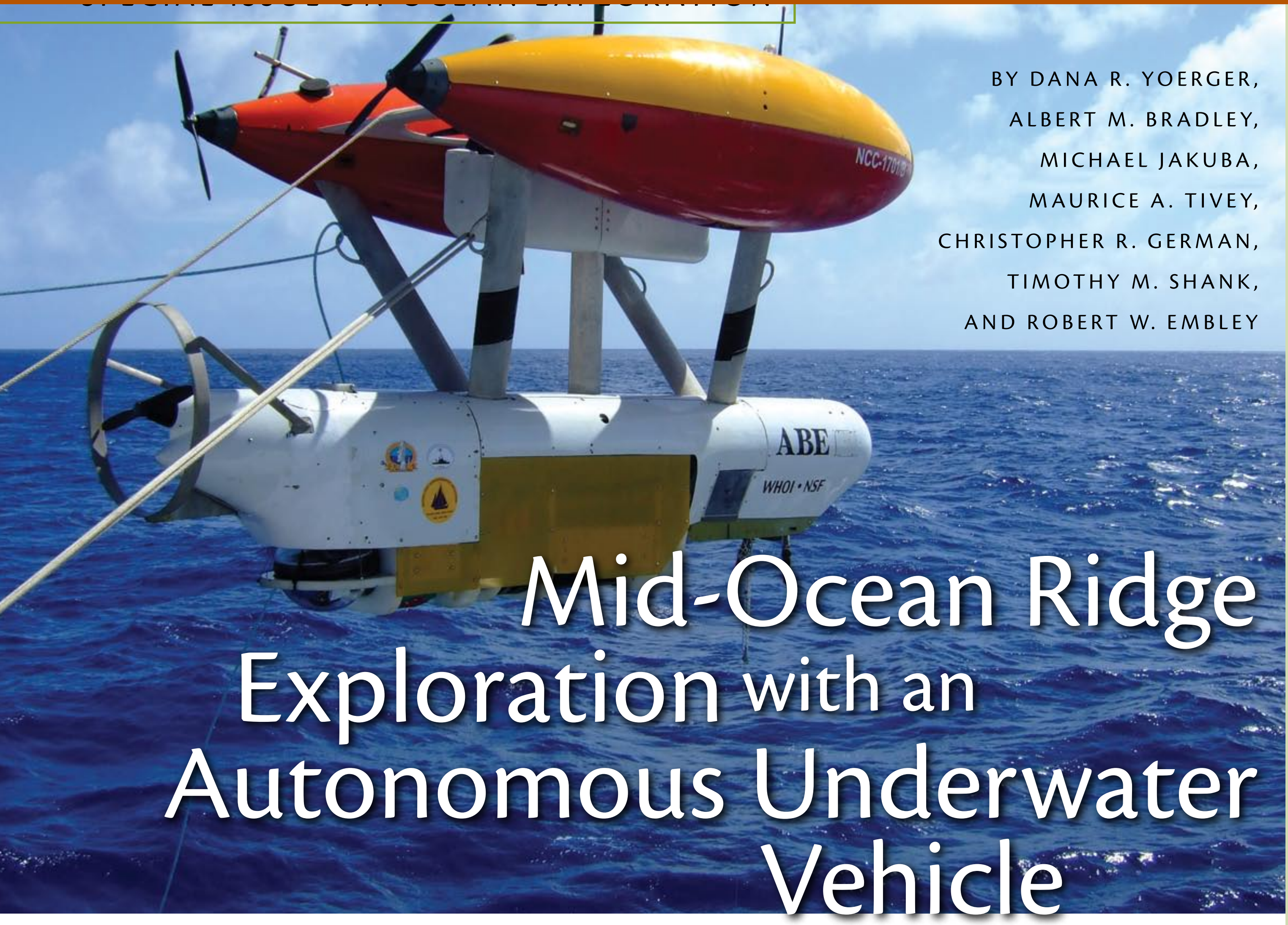

BY DANA R. YOERGER,
ALBERT M. BRADLEY,
MICHAEL JAKUBA,
MAURICE A. TIVEY,
CHRISTOPHER R. GERMAN,
TIMOTHY M. SHANK,
AND ROBERT W. EMBLEY

Mid-Ocean Ridge Exploration with an Autonomous Underwater Vehicle

Human-occupied submersibles, towed vehicles, and tethered remotely operated vehicles (ROVs) have traditionally been used to study the deep seafloor. In recent years, however, autonomous underwater vehicles (AUVs) have begun to replace these other vehicles for mapping and survey missions. AUVs complement the capabilities of these pre-existing systems, offering superior mapping capabilities, improved logistics, and better utilization of the surface support vessel by allowing other tasks such as submersible operations, ROV work, CTD stations, or multibeam surveys to be performed while the AUV does its work. AUVs are particularly well suited to systematic preplanned surveys using sonars, in situ chemical sensors, and cameras in the rugged deep-sea terrain that has been the focus of numerous scientific expeditions (e.g., those to mid-ocean ridges and ocean margin settings). The *Autonomous Benthic Explorer* (*ABE*) is an example of an AUV that has been used for over 20 cruises sponsored by the National Science Foundation (NSF), the National Oceanic and Atmospheric Administration (NOAA) Office of Ocean Exploration (OE), and international and private sources. This paper summarizes NOAA OE-sponsored cruises made to date using *ABE*.

ABE commonly operates with full autonomy; after launch, the vehicle completes its mission without human intervention, often at distances that preclude acoustic contact with the support vessel. Unlike towed assets, *ABE* can travel close to the seafloor along well-controlled tracklines, enabling high-resolution seafloor imaging through a variety of modalities. *ABE* generally collects co-registered bathymetric and magnetic data while determining its position through a combination of long-baseline acoustic transponders, a Doppler velocity log, and a fluxgate magnetic compass (Yoerger et al., 2007). Equally important, *ABE* also measures water-column properties using dual conductivity/temperature probes, an optical backscatter sensor, and a redox potential probe.

