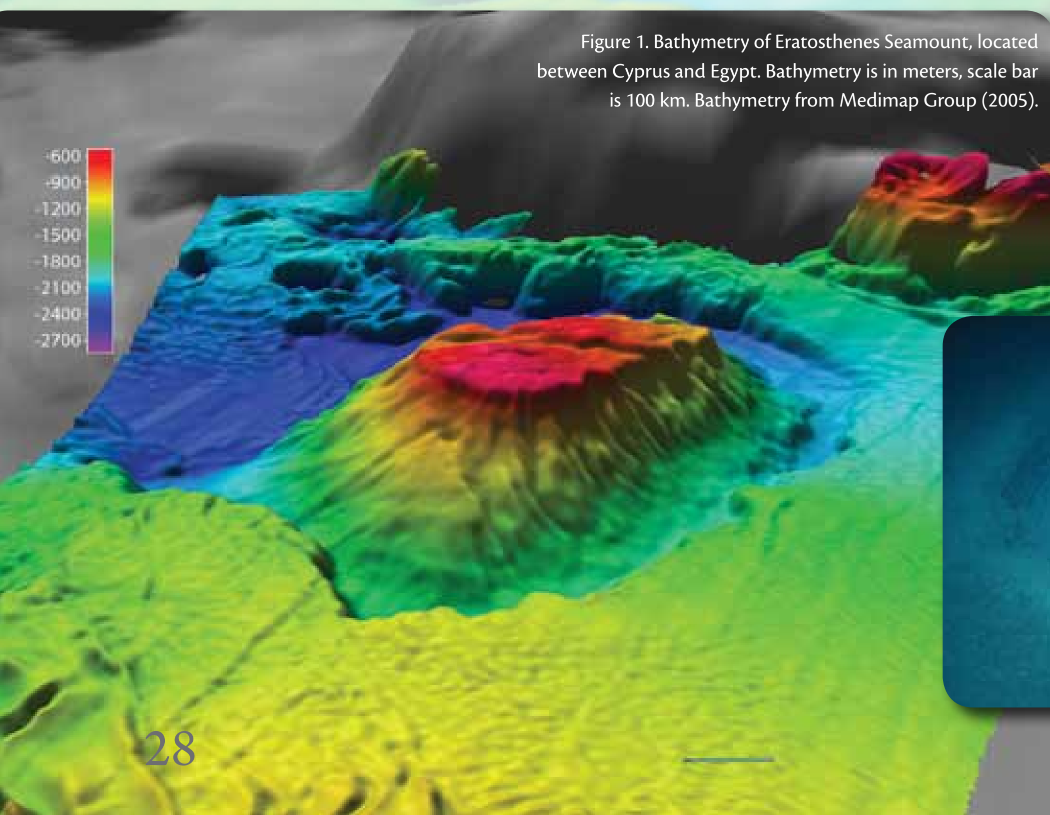


Figure 1. Bathymetry of Eratosthenes Seamount, located between Cyprus and Egypt. Bathymetry is in meters, scale bar is 100 km. Bathymetry from Medimap Group (2005).

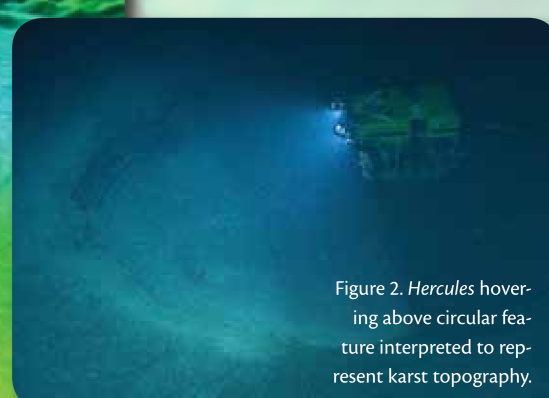


Figure 2. *Hercules* hovering above circular feature interpreted to represent karst topography.

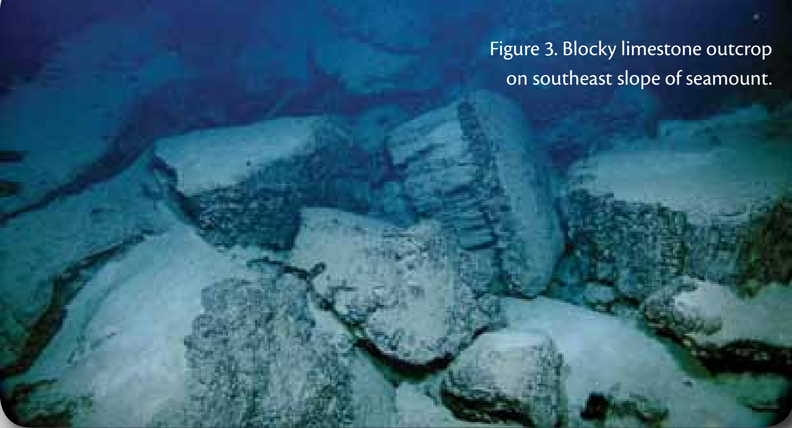


Figure 3. Blocky limestone outcrop on southeast slope of seamount.

the circular features imaged were the result of karst-like collapse features (sinkholes)—the result of subaerial exposure of deep-sea carbonates during the Messinian that created an exotic submerged seascape.

