Fine-Scale Seafloor Survey in Rugged Deep-Ocean Terrain with an Autonomous Robot

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Abstract

The rugged mountainous regions of the deep seafloor hold both great scientific interest as well a host of difficult challenges for autonomous robots. Exploiting its abilities for precise navigation, trackline following, and bottom-following in rough terrain, the Autonomous Benthic Explorer (ABE) collected fine-scale bathymetry, magnetics, temperature, optical backscatter, and conductivity over a rugged, neovolcanic and active tectonic zone of the southern East Pacific Rise (18°S). These data sets were combined to produce a variety of maps showing details of the terrain as well as hydrothermal venting.

1. Introduction

The Earth's ocean floor contains the most accurate and complete record of geologic and tectonic history available in our solar system, covering a span of over 200 million years. The unraveling of plate tectonic processes through the paradigm of seafloor spreading and the exploration and study of seafloor terrain throughout the world's oceans has revolutionized the earth and oceanographic sciences over the last 30 years. This work has provided a quantitative context for mineral exploration, land utilization, and earthquake hazard assessment, and provided conceptual models for the structure and morphology of other planets in our solar system.

A variety of technologies have been employed to make these important discoveries. Seismic surveys, surface and deep-towed magnetic studies, towed camera and sonar sleds, and manned submersibles have all made key contributions to our understanding of the overall structure of the Mid-Ocean Ridge. Manned submersibles and more recently Remotely Operated Vehicles (ROVs) have enabled detailed studies of hydrothermal vents with their associated chemosynthetic ecosystems.

Recently, our community has begun to employ Autonomous Underwater Vehicles (AUVs) to fill important gaps in our ability to collect detailed, multisensor data sets. AUVs have been used to conduct surveys in the water column and on the seafloor [1,2]. For near-bottom survey on the Mid-Ocean Ridge, an AUV must deal with difficult terrain such as steep slopes, scarps, and fissures.

AUVs fit into our suite of oceanographic tools in several important ways. Their ability to conduct carefully navigated, finely controlled survey tracks permit them to collect datasets with outstanding detail and consistency. We have also shown that AUVs can extend our existing oceanographic expeditionary paradigm, gathering additional data while permitting the vessel to attend to other tasks. As these vehicles gain additional endurance and autonomy, these benefits will increase.

Additional on-board intelligence will also improve our capabilities. Most operational work to date has employed preplanned survey tracks. Adaptive sampling techniques [3] will permit AUVs to seek out interesting phenomena and expend their limited resources gathering the most critical data. In the future, multiple AUVs will communicate acoustically with each other, fixed moorings, and vessels, allowing the use of on-line models to refine survey strategies.

In February 1999, we utilized the the Autonomous Benthic Explorer (ABE) of the Woods Hole Oceanographic Institution to obtain a high-resolution data set on the southern East Pacific Rise, working near the seafloor over rugged volcanic terrain at depths of 2600 meters. ABE's capabilities for precise navigation and control were exploited to produce a multisensor data set that revealed fine-scale details of the seafloor. We joