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Exploration of Eratosthenes Seamount – A continental fragment being forced down an oceanic trench

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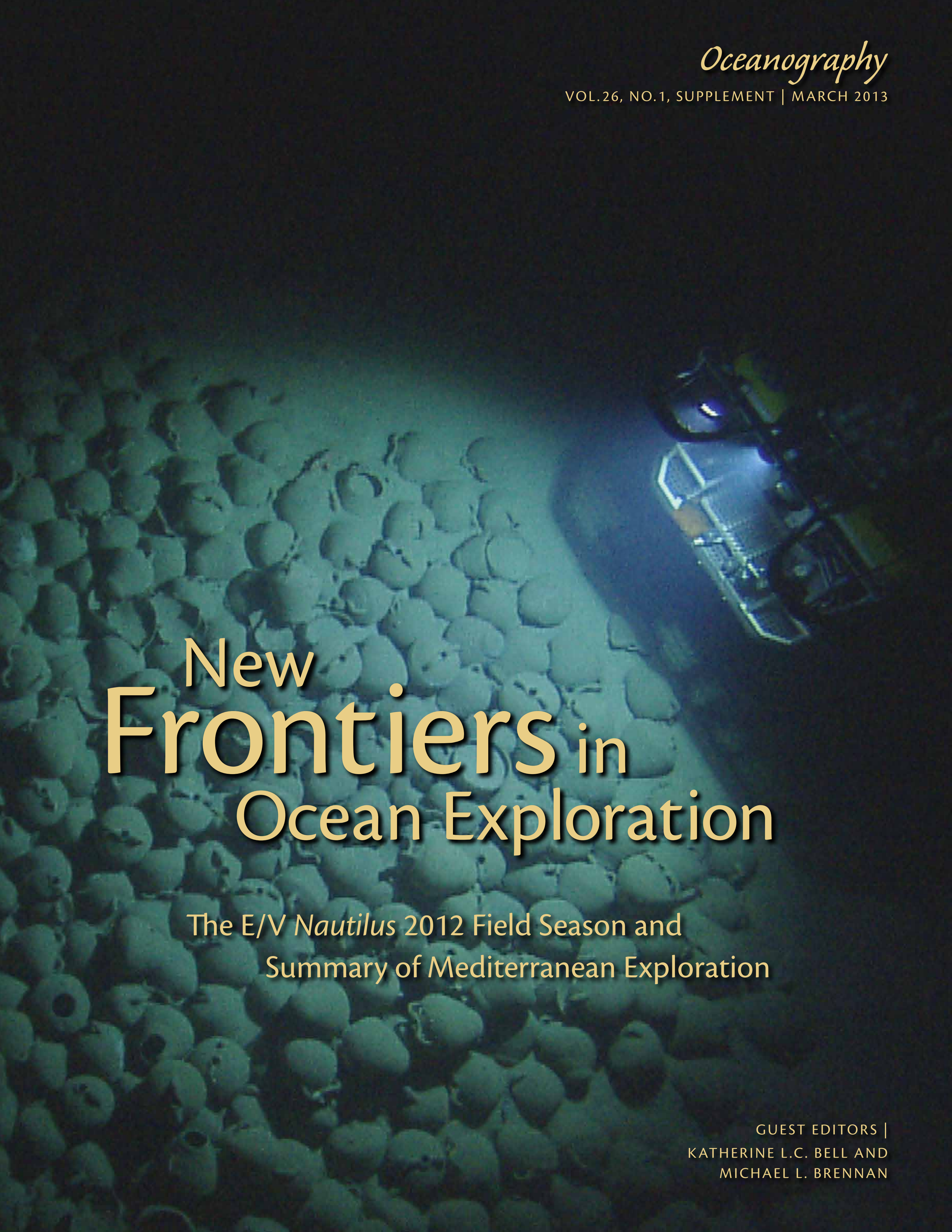