Exploration of the southwest flank of the seamount revealed near-vertical walls of massive, blocky limestone with many collapse features (Figure 3). As we moved downslope, we encountered a region of brown staining centered around 950-m depth along mostly vertical cracks, and there were concentrations of vent-like communities, including small tube worms (*Siboglinidae* sp.), clams, urchins, and small crabs (Figure 4). Shimmering water was visibly associated with the tube worms and temperature measurements made in proximity to the tube worms were as much as 1°C above ambient temperature. At the base of the massive limestone outcrop, we found many thousands of small bivalve shells (mostly just shells—very few live clams; Figure 5). These clams were present for many kilometers along the base of the outcrop. In addition to this clear indication of fluid expulsion on the southeast flank of the seamount, we found further evidence of active tectonism during a *Hercules* dive along the northern flank of the large, east-west trending fault that crosses the top of the seamount. This dive revealed spectacular slickensides on a near-vertical wall at base the fault (Figure 6). This layer could be traced for several meters, and then it transitioned into another blocky limestone layer that was covered with living and dead scleractinian corals.

As hoped, Eratosthenes Seamount proved to be a remarkable target for exploration and discovery. It is one of the few accessible examples of a continental fragment that is colliding with a subduction zone. Further study will unquestionably shed new light on the processes of accretion and the fluid flow associated with it.

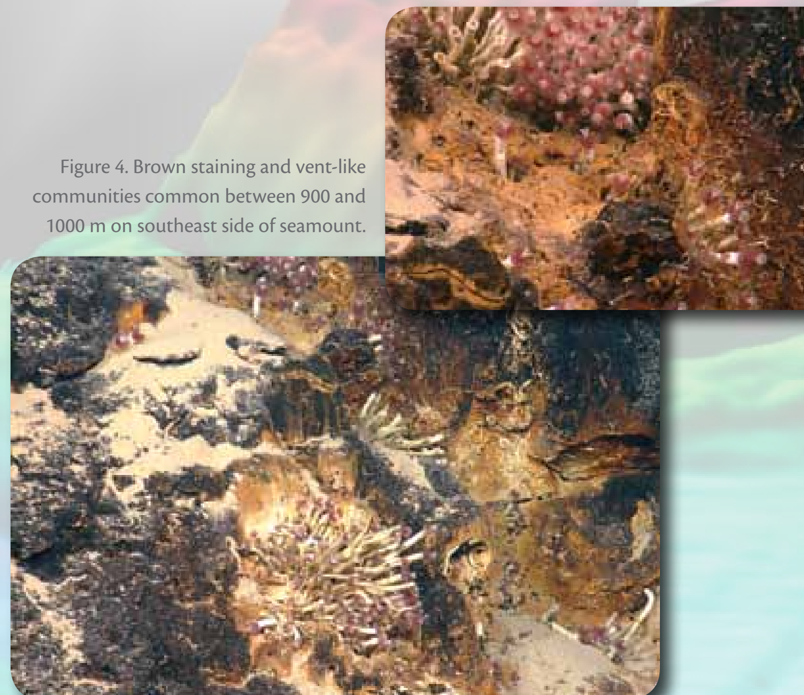


Figure 4. Brown staining and vent-like communities common between 900 and 1000 m on southeast side of seamount.

Figure 5. Massive occurrence of small clam shells associated with vent activity along base of a limestone outcrop.

Figure 6. Slickensides seen on vertical outcrop on northern wall of central fault on top of Eratosthenes Seamount.

Archaeological Discoveries on Eratosthenes Seamount

By Shelley Wachsmann, Stella Demesticha, Irini Chryssoheri, and Katherine L. Croff Bell

Eratosthenes Seamount is of particular interest to archaeologists because it lies astride the ancient sea route between Cyprus and Egypt. This blue-water pathway was well established by the 14th century BCE, when Rib-Addi, the beleaguered king of Byblos (modern Gebail in Lebanon), sent a clay tablet written in Akkadian to the Egyptian pharaoh documenting the voyage of an Egyptian official named Amanmasha to Egypt "via *Alashia*" (Wachsmann, 1986). This text both confirms that the geographical term *Alashia* must refer to all or part of Cyprus and also serves as the earliest textual evidence of the Cyprus-Egypt sea route, which must have crossed Eratosthenes Seamount. Additionally, the seamount's geographical features and the current regime in the eastern Mediterranean Sea result in a minimal sedimentation rate—vital for locating ancient shipwrecks, as sediments can bury them, making them virtually invisible to modern benthic search techniques.

The expedition team documented archaeological remains, but no artifacts were raised, or even touched. We observed numerous ceramic artifacts on the seafloor, many in pristine condition, consisting primarily of amphoras (two-handled storage jars), but also cooking pots, bowls, and a flask. We date the earliest artifact tentatively to the Iron Age II, ca. 10th–6th centuries BCE (Figure 1). The majority of the solitary finds, however, span the end of the Roman and beginning of the Byzantine periods, roughly 4th–6th centuries CE. Particularly common were the long, torpedo-shaped jars typical of this period (Figure 2), which may represent cargo jettisoned by ships in distress (see Jonah 1:5; Acts 27:18).

The survey revealed two fairly recent shipwrecks. Shipwreck FS131 carried a pair of iron grapnel anchors (Figure 3). The second (Shipwreck FS155) contained an admiralty anchor attached to a chain and what appears to be a heavily concreted flintlock musket (Figure 4). As anchor chain was only introduced in the early 19th century, it gives a *terminus post quem* (time after which) for that wreck (Curryer, 1999). The musket also suggests a 19th century date within this context. A copper or bronze cauldron was presumably used to cook the crew's meals.

The results of the 2010 survey confirm that Eratosthenes Seamount is a prime area for future archaeological exploration.

Figure 1. Iron Age Amphora, (ca. 8th–7th centuries BCE).

Figure 2. Byzantine amphora.

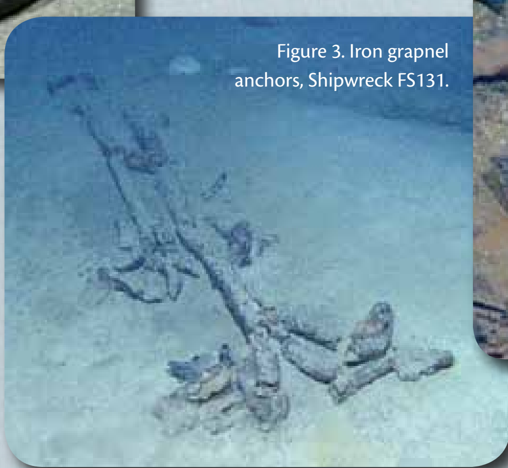


Figure 3. Iron grapnel anchors, Shipwreck FS131.

Figure 4. Flintlock musket, Shipwreck FS155.

Potential Marine Mammal-Induced Seafloor Scours on Eratosthenes Seamount

By Richard J. Bell, Larry Mayer, Kostas Konnaris, Katherine L. Croff Bell, and Robert Ballard

During visual survey work on the top of Eratosthenes Seamount, we discovered large areas covered by shallow scours in the seafloor at 800–1000-m depth. The scours were typically 10–15-cm wide, 10–20 cm deep and several meters long (Figure 1). Single scours were quite numerous throughout the surface of the southern region of the seamount, and often three to five grooves followed a single, slightly wavy line (Figure 2). Some of the scours seemed to be freshly cut with steep sides, while others were highly sedimented, which may indicate that the cuts have been made over a long period of time (Figure 3). The lack of trawl marks on the seamount, short length of scour sequences (< 100 m), haphazard distribution, and physical appearance of the grooves suggest that they were not caused by fishing gear. The scour pattern and amount of sediment displaced suggested a plowing action from a large-bodied animal.

Beaked whales are large-bodied marine mammals that inhabit the eastern Mediterranean Sea (Frantzis et al., 2003) and have been recorded foraging at depths of 1885 m (Tyack et al., 2006). Their rostrums (beaks) are long and thin, approximately 10–15-cm across (Siciliano and César de Oliveira Santos, 2003), roughly matching the width of the seafloor scours. Similar grooves found elsewhere in the eastern Mediterranean on the Kula and Napoli mud volcanoes at 1700–2100-m depth are attributed to Cuvier's beaked whale *Ziphius cavirostris* (Woodside et al., 2006). The scours that we observed on Eratosthenes Seamount were very similar in morphology to those described on the mud volcanoes and may represent the result of foraging activities or the removal of parasites and dead skin by scraping along the seafloor.

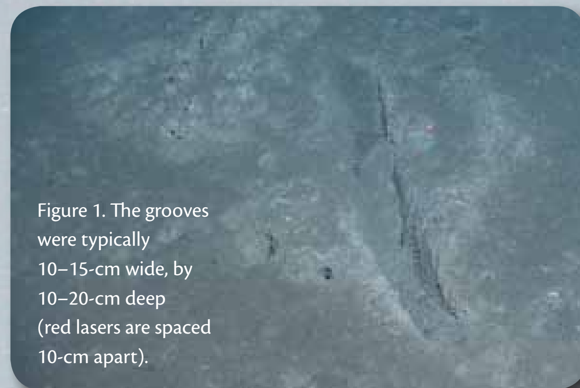


Figure 1. The grooves were typically 10–15-cm wide, by 10–20-cm deep (red lasers are spaced 10-cm apart).

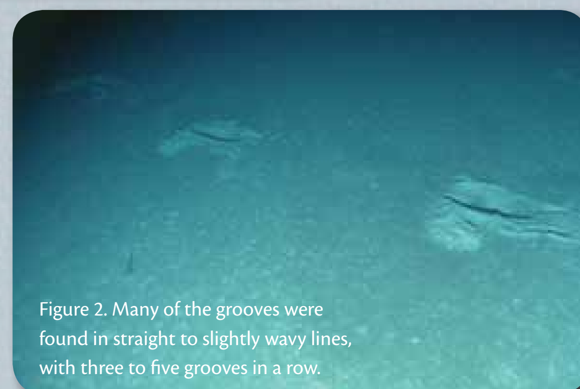


Figure 2. Many of the grooves were found in straight to slightly wavy lines, with three to five grooves in a row.