Since its initial trials in 1994, *ABE* has completed 210 deep-ocean dives, covering over 3600 km of bottom tracks at an average depth exceeding 2000 m (Yoerger et al., 2007). The mid-ocean ridge has been the focus of most of these efforts, particularly sites with hydrothermal activity. Some cruises featured detailed study of previously discovered sites, while other cruises focused on unexplored areas. NSF funded initial *ABE* development and field deployments. Since 2002, five cruises have been sponsored by the NOAA OE program, accounting for about one-third of *ABE*'s at-sea time. During these cruises, we made many important additions to *ABE*'s technical capabilities. Those funded by NOAA OE include the addition of a multibeam mapping sonar, installation of a Doppler velocity log, and development of an anchoring system to allow *ABE* to "park" itself on the seafloor at the end of a dive or in the event of a serious fault. This capability greatly improves our ability to operate *ABE* unattended, freeing up the vessel for other work. It also greatly improves *ABE*'s ability to work simultaneously with ROVs.

GALÁPAGOS 2002 EXPEDITION

The goals of our Galápagos expedition were to revisit the sites where hydrothermal vents were first discovered in 1977 and 1979 in the vicinity of 0°48´N, 86°13´W and to study how those sites changed in the ensuing years. We also surveyed unexplored sites near 89°W. This cruise was supported by the NOAA OE program, NSF, and the Woods Hole Oceanographic Institution.

We operated *ABE* cooperatively with DSV *Alvin*, with *ABE* performing systematic mapping at night while the *Alvin* dives focused on detailed inspection and sampling during the day (Shank et al., 2003). *Alvin* safety considerations precluded simultaneous operations, so *ABE* averaged about 7.5 hours of bottom time over seven dives, covering a total of 107 km of bottom tracks. During these dives, *ABE* collected high-resolution bathymetric data using a 675-kHz scanning sonar with a nominal pixel resolution of 2–5 m with concomitant recording of conductivity and temperature data.

One key objective of our 2002 cruise was to revisit the Rose Garden site that was first discovered in 1979 by scientists in *Alvin* and revisited in 1988 and 1990 (Hessler et al., 1988). This site's lush faunal communities that featured dense tubeworm clusters made it an icon of hydrothermal vent research. We found, however, that the Rose Garden site had been paved over by lava flows since the last visit by *Alvin*. No sign of the vent site was found by either *ABE* or *Alvin*, nor did we find any signs of previous dives such as markers or dive weights. The absence of temperature anomalies in *ABE* data helped confirm that our inability to detect hydrothermal vent features from *Alvin* was not due to navigational error. These conclusions were also supported by *ABE* magnetic data, which showed a reduced zone of magnetism at the paved-over Rose Garden site (Shank et al., 2003). Such reduced zones of magnetism have been associated with active and extinct hydrothermal sites (Tivey and Johnson, 2002).

Near 86°W, *ABE* made four dives at a nominal survey height of 40 m and a trackline spacing of 60 m to produce a bathymetric map of the rift valley. This survey included the Rosebud site discovered by scientists in *Alvin* on the same cruise. *ABE* also identified several smaller vents, primarily through temperature anomalies on the order of 50 millidegrees that were later investigated using *Alvin*. CTD casts and tow-yo runs showed the water column to be well stratified near the seafloor, which made the small temperature anomalies caused by the vent plumes conspicuous. In each case, the combination of *ABE*'s bathymetric mapping and delineation of water-column anomalies enabled scientists in *Alvin* to find the vent. These exercises illustrated the value of an AUV-based vent search, and showed that temperature anomalies encountered at our nominal survey height could be used to find vents, at least under favorable conditions. Figure 1 shows the assembled bathymetric map, the locations of the measured temperature anomalies, and the locations of the vent sites.

The second site we visited on the Galápagos Spreading Center, near 89°W, taught us more important lessons. Three dives in this area enabled production

> Unlike towed assets, *ABE* can travel close to the seafloor along well-controlled tracklines, enabling high-resolution seafloor imaging through a variety of modalities.

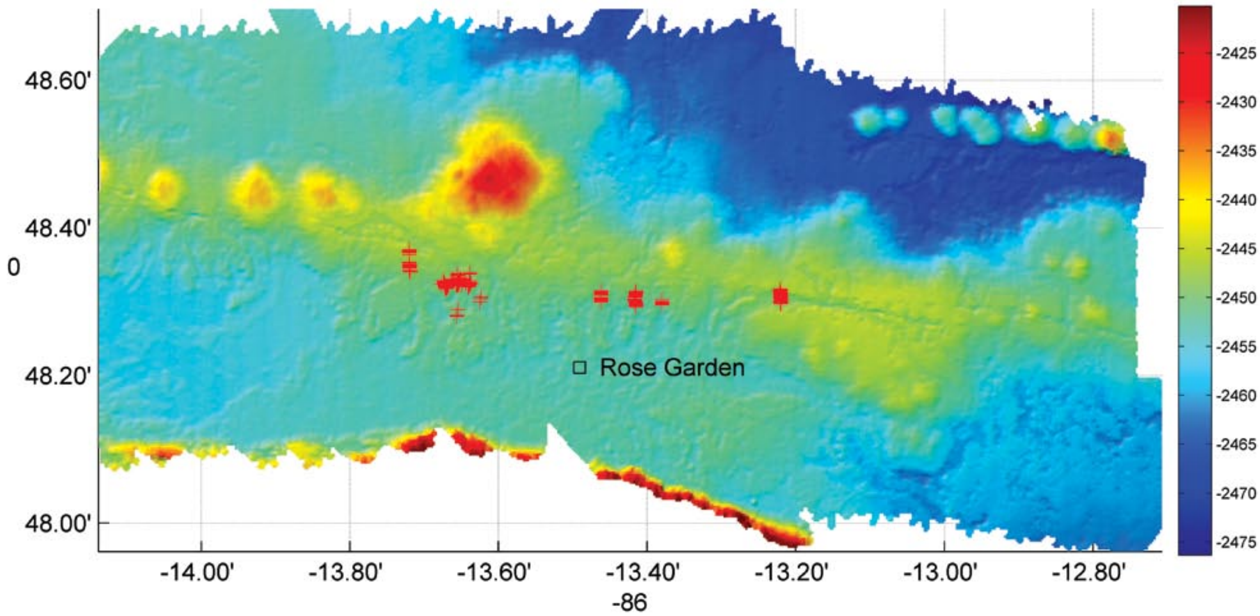

Figure 1. A bathymetric view of the floor of the Galápagos Spreading Center rift valley at 86°W obtained with a scanning sonar and gridded at 5 m. The red crosses indicate locations where temperature anomalies were detected by *ABE* while surveying ~ 40 m above the seafloor, including the nascent Rosebud vent and the small ALR vent. The highly stratified water column made temperature anomalies as small as ~20 millidegrees conspicuous. No sign of hydrothermal activity was found near the Rose Garden site. *ABE* data showed a magnetic low at the reported Rose Garden location, a result consistent with previous hydrothermal activity.

of another bathymetric map, which included the Calyfield vent site that had been found using *Alvin*. Unlike the 86°W site, the Calyfield site could not be clearly distinguished through temperature anomalies in the *ABE* data. While the ~ 2450-m deep 86°W site is located in the rift valley, the 89°W area lies near a topographic high in less than 1700 m of water on the flank of the rift. CTD data showed that the near-bottom hydrography was more complex than at 86°W, and we could find no correlation between temperature anomalies seen in the *ABE* data and the Calyfield site.

We concluded that our vent-searching technique required additional sensing, and fortunately our collaboration with Ko-ichi Nakamura of the Japanese National Institute of Advanced Industrial Science and Technology provided just such a sensor: the redox potential (Eh) probe, which we had first run on *ABE* in 2000.

EXPLORER RIDGE 2002 EXPEDITION

We investigated the southern Explorer Ridge, Northeast Pacific Ocean, in order to locate the actively venting Magic Mountain hydrothermal field that was originally discovered in 1985 and last visited by submersible in 1986. The site

DANA R. YOERGER *(dyoerger@whoi.edu) is Associate Scientist, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* ALBERT M. BRADLEY *is Principal Engineer (Retired), Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* MICHAEL JAKUBA *is Postdoctoral Investigator, Department of Applied Ocean Physics and Engineering, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* MAURICE A. TIVEY *is Associate Scientist, Department of Geology and Geophysics, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* CHRISTOPHER R. GERMAN *is Senior Scientist, Department of Geology and Geophysics, and Chief Scientist for Deep Submergence, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* TIMOTHY M. SHANK *is Associate Scientist, Department of Biology, Woods Hole Oceanographic Institution, Woods Hole, MA, USA.* ROBERT W. EMBLEY *is Senior Research Scientist, Pacific Marine Environmental Laboratory, National Oceanic and Atmospheric Administration (NOAA), Newport, OR, USA.*

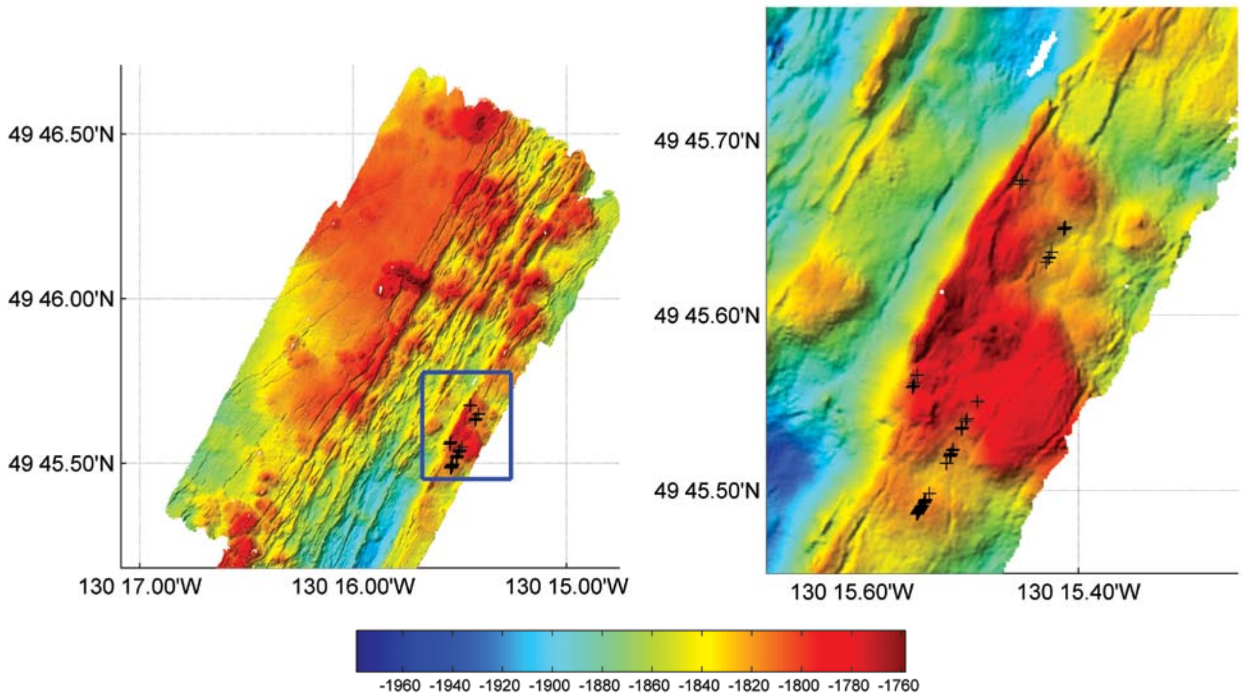

Figure 2. Bathymetry results from the summit of the Southern Explorer Ridge using a multibeam sonar on *ABE*. The multibeam data permitted quantitative assessment of the faulting of the axial summit graben floor and provided new insights into the formation of the Magic Mountain site, shown in the expanded view. Contradictory to previous reports, the vents were located outside the axial rift graben adjacent to the graben's large eastern bounding fault. The plots also show the location of collocated redox potential signals and temperature anomalies that provided a reliable indication of hydrothermal activity even in complex terrain in the presence of significant currents.

was not fully characterized in the previous expeditions and its exact location and tectonic setting were unknown.

This expedition featured a new capability for *ABE*, the Simrad SM2000 multibeam sonar, which we demonstrated under NOAA OE sponsorship. The experimental setup used in 2002 was later integrated fully into *ABE*. Using the SM2000, we were able to obtain 128 beams over a 90° swath from survey heights ranging from 50 to 150 m. This instrument represented more than an order of magnitude improvement over the scanning sonar used on *ABE* previously. We also used the Nakamura redox potential (Eh) probe on *ABE* during this cruise to aid in identifying localization of active vent sites.

Because we had no requirement to coordinate operations with any other vehicles, we could operate *ABE* without outside scheduling constraints. During the seven *ABE* dives, we conducted simultaneous operations, such as CTD casts and hull-mounted multibeam mapping, from the research vessel *Thomas G. Thompson*. During the course of the cruise, *ABE* covered 181 km of bottom tracks over those seven dives. On the last two dives, the SM2000 failed due to a problem in the logging software. *ABE* continued to collect soundings from its scanning sonar that provided lower-resolution bathymetry. The SM2000 logging problems were readily resolved during the subsequent integration effort.

Figure 2 shows results from the northern portion of the survey area, which was fully covered with the SM2000 multibeam sonar. The multibeam sonar produced a "point cloud" of bathymetric soundings that allowed us to create a grid of 1-m pixels and in some places a 25-cm pixel size. This resolution level collected over an area of several kilometers provided a unique opportunity to investigate the faulting that is so prominent in this area (Deschamps et al., 2007).

Prior to this study, most analyses of seafloor faulting used ship-based multibeam bathymetry and individual profiles made from deep-towed bathymetry, which have limited resolution, especially for distinguishing between volcanic- and fault-controlled topography and resolving processes such as fault linkage. *ABE*'s high-resolution multibeam data provided a much more complete characterization of fault geometry over a sufficiently wide area to be statistically relevant. Contrary to the prevailing paradigm of seafloor faulting based on subaerial fault systems, the *ABE* results demonstrated that the ratio of fault length to fault height is not constant, which highlights the importance of fault linkage and fault growth within the relatively thin, brittle layer of oceanic crust (Deschamps et al., 2007). Faults thus grow by coalescing rather than by propagation and are probably limited by the depth of the brittle-ductile transition.

Collocated anomalies of temperature and redox potential in combination with bathymetry allowed us to pinpoint and document the Magic Mountain site. To our surprise, we found the field outside of the axial rift graben and adjacent to its large eastern bounding fault. The fault association is likely an important aspect in the longevity of the vent field. The large size and geometry of the fault suggests that it probably extends to the brittle-ductile transition and likely provides a robust and long-lived pathway for hydrothermal fluid to reach the actively venting site.

In addition to the Magic Mountain site, *ABE* located another likely vent site about 3 km to the southeast of Magic Mountain. Multiple simultaneous redox-potential readings and temperature anomalies as high as 150 millidegrees provided solid evidence of active venting. This site remains unexplored.

On a cruise immediately following the *ABE* cruise, our collaborators used the bathymetry and water-column anomaly maps of the Magic Mountain site to guide ROV dives using the Canadian *ROPOS* system (Embley, 2002).

SOUTHERN MID-ATLANTIC RIDGE, 2005 AND 2006

Working together with the UK's Southampton Oceanography Centre (SOC) in 2005, we were able to locate the first vent sites anywhere in the southern Atlantic Ocean. Based on our preliminary investigations, the first conducted by *ABE* from a non-US research vessel, we were able to pinpoint new vent sites and photograph both the vents and animals. Based on the resulting data, we were able to guide a German interdisciplinary team equipped with their Center for Marine Environmental Sciences (MARUM) ROV *Quest* directly to these vent sites just three weeks after we had first mapped the seafloor in this area. Impressed with the efficiency of this novel approach, we were invited back to the area aboard the German ship FS *Meteor* in June 2006, where we continued to find new vents in three separate areas, at 5°S, 9°33´S, and at 8°18´S.

We investigated the southern Mid-Atlantic Ridge in general, and the ridge-crest immediately south of the Chain and Romanche Fracture Zones in particular, to test a hypothesis that these fracture zones, assumed to be hydrothermally barren, might act to separate two distinct biogeographic provinces of vent fauna from the northern and southern sections of the Mid-Atlantic Ridge. We already knew that the fauna of the northern Mid-Atlantic Ridge were quite distinct from those of the Pacific and Indian Oceans but, with no known vent sites having been discovered in the Atlantic Ocean south of the equator, hypotheses on what controlled these biological "disconnects" remained untestable as well as untested. Thus, these cruises represented an important convergence of ideals between NOAA's OE Program and a key component of the Census of Marine Life ChEss Program, which is dedicated to understanding vent-faunal biogeography and biodiversity.

Our 2005 cruise highlighted the role of an AUV in a fundamental exploration effort. The cruise was split into two legs aboard the UK's Natural Environment Research Council RRS *Charles Darwin*. On the first leg of the cruise, we started work by mapping the seafloor along a previously unexamined section of the ridge crest using the ship's EM120 multibeam system. This survey was followed by deep-tow surveys using the Southampton Oceanography Centre's 30-kHz side-scan sonar, TOBI (Towed Ocean Bottom Instrument), to image the underlying seafloor. TOBI was augmented with a series of in situ MAPR (miniature autonomous plume recorder) units to detect hydrothermal plumes in the overlying water column. The combination of multibeam, side-scan, and water-column data from TOBI converged

Working together with the UK's Southampton Oceanography Centre (SOC) in 2005, we were able to locate the first vent sites anywhere in the southern Atlantic Ocean.

to identify two sites of active hydrothermal venting between 2° and 5°S (German et al., in press). With *ABE* aboard ship for the second leg of the cruise, we returned to 5°S where all the data pointed to a saddlelike area in the center of the ridge segment. At a depth of nearly 3000 m, the saddle comprised the shallowest point of the ridge axis in this area. As we prepared *ABE* for deployment, follow-up CTD investigations of the water column indicated the presence of at least three nonbuoyant plumes, implying the possible presence of multiple active vent sites within a few kilometers. (Based on this work, S.A. Bennett and colleagues have prepared a paper on the distribution and stabilization of dissolved Fe in deep-sea hydrothermal plumes.) Consistent with water-column observations, the TOBI side-scan data showed a smooth, unfractured area consistent with geologically fresh lava flows extending over an area of 18 km^2 (German et al., in press).

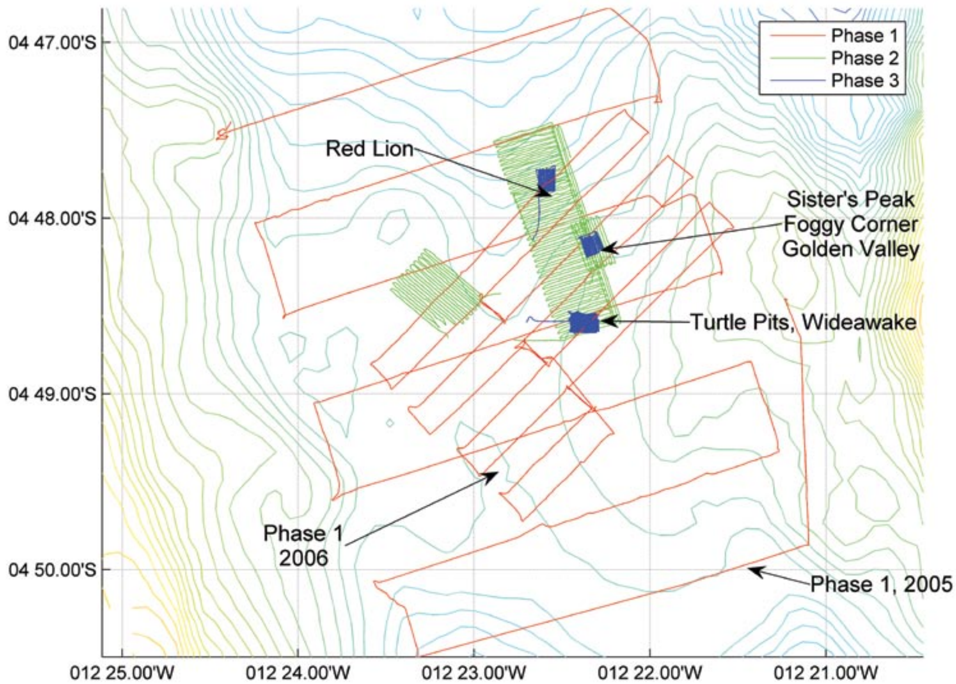

Figure 3. *ABE* tracklines for dives at the 5°S site on the southern Mid-Atlantic Ridge in 2005 and 2006. The initial Phase 1 survey (in red) in 2005, which used very wide trackline spacing and alternated depths, provided clues leading to the discovery of three hydrothermal sites, including one diffuse field (Wideawake) and two black smoker sites (Turtle Pits and Red Lion). In 2006, a tighter Phase 1 dive confirmed the existence of a vent site to the east. The more detailed and closer up Phase 2 and Phase 3 dives that followed led to the discovery of a black smoker site (Sister's Peak) and two diffuse fields (Golden Valley and Foggy Corner).

To track the nonbuoyant plume signals to their sources on the seafloor, we used *ABE* to execute a three-phase strategy first demonstrated on an NSF Ridge2000 cruise to the Lau Basin in 2004 (Yoerger et al., 2006; German et al., 2007). The approach starts with a constant-depth survey within a dispersing nonbuoyant hydrothermal plume. The appropriate depth to intercept the nonbuoyant plume is first determined by CTD. Phase 1 survey lines are usually planned several hundred meters apart. Anomalies in temperature, optical backscatter, and redox potential from the Phase 1 survey are then used, together with current-meter data, to predict the source area on the underlying seafloor. Based on the Phase 1 results, we design Phase 2 surveys to intercept rising plume fluids while mapping the appropriate region of the seafloor. Phase 2 surveys are conducted at a height of 50 m above the seafloor with a trackline spacing of 30 m. In the best case, the vehicle will be forced up when it passes through the rising plume stem on at least two adjacent tracklines, in addition to registering anomalies in the quantities measured in Phase 1. A favorable Phase 2 result usually allows a new source of venting to be located to within < 100 m. In the Phase 3 survey, the vehicle takes photos from a height of about 5 m to pinpoint the vent site and to identify fauna.

Our time at the 5°S site in 2005 was very limited, so we employed a somewhat risky strategy for our initial Phase 1 survey. Tracklines were spaced at 1 km with alternating depths of 2750 and 2875 m—the depths of the two strongest nonbuoyant plumes we had encountered from CTD investigations. Fortunately, two consecutive Phase 1 lines showed solid redox potential signals, some of which correlated with increased optical backscatter. Based on the position of the largest Phase 1 anomalies, we planned a Phase 2 dive using our standard line spacing (30 m) and survey height (50 m). This dive yielded solid indications of vent sites beneath one of our Phase 1 tracklines, near the southern extent of our Phase 2 survey (later identified as the Turtle Pits black smoker site and Wideawake diffuse venting field).

Remarkably, however, *ABE* also encountered very strong anomalies beneath another of our Phase 1 tracklines. These were apparent on the northernmost Phase 2 trackline (later identified as the Red Lion black smoker site). In essence, our Phase 2 dive identified not one but two different high-temperature hydrothermal fields, spaced more than 1 km apart, at the southern and northern extremes of the survey grid. A follow-up Phase 3 dive at the southern site verified the presence of active vents through water-column measurements, but a flooded camera cable prevented any photographs from being gathered. While the camera was being repaired, we expanded the Phase 2 coverage to the north and east. This dive confirmed the presence of a vent site to the north (the Red Lion black smoker site) and provided preliminary evidence of vent sites to the east (confirmed in the next year's cruise).

Following repairs to *ABE*'s camera system, we ran two more Phase 3 surveys, one at Turtle Pits and Wideawake, and another at Red Lion. Diffuse-flow areas were found at Wideawake and black smokers were imaged at Turtle Pits and Red Lion. The monochrome photos revealed a variety of animals, including mussels, clams, and shrimp. Approximately three weeks later, our German colleagues used our maps to guide dives to Turtle Pits, Wideawake, and Red Lion fields with the MARUM *Quest* ROV. They took close-up images and collected geological, biological, and fluid samples (Haase et al., 2007) that were collaboratively provided to our team to test hypotheses related to whether or not the southern Mid-Atlantic Ridge represents a new vent faunal province.

The following year, we returned to the 5°S site on a cruise in partnership with the same MARUM *Quest* ROV team and our scientific colleagues from Germany. For most of the cruise, *ABE* and *Quest* alternated time in the water, although we also made some concurrent dives. This collaboration proved to be very efficient and productive; in several instances, *Quest* dove directly onto targets a few hours after they were discovered by *ABE*. For example, *ABE* arrived on deck late one Sunday morning and, within 12 hours, *Quest* had dived to the seafloor and investigated three new vent sites pinpointed during *ABE*'s just-completed dive. Although the vents were spread out over an area of ~ 200 m in diameter, navigation fixes for *ABE* and *Quest* were consistent to within 1–5 m on the seafloor. This strategy greatly improved the efficiency of *Quest* operations and improved sample yield.

Our return to the 5°S site began with a more focused Phase 1 survey to detect any plumes that might have been missed during the loose Phase 1 survey done the previous year. The new survey provided further evidence of venting between the Turtle Pits and Red Lion sites and indicated another vent site to the west. A series of Phase 2 and Phase 3 dives pinned down the site between the two previously discovered sites. The area was called Comfortless Cove and contained a black smoker site (Sister's Peak) and two diffuse-flow sites (Golden Valley and Foggy Corner). *Quest* visited these sites shortly after they were detected by *ABE* to make more detailed surveys and take samples. Another Phase 3 dive revisited the Wideawake and Turtle Pits fields first imaged in 2005; Figure 4 is a photomosaic from Wideawake. In 2005, our photographs showed that the lavas in this area were fresh and glassy and in some areas they had flowed over the top of Wideawake vent fauna. They were not just geologically young but genuinely recent, perhaps years or even months old. Dating of the lavas is underway to find the exact timing of eruption while intercomparison of *ABE* photographs from 2005 and 2006 will allow us to examine time-series changes in the biological communities discovered the year before.

Further south, we made two *ABE* dives in the Lilliput area (9°33´S) where *Quest* found two diffuse hydrothermal fields in 2005. A Phase 2 *ABE* dive yielded a bathymetric map of the site, provided an improved geological context for the 2005 *Quest* discoveries, and collected redox potential signals that provided strong indications of several new vent sites. Our second dive in this area, a Phase 3 dive, provided photos of four newly discovered diffuse vent sites to add to the two already known in this ridge segment (Koschinsky, 2006).

ABE made a three-phase survey in the Niebelungen area, 8°18´S, searching for vents that had been detected by our German colleagues in 2005. Although the plume was extensive, complex currents and rough terrain made the search difficult. The vent source remained undiscovered despite several *Quest* dives dedicated to finding it in 2005. Following our three-phase search method, we were successful in locating a black smoker (der Drachenschlund, or The Dragon's Throat) on the third *ABE* dive. The vent, a single black smoker, was located in a crater on a steep slope and then surveyed by *Quest* a few hours after *ABE* returned to the surface. The previous year, the

Quest ROV had approached to within less than 200 m of the vent, but investigators had turned away because the geologic setting appeared unlikely to sustain high-temperature venting (Koschinsky, 2006), and they did not have three-phase data such as that provided by *ABE*.

We also made Phase 1 and Phase 2 *ABE* dives at 7°57′S, but no vents were discovered before our on-station time ended.

KERMADEC ARC

Under NOAA OE sponsorship in 2007, we joined colleagues from the United States, New Zealand, and Germany to study Brothers volcano, an intra-oceanic arc submarine volcano located 310 km northeast of New Zealand in the Kermadec arc (de Ronde et al., 2005). Brothers is one of the most studied submarine arc volcanos, but had never been mapped at the fine scale that can be achieved with an AUV.

This effort combined many types of activities, including test dives for the new University of Kiel Research Center for Marine Geosciences *Quest6000* ROV, deep-water testing of the ROV winch, CTD casts and tow-yos, and vessel multibeam mapping. Many of these activities were distant from the survey site and were conducted while *ABE* surveyed the seafloor out of acoustic range of the vessel. The anchoring system was critical for this cruise because it allowed *ABE* to operate safely without interfering with the other cruise activities. Because *ABE* can anchor when its batteries are depleted or in the event of a critical fault, the vessel can leave the site with no requirement to return for at least 48 hours, which greatly facilitates scheduling the other tasks. Overall, *ABE* surveyed 161 kilometers over eight dives and spent nearly 20 hours "sleeping" on the seafloor while other activities were completed. We conducted one joint dive with the *Quest6000*, launching *ABE* after the ROV reached the seafloor.

ABE completed three kinds of survey lines while mapping the Brothers caldera. Most were focused on bathymetry at a survey height of 50 m, with simultaneous water-column and magnetic-field mapping. Based on existing multibeam maps (EM300) and observations from ROVs and submersibles, we knew the caldera walls had a slope of about 45° on average, but included many steep faces that would not show up in the existing multibeam maps. Tracklines were programmed to follow along-contour based on the existing bathymetry, with spacing of approximately 60 m to ensure overlap in the steep terrain. *ABE* also made two intensive temperature surveys with very closely spaced tracklines (10 m) over known vent sites and ran a few single lines to collect magnetic field data.

Figure 5 shows the tracklines from all dives in the upper panel and the assembled bathymetry in the bottom panel. The lower parts of the caldera map were filled using EM300 data (region outlined in black). The areas with many closely spaced lines over the smaller cone and on the northern face indicate the regions where the temperature surveys were performed; the long isolated lines show the locations of the magnetic-field data surveys.

This bathymetric map provides what is probably the most detailed, overall view of a submarine arc volcano produced to date. The large smooth cone is probably the site of recent volcanic eruptions. Temperature, redox potential, and optical

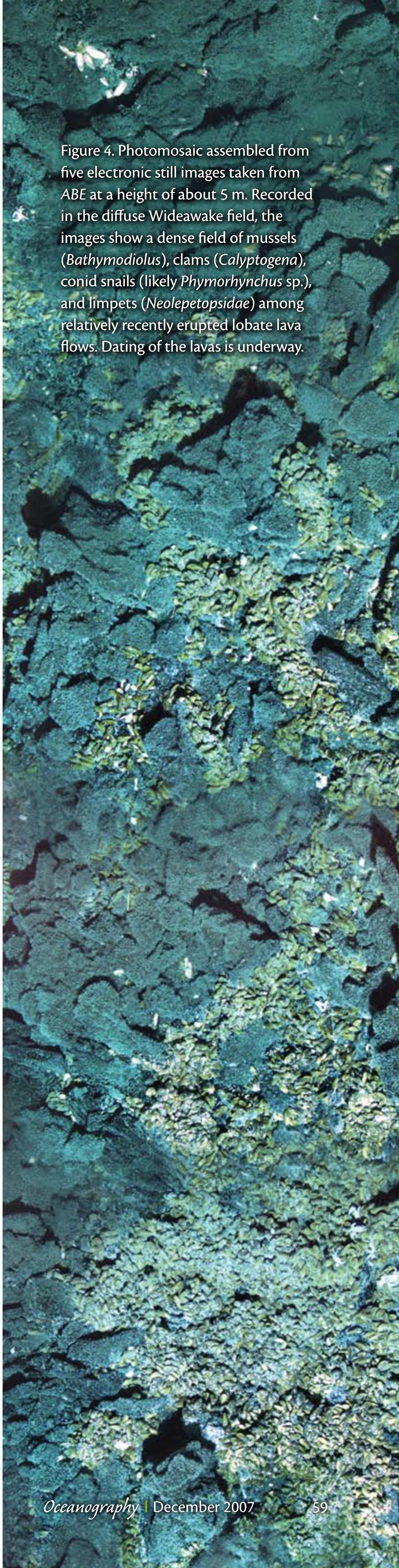

Figure 4. Photomosaic assembled from five electronic still images taken from *ABE* at a height of about 5 m. Recorded in the diffuse Wideawake field, the images show a dense field of mussels (*Bathymodiolus*), clams (*Calyptogena*), conid snails (likely *Phymorhynchus* sp.), and limpets (*Neolepetopsidae*) among relatively recently erupted lobate lava flows. Dating of the lavas is underway.