New Frontiers in Ocean Exploration

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

GUEST EDITORS |
KATHERINE L.C. BELL AND
MICHAEL L. BRENNAN

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

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

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

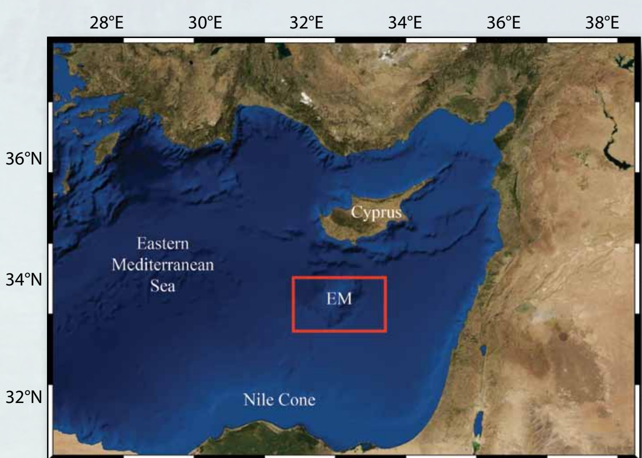
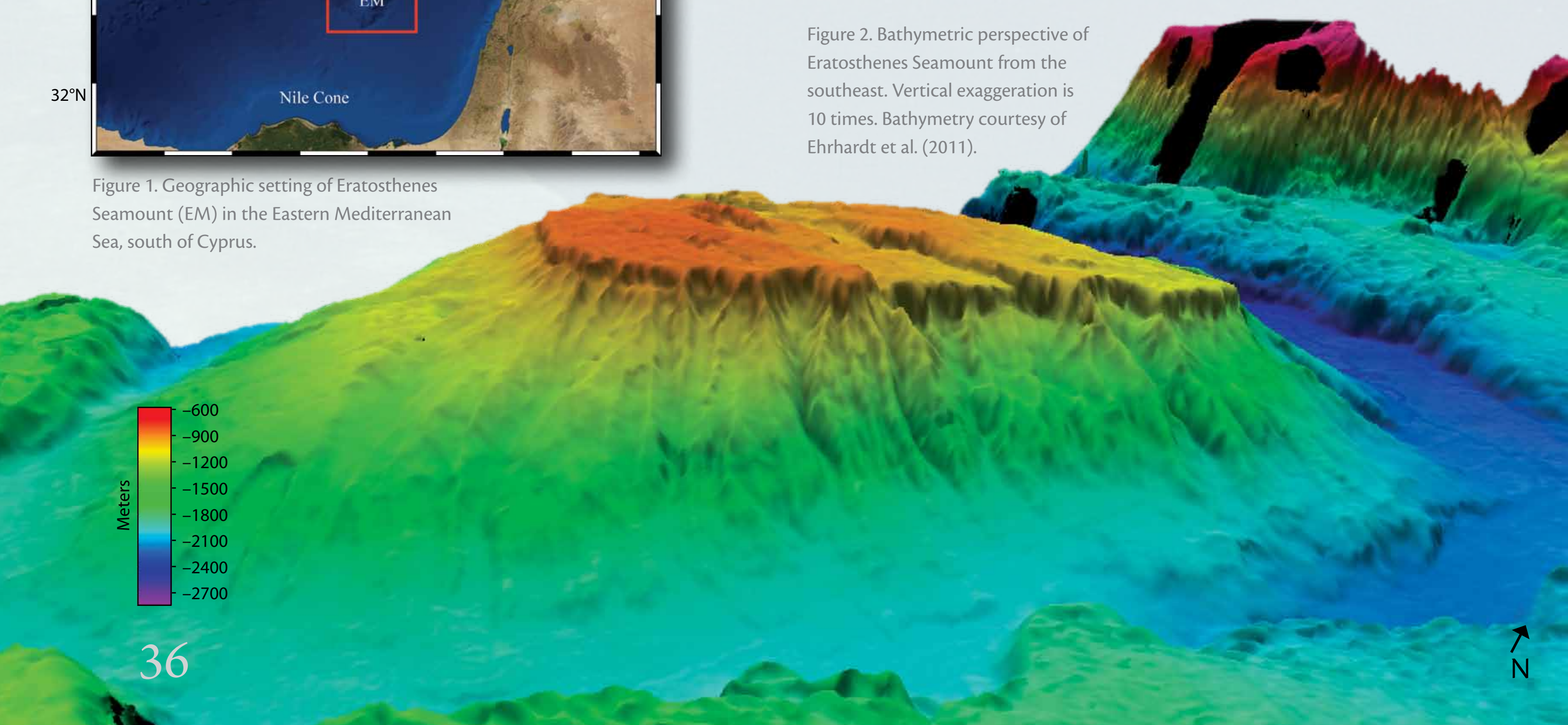


Figure 1. Geographic setting of Eratosthenes Seamount (EM) in the Eastern Mediterranean Sea, south of Cyprus.