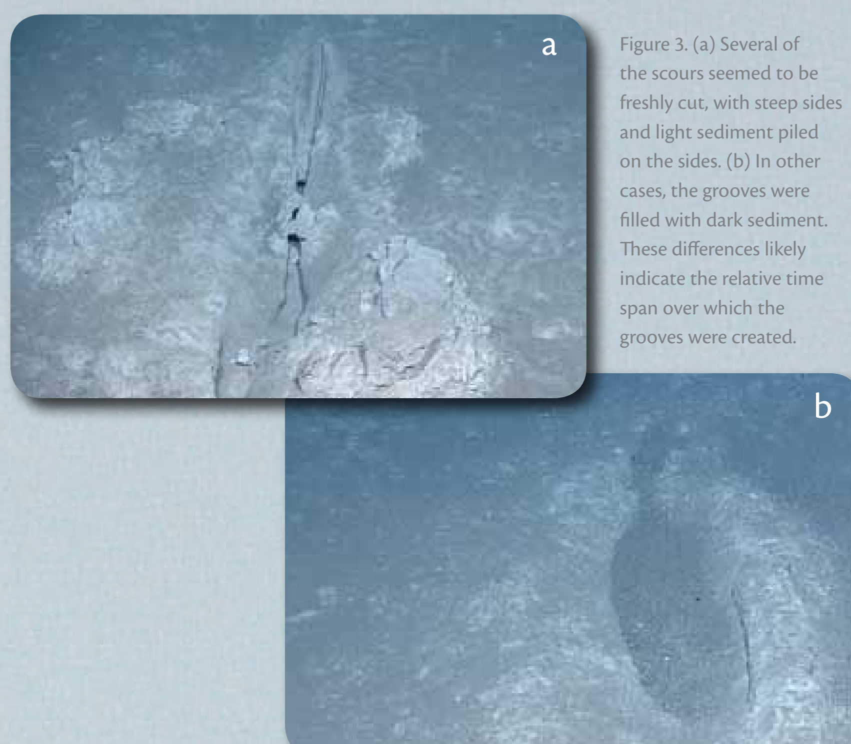


Figure 3. (a) Several of the scours seemed to be freshly cut, with steep sides and light sediment piled on the sides. (b) In other cases, the grooves were filled with dark sediment. These differences likely indicate the relative time span over which the grooves were created.

Exploring the Continental Margin of Israel

By Dwight F. Coleman, James A. Austin Jr., and Zvi Ben-Avraham

Israel's continental margin is situated in the southeastern Mediterranean, bounded to the north and east by the Cypriot Arc and the continental margins of Syria and Lebanon, and to the south and west by the Palestinian Authority's Gaza Strip, the Egyptian margin, and Nile Fan (Figure 1). This margin consists of two prominent segments, separated by the Carmel Fault structure, an active left-lateral splay of the Dead Sea Transform (Figure 1, inset) that crosscuts central Israel and extends offshore to the northwest (Schattner and Ben-Avraham, 2007). These segments exhibit different crustal thicknesses and structure. The southern segment resembles a passive rifted margin, while the northern segment resembles a sheared margin with thinner crust and narrower, steeper margin slopes. The *Nautilus* expedition was conducted entirely in the southern segment, except for some exploration of Achziv Canyon. Large slump and slide features, notably, the Palmachim Disturbance, also characterize this margin, influenced in part by active salt tectonic processes (Ben-Avraham et al., 2006).

In 2010, we conducted a two-week expedition aboard *Nautilus* entirely in the southern segment, except for some exploration of Achziv Canyon. During this expedition, we collected more than 100 km of high-resolution side-scan sonar data, investigated numerous acoustic targets identified during the sonar surveys, conducted ROV dives within three areas of Israel's margin (Figure 1), and took dozens of biological and geological samples.

ROV and side-scan sonar surveys aboard *Nautilus* relied on previously collected and processed bathymetric data from a number of sources, including the Geological Survey of Israel and the oil and gas industry. Each sonar survey identified acoustic targets on the seafloor for further visual inspection, characterization, imaging, and sampling by the *Argus-Hercules* ROV combination (Figure 2a).

In Area 1 (Figure 1), *Nautilus* explored three regions: (1) Achziv Canyon along the border with Lebanon, (2) the Dor Disturbance, a region of disturbed seafloor off Haifa adjacent to the offshore extension of the Carmel Fault structure, and (3) a large area of the central continental margin characterized by small submarine canyons. During a transect across the mouth of Achziv Canyon, we used *Hercules* to collect sediment push cores and biological and slurp samples. The sedimented, gently undulating canyon floor is composed of fine silt and clay. These sediments are often bioturbated by worms, fish, and small crabs. Sedimented canyon walls are often characterized by slumps. Small submarine canyons occur along the central continental slope, south of the offshore extension of the Carmel Fault in 700–1000-m water depth. Unlike Achziv Canyon, these canyons are characterized by steeper walls and narrower widths. We imaged and sampled near-vertical walls, including possible gas vent structures (Figure 2b).

Area 2 (Figure 1) includes a deep

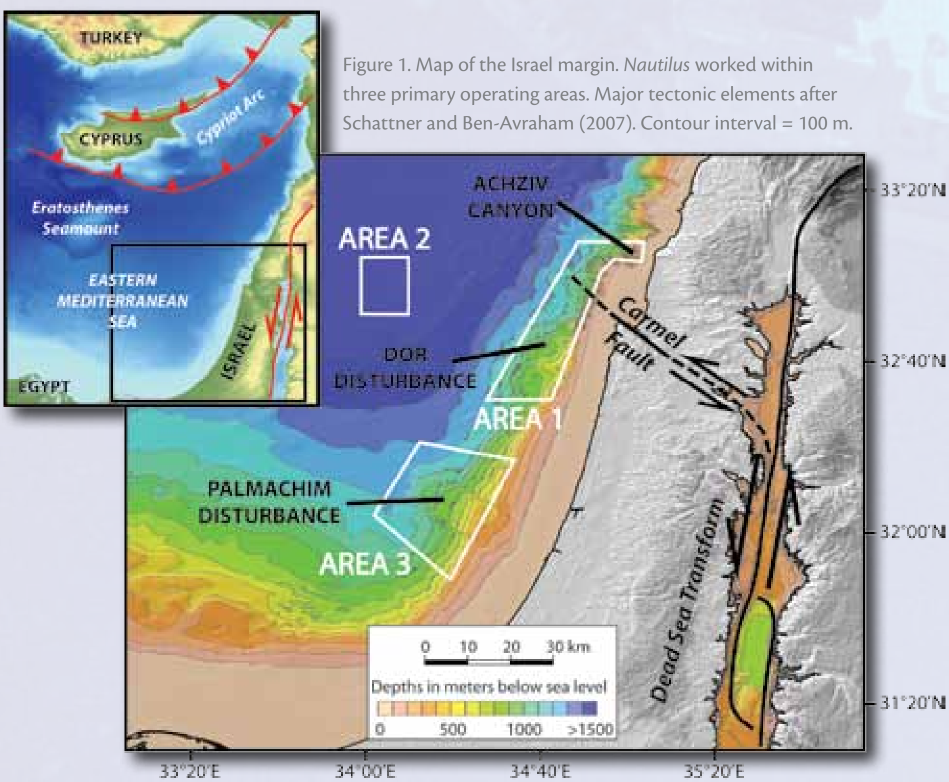


Figure 1. Map of the Israel margin. *Nautilus* worked within three primary operating areas. Major tectonic elements after Schattner and Ben-Avraham (2007). Contour interval = 100 m.