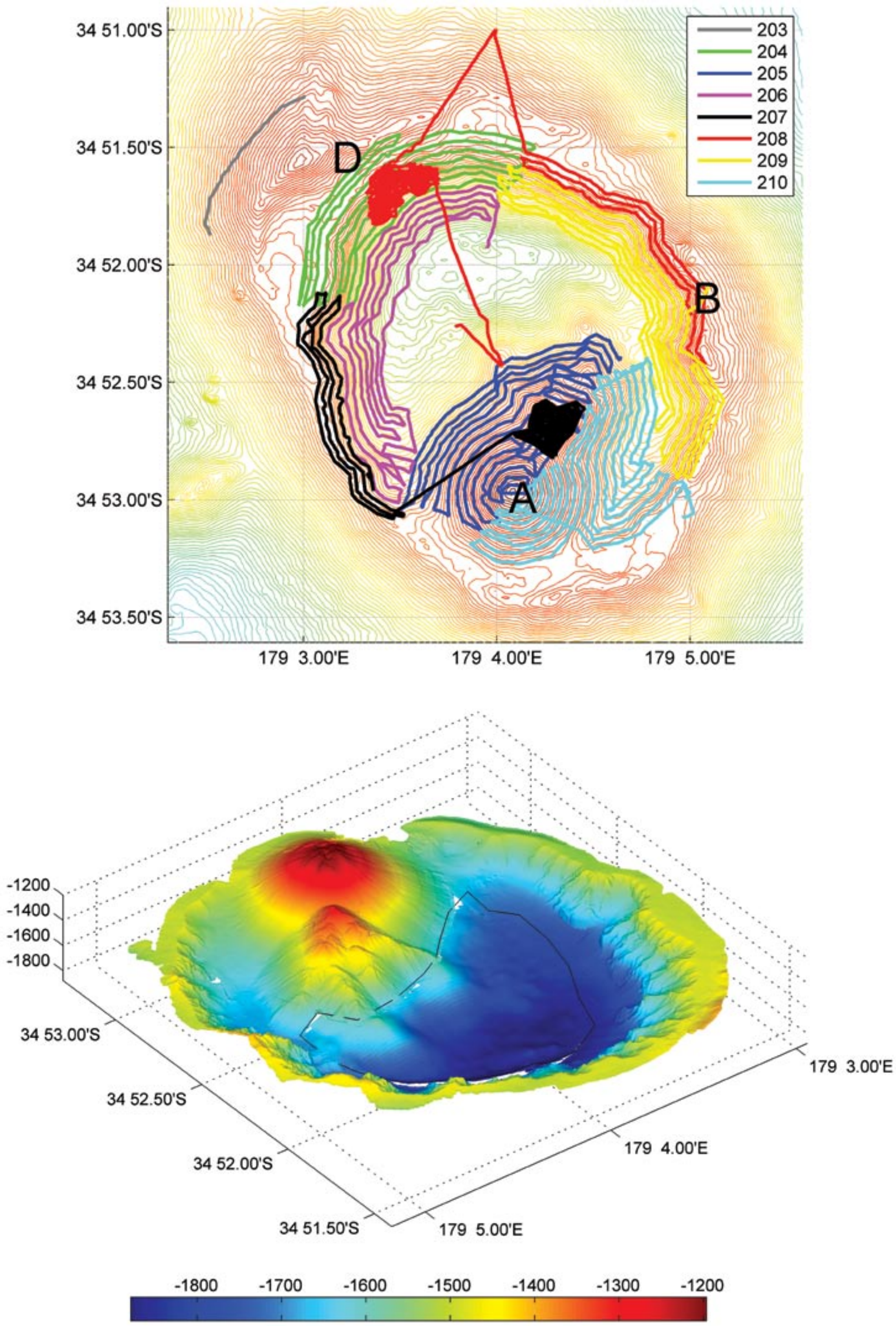

Figure 5. The upper panel shows the tracklines used to map Brothers volcano in the Kermadec arc. The majority of the lines were chosen to provide bathymetric and near-bottom magnetic data while following along-contour based on previously collected EM300 multibeam bathymetry. The vehicle flew at a height of ~50 m above the seafloor and the nominal trackline spacing was 60 m to avoid data gaps in the steep terrain. The lower panel shows the resulting bathymetry gridded at 2 m, with the center section (outlined in black) filled with EM300 data.

backscatter measurements confirmed the presence of hydrothermal activity from the small crater at the top of the cone. The smaller, more-weathered cones on the flanks of the large cone are probably older but also show hydrothermal activity that extends to the caldera's floor. The rough, eroded topography on the caldera walls has likely been undermined by hydrothermal activity. *ABE* dives delineated the extent of the previously known vent sites, identified at least one new site based on both water-column and magnetic-field measurements, and located an extinct field through seafloor magnetics.

CONCLUSION

This paper summarizes a series of oceanographic cruises using the *Autonomous Benthic Explorer* (*ABE*) and related technological developments supported by the NOAA Ocean Exploration Program between 2002 and 2007. These cruises made up about one-third of *ABE*'s sea time over this period, with other seagoing efforts sponsored by the National Science Foundation and by private and international sources. On these cruises, *ABE* made several different types of surveys and operated simultaneously with a number of other shipboard operations such as CTD work, vessel multibeam mapping, ROV dives, and tow-sled operations.

Fine-scale, near-bottom bathymetric measurements made by *ABE* with a multibeam sonar produce high-resolution maps that enable detailed analyses of active hydrothermal sites and permit quantitative analyses of phenomena such as seafloor faulting. The high spatial resolution allows volcanic topography to be distinguished from fault-controlled topography and permits key processes such as fault linkage to be quantified with statistical certainty. Ocean-crust fault models based on *ABE* bathymetry contradict earlier studies made from lower-resolution, ship-based, multibeam data and also show that mechanisms for fault linkage and fault growth on the seafloor differ significantly from typical subaerial systems.