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

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

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



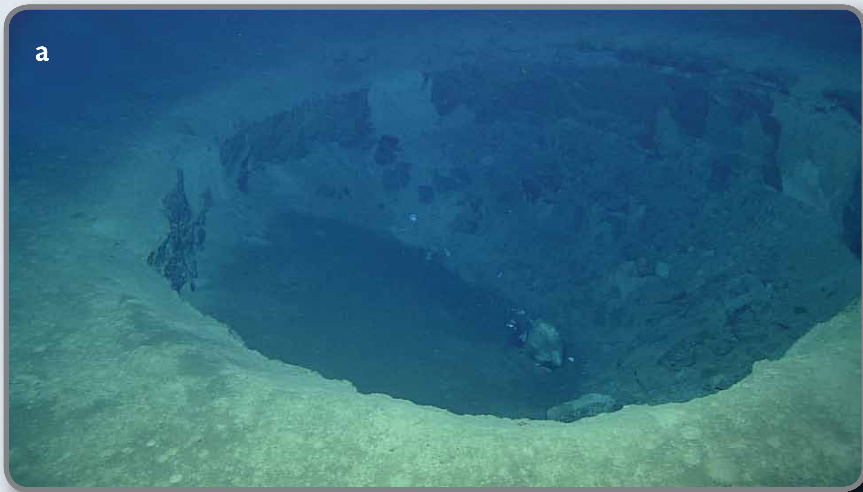


Figure 3. (a) One of the many circular sinkholes scattered on the summit of Eratosthenes Seamount. These sinkholes had diameters up to 40 m with depths to 10 m. Almost every one had trash accumulated in the bottom. (b) Outcrop of carbonate layers on rim of sinkhole.

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

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

2010 E/V *Nautilus* Cruise NA008

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

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

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

2012 E/V *Nautilus* Cruise NA023

EXPLORATION OF THE SUMMIT

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

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

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

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

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

EXPLORATION OF THE SOUTHEAST FLANK

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

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

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

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

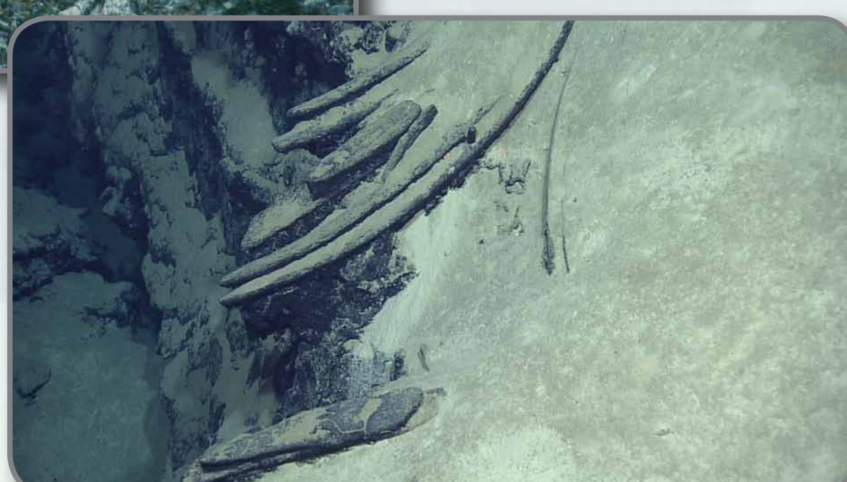


Figure 8. Phosphorized whale ribs discovered while exploring Eratosthenes and identified by the shore-based Doctors on Call.