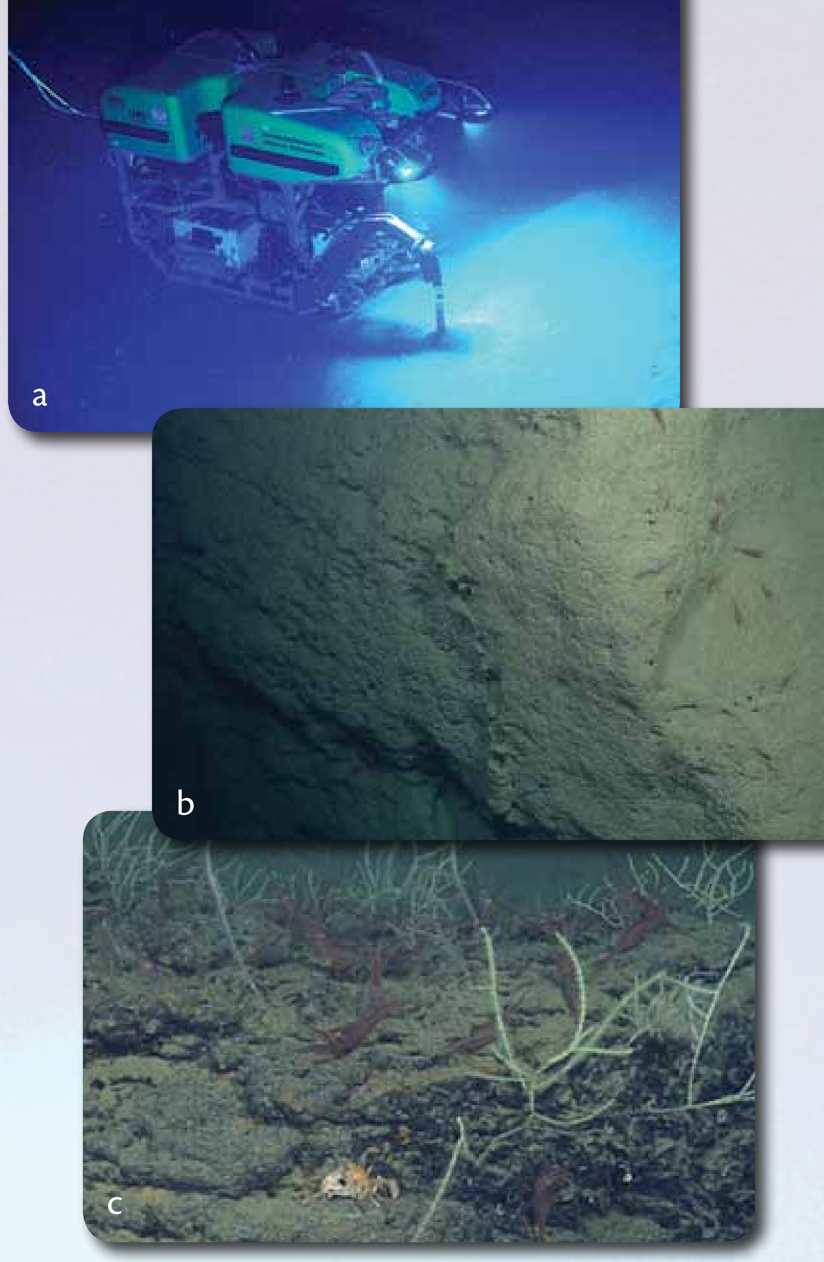


Figure 2. (a) Image taken from the *Argus* ROV of the *Hercules* ROV collecting a push core sample on the flank of a sediment mound on the floor of a submarine canyon within Area 1 (Figure 1). (b) Image of a near-vertical sediment wall flanking a small canyon along the central Israel margin within Area 1. Stratigraphic layering is revealed to the left, crosscut by a possible fluid-escape structure that is slightly more resistive to erosion than the surrounding sediment. In the right-center are small shrimp and fish congregating around what could be some kind of nutrient source within the sediment wall. (c) Corals, shrimp, and crabs in water depths exceeding 500 m along the north-eastern border of the Palmachim Disturbance (Area 3, Figure 1). Hard substrate, perhaps limestone from the continental shelf, has moved downslope during continued slumping, forming the foundation of this complex ecosystem. This coral community may be designated a natural undersea preserve by the government of Israel; corals were previously unknown and unexpected from this deep-water environment.

meandering channel and an adjacent sedimentary ridge in water depths up to 1800 m along the upper continental rise. In this area, we were guided by a proprietary high-resolution bathymetric map from the oil and gas industry; it revealed seafloor features that are likely influenced by bottom-water transport associated with the mouth of the Nile River. We conducted two ROV dives, one within the area's meandering channel-levee system and the other crossing its long linear ridge. We collected a limited number of samples, especially within the deep meander where we discovered a large number of sedimentary mounds (Figure 2a shows similar mounds within Area 1). These mounds, heavily bioturbated and containing possible gas-escape structures, are located in the deepest part of the meander, and are up to a few meters in diameter and less than a meter high. Although the origin and exact nature of these mounds remain unknown, they may be the result of biological activity associated with possible gas venting along the eroded sedimentary channel system.