The combination of bathymetry and magnetic-field measurements from an AUV such as *ABE* provides estimates of crustal magnetization, which in turn permits the age and thickness of lava flows to be determined. Combined maps made by *ABE* have been used to identify volcanic features such as lava flow units, delimit their fronts, and estimate their thicknesses. Additionally, as active and extinct hydrothermal sites may show low crustal magnetization, these maps provide an important tool for determining the location and distribution of vent sites in basalt-hosted systems.

We also used our three-phase search methodology to locate and survey hydrothermal vents based on clues provided by towed systems. In addition to locating the vent sites, we made fine-scale bathymetric maps of the vent sites prior to taking photographs, enabling detailed study of the geology as well as the identification of vent fauna. Using these methods on cruises sponsored by the NOAA Office of Ocean Exploration and Research, we found and documented the first known South Atlantic vent sites.

The NOAA Office of Ocean Exploration and Research support also provided continuous improvement of the vehicle system. Technological upgrades and enhancements included the multibeam sonar, Doppler velocity log, and *ABE*'s anchoring system. These upgrades were critical to *ABE*'s success because they substantially improved the vehicle's scientific mapping capabilities and its ability to work productively under a variety of cruise constraints.

ACKNOWLEDGEMENTS

We are grateful to the crews of the research vessels *Atlantis, Thomas G. Thompson, Charles Darwin, Meteor,* and *Sonne* for their assistance in *ABE* operations during these NOAA Office of Ocean Exploration and Research-sponsored cruises. Alan Duester, Andrew Billings, and Rodney Catanach provided critical engineering and logistical support for *ABE* operations. Ko-ichi Nakamura of the National Institute of Advanced Industrial Science and Technology in Japan has been an invaluable collaborator, and we thank him for providing his expertise and his redox potential (Eh) probe on many ABE cruises. Other key collaborators include Dan Fornari from the Woods Hole Oceanographic Institution (WHOI), Edward Baker and William Chadwick of PMEL/NOAA, Andrea Koschinsky of the Jacobs University Bremen, Colin Devey and Klas Lackschewitz of IFM-GEOMAR at the University of Kiel, and Cornel de Ronde of GNS Science, New Zealand. The authors also thank the anonymous reviewers whose comments improved this paper significantly. Judy Fenwick of WHOI also made valuable editorial contributions. In addition to the NOAA Office of Ocean Exploration and Research, the expeditions presented in this paper were also funded in part by the National Science Foundation, WHOI, the UK Natural Environment Research Council, and the Deutsche Forschungsgemeinschaft.

REFERENCES

de Ronde, C.E.J., M.D. Hannington, P. Stoffers, I.C. Wright, R.G. Ditchburn, A.G. Reyes, E.T. Baker, G.J. Massoth, J.E. Lupton, S.L. Walker, and others. 2005. Evolution of a submarine magmatic-hydrothermal system: Brothers Volcano, Southern Kermadec Arc, New Zealand. *Economic Geology* 100:1,097–1,133.

Deschamps, A., M. Tivey, R.W. Embley, and W.W. Chadwick. 2007. Quantitative study of the deformation at Southern Explorer Ridge using high-resolution bathymetric data. *Earth and Planetary Science Letters* 259(1–2):1–17.

Embley, R.W. 2002. Rediscovery and exploration of Magic Mountain, Explorer Ridge, NE Pacific. *Eos Transactions, American Geophysical Union, 83(47), Fall Meeting Supplement*, Abstract T11C-1264.

German, C.R., S.A. Bennett, C. Boulart, D.P. Connelly, A.J. Evans, B.J. Murton, L.M. Parson, R.D. Prien, E. Ramirez-Llodra, M. Jakuba, and others. In press. Hydrothermal activity on the southern Mid-Atlantic Ridge: Tectonically and volcanically controlled venting at 4–5°S. *Earth and Planetary Science Letters*.

German, C.R., D.R. Yoerger, M. Jakuba, T.M. Shank, C.H. Langmuir, K. Nakamura. 2007. Hydrothermal exploration with the *Autonomous Benthic Explorer*. *Deep Sea Research Part I* doi:10.1016/j.dsr.2007.11.004.

Haase, K.M., S. Petersen, A. Koschinsky, R. Seifert, C. Devey, N. Dubilier, S. Fretzdorff, D. Garbe-Schönberg, C.R. German, O. Giere, and others. 2007. Young volcanism and related hydrothermal activity at 5°S on the slow-spreading southern Mid-Atlantic Ridge. *Geochemistry, Geophysics, and Geosystems* 8:Q11002, doi:10.1029/2006GC001509.

Hessler, R.R., W.M. Smithey, M.A. Boudrias, C.H. Keller, R.A. Lutz, and J.J. Childress. 1988. Temporal changes in megafauna at the Rose Garden hydrothermal vent, Galápagos Rift, eastern tropical Pacific. *Deep Sea Research* 35(10–11):1,681–1,709.

Koschinsky, A. 2006. Discovery of new hydrothermal vents on the southern Mid-Atlantic Ridge (4S–10S) during cruise M68/1. *InterRidge News* 15:9–15.

Shank, T., D. Fornari, D.R. Yoerger, S. Humphris, A. Bradley, S. Hammond, J. Lupton, D. Scheirer, R. Collier, A.-L. Reysenbach, and others. 2003. Deep submergence synergy – *Alvin* and *ABE* explore the Galápagos Rift at 86°W. *EOS, Transactions of the American Geophysical Union* 84(41):425.

Tivey, M.A., and H.P. Johnson. 2002. Crustal magnetization reveals subsurface structure of Juan de Fuca Ridge hydrothermal vent fields. *Geology* 30(11):979–982.

Yoerger, D.R., A. M. Bradley, M. Jakuba, C. German, T. Shank, M. Tivey, 2006. Autonomous and remotely operated vehicle technology for hydrothermal vent discovery, exploration, and sampling. *Oceanography* 20(1):152–161.

Yoerger, D.R., M. Jakuba, A.M. Bradley, and B. Bingham. 2007. Techniques for deep sea near bottom survey using an autonomous underwater vehicle. *The International Journal of Robotics Research* 26(1):41–54, doi:10.1177/0278364907073773.