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

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

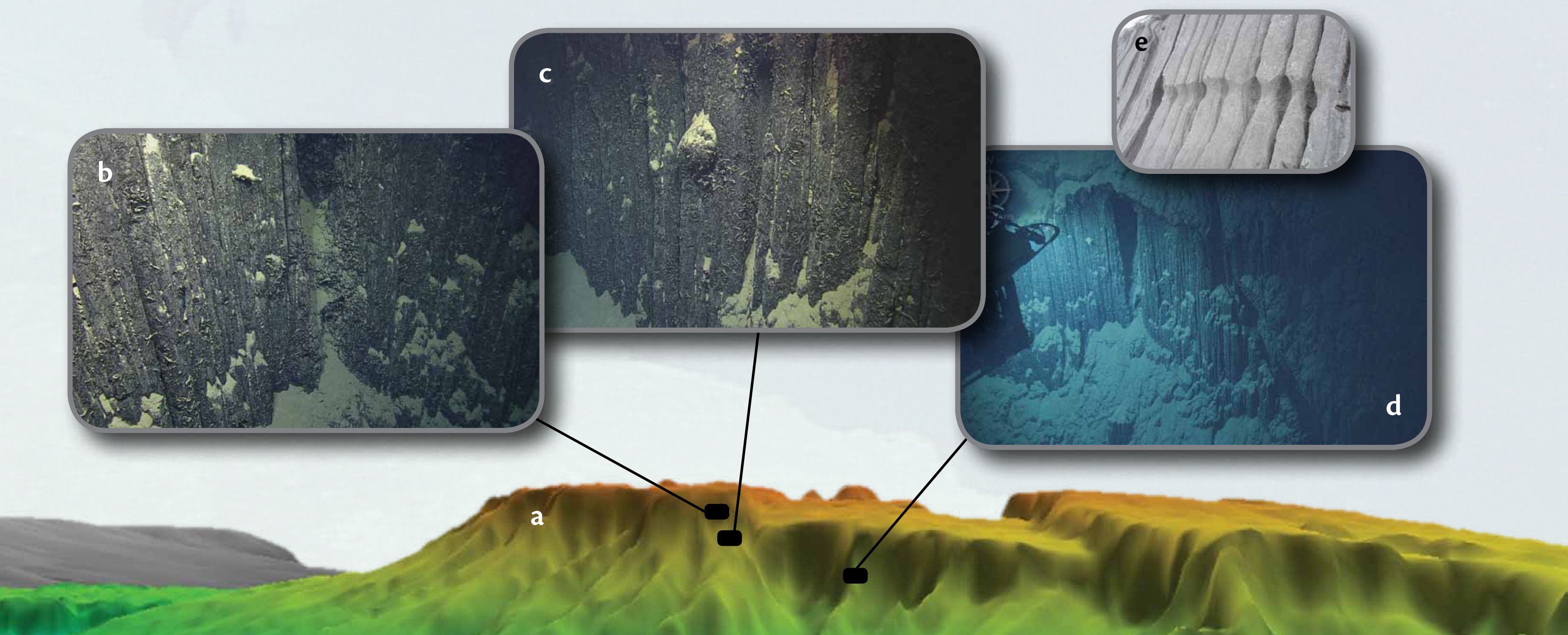


Figure 10. (a) Location of the karren karst morphology found along the steep gradient of the southeast flank of Eratosthenes Seamount. (b–d) Various images of observed karren on the seamount. (e) A terrestrial analogy. Image from http://www.geographie.unistuttgart.de/exkursionsseiten/Alpen2007/index.php?page=32

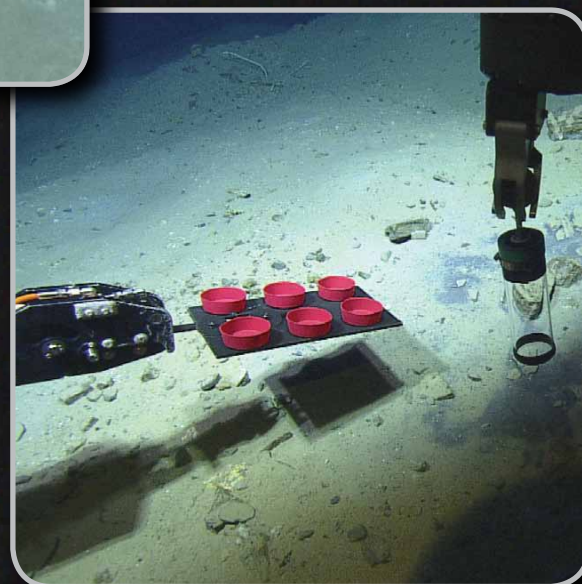
Finally, we reconfigured the mapping sensors on *Hercules* to survey the vertical fault wall where slickensides had been found in 2010. This fine-scale, high-resolution survey detailed the orientation of the slickenside grooves in the face of the outcrop; the results will be used to make a micromosaic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

Summary

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

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

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



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