The southern Israel continental margin is dominated by the Palmachim Disturbance (Area 3, Figure 1), a broad area of older seafloor deposits that slump seaward, away from the continental shelf down the modern slope. The likely cause of this large slump feature is mobilization atop a laterally extensive, thick deposit of underlying ~5 million-year-old evaporite sediments (Garfunkel et al., 1979); downslope flow of these evaporites is perhaps triggered by intermittent seismic activity. *Argus* side-scan sonar images taken around the perimeter of the disturbance reveal only subtle seafloor slopes. Time constraints restricted ROV exploration of the disturbance's northern boundary, where we encountered a number of rocky outcrops, possible gas-charged sediments, and intense associated biological activity. Bottom waters in this region appeared turbid, with large quantities of suspended particulate matter. We used *Hercules* to collect rocks, sediment push cores, and biological samples. Close visual inspection of the larger rock formations revealed dense populations of deep-water corals and associated macrofauna living within the habitat (Figure 2c). We suspect that the rock formations are the result of ongoing slumping, which has rafted material downslope from the shelf. Sonar and video data are being processed and the geological and biological samples analyzed to complete a more detailed characterization of this area. Our Israeli colleagues had never encountered such habitats along this part of their margin before. The entire area is now being considered for protection as a sanctuary by the Israeli government.

Maritime History of the Crimean Continental Shelf

By Katherine L. Croff Bell, Michael L. Brennan, Ilya Buynevich, Art Trembanis, Dwight Coleman, Bridget Buxton, Dennis Piechota, Dan Davis, Alexis Catsambis, Kathleen Cantner, Serhiy Voronov, and Robert Ballard

The northern coast of the Black Sea has been an active center of maritime activity for centuries, from ancient Greek colonies to World War II battles. The Black Sea is an anoxic basin; below 150-m depth, the water contains little to no oxygen and is rich in hydrogen sulfide. This anoxia creates an environment that is hostile to wood-boring worms and other organisms that are known to destroy archaeological sites underwater. It is thus an ideal environmental setting in which to survey and study the marine archaeology and history of this region.

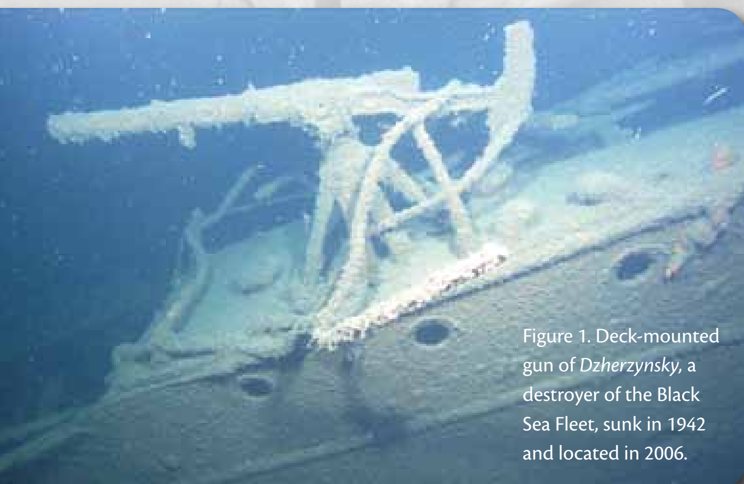


Figure 1. Deck-mounted gun of *Dzherzynsky*, a destroyer of the Black Sea Fleet, sunk in 1942 and located in 2006.

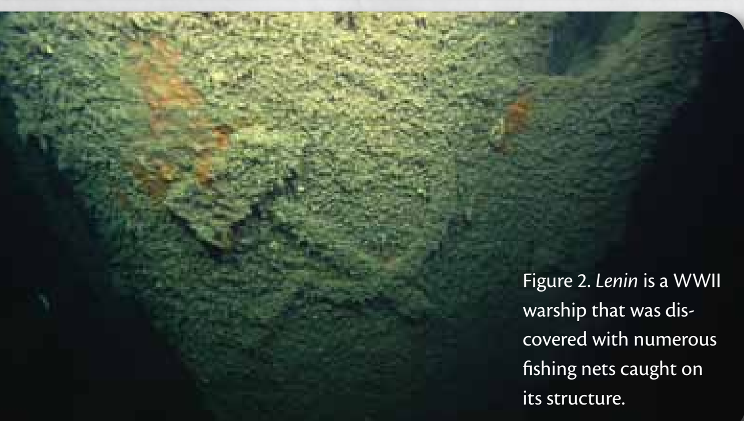


Figure 2. *Lenin* is a WWII warship that was discovered with numerous fishing nets caught on its structure.

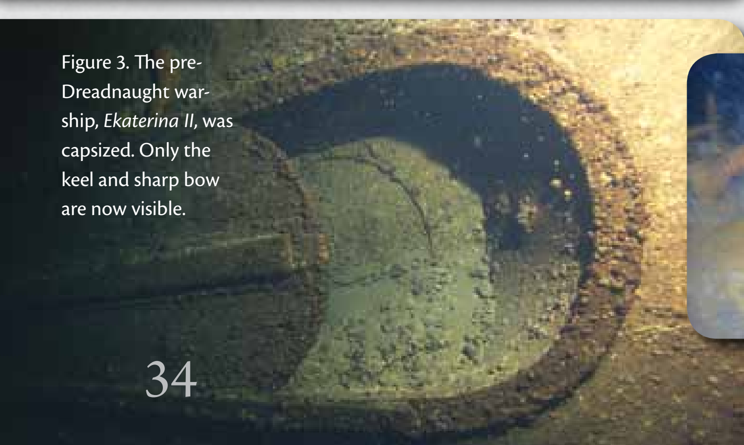
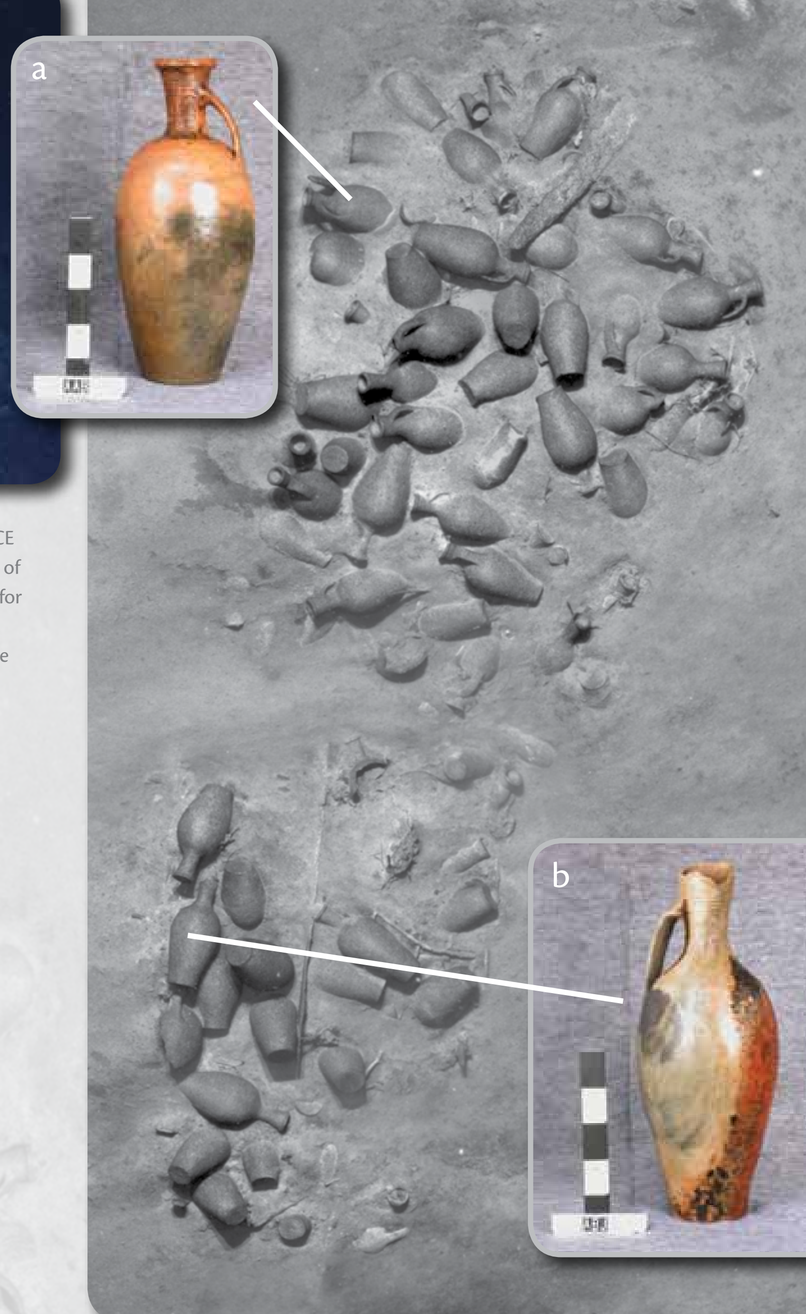


Figure 3. The pre-Dreadnaught warship, *Ekaterina II*, was capsized. Only the keel and sharp bow are now visible.

From 2006 to 2008, we undertook a series of projects to acoustically map the Crimean continental shelf with multibeam (approximately 2,000 km^2) and side-scan sonar (735 km^2), and to visually identify sonar targets with the ROVs *Hercules* and *Argus*. The surveys resulted in the location of more than 600 sonar targets. Of those, 50 were visually inspected and 18 (36%) were identified as archaeological or historical sites. The identified wrecks include: *Dzherzynsky*, *Lenin*, *Ekaterina II*, *Prut*, *Doob*, two patrol boats, one barge, four submarines, one helicopter, two airplanes, two Byzantine shipwrecks (Chersonesos A and Foros A), and an unidentified steamer-frigate.

In 2007, we collected a number of archaeological and geological samples, which are being analyzed to study environmental dynamics around Chersonesos A, located approximately 22 km west of Sevastopol at a depth of 135 m (Brennan et al., 2011). We deployed two sets of experiments made of rawhide, bone, pine, oak, copper, lead, steel, and barley near the wreck site that were designed to achieve two goals. First, we wanted to determine the mechanics and rates of long-term decay that artifacts and ship construction materials undergo in the sediment and open-water environments of the site. Second, we wanted to know if it is safe to display selected seabed artifacts in a future underwater museum. Both sets of experiments will be recovered periodically over the course of decades to characterize the conditions of cultural materials buried at this wreck site.

An acoustic Doppler current profiler, rotary fanbeam sonar, and a conductivity and temperature sensor were placed on the seabed to measure the currents and nearbed fluid-flow physics and sediment dynamics in the vicinity



Figures 4. Chersonesos A is a Byzantine shipwreck dated to the 9th to 11th centuries CE that lies at 135-m depth in the suboxic zone of the Black Sea. This site was the focus of initial excavation, high-resolution mapping, environmental monitoring, and testing for an underwater museum in 2007 (Ballard et al., 2008). Two jars, artifacts AAB (a) and ABJ (b), were recovered for analysis and are currently undergoing conservation at the Museum of Archaeology, Ukrainian Academy of Sciences.

of the Chersonesos A site (Trembanis et al., 2011). We digitized large bedforms on the shelf imaged from the side-scan sonar and examined their lengths and orientations in the context of the measured coastally trapped waves that transport fluids along and across the shelf. These findings suggest mechanisms that may explain the excellent preservation of artifacts above the nominal anoxic zone.

In addition to archaeological discoveries, multibeam mapping of the northern shelf of the Black Sea revealed significant deposits of mass-wasting events on the continental slope. These data, along with side-scan sonar and 3.5-kHz subbottom profiles, will be analyzed further for studies of the relationship between tectonic activity and landslide events in the region, and for hazard assessment. One sonar target looked like a circular depression, and may be related to gas venting or mud volcanism, which are common in this region. Further visual investigation by an ROV and sediment sampling are required to test this hypothesis.

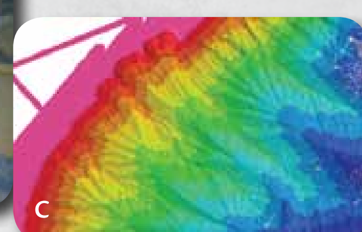


Figure 5. (a) A Soviet helicopter still has the red stars painted on the fuselage, though the cockpit was crushed. (b) In 2009, our Ukrainian colleagues identified one of the targets from our 2008 ROV survey as a large Byzantine shipwreck, *Foros A*. This wreck is well preserved with a large amount of the wood still present. (c). Multibeam mapping of the continental shelf and slope revealed vast areas of mass wasting into the deep basin of the Black Sea.

Epilogue

We learned a great deal from our 2010 deployment of E/V *Nautilus*, and this knowledge will have a significant impact on our planning effort for 2011. The two overriding factors that will dictate the 2011 program are funding and acquiring the necessary permits from the countries whose waters we hope to explore.

Our overall goal is to coordinate with NOAA so that E/V *Nautilus* and *Okeanos Explorer* each spend six months at sea every year operating "back-to-back." Such an operational scenario would make it possible to share technical personnel and technology between the two ships, efficiently use the Inner Space Center and its Doctors-on-Call network, and provide year-round educational outreach programs for both our informal and formal venues.

The initial decision to base E/V *Nautilus* in the eastern Mediterranean was predicated upon two major factors: (1) we wanted to determine whether the deep sea contained a large inventory of ancient shipwrecks lost along hypothesized deep-water trade routes of the Mediterranean and Black Seas and the state of preservation of those shipwrecks, and (2) we wanted to exploit the easy access from the eastern Mediterranean through the Red Sea to the Indian Ocean, where we hoped to carry out half of our program each year.

We have been extremely successful in meeting our first objective. Beginning in 1999, before *Nautilus* came online, our program began locating ancient shipwrecks in the Black Sea off the coasts of Turkey, Ukraine, Bulgaria, and Romania (Ballard et al., 2001; Brennan et al., 2011). Two deployments by *Nautilus* in the Aegean and eastern Mediterranean Seas also resulted in the discoveries of numerous additional contemporary and ancient ships. This work, coupled with earlier exploration in the central Mediterranean and along the Sinai coast (Ballard et al., 2000, 2002), revealed that the ancient mariner traveled far from shore and that shipwrecks lost in the deep sea are highly preserved, especially in the Black Sea's anoxic bottom waters.

Unfortunately, we have not been successful in meeting our second objective because of continuing piracy in the Red Sea, Gulf of Aden, and western Indian Ocean. This problem, coupled with the decision by NOAA's Office of Ocean Exploration to move *Okeanos Explorer* to its new base in Rhode Island in late 2011 to begin working in the Atlantic Ocean and Caribbean Sea, has caused us to rethink our present basing strategy.

At a recent meeting, the *Nautilus* Advisory Board decided to move *Nautilus* to a new base of operations in the eastern Indian Ocean/western Pacific Ocean beginning in 2013. Until that time, *Nautilus* will spend 2011 and 2012 working in the Black, Aegean, and Mediterranean Seas, eastern Atlantic Ocean and, if possible, the Red Sea to finish this phase of our global program.

These exploratory efforts will involve working again with the governments of Turkey, Greece, Cyprus, and Israel. We are also in the process of securing permits from the governments of Spain, Italy, Saudi Arabia, and Libya.

Approximately 25–30% of the *Nautilus* exploratory program focuses on archaeological imaging, while 70–75% of our sea time deals with basic oceanographic exploration. We expect this ratio to continue in 2011 and 2012, after which we anticipate an increase in our oceanographic exploration program once *Nautilus* moves to the eastern Indian and western Pacific Oceans in 2013.

Beginning in 2011, we plan to double the number of educators aboard all *Nautilus* missions, drawing from the growing number of schools, Boys & Girls Clubs, museums, science centers, and aquariums that are becoming involved in our various formal and informal educational outreach programs.

We also anticipate growth in our Doctors-on-Call network of remote science consoles located at various universities and research facilities involved in our program.

Finally, we plan to continue investing in the telepresence technology needed to support this exploratory program, including installation of 1 x 1 degree multibeam sonar on *Nautilus*, a new shipboard command/control center, and a new impact hammer to chip samples from hard rock outcrops. We also plan to acquire high-temperature water samplers and a new autonomous underwater vehicle, and continue development of exploratory and mapping sensors for our various vehicle systems.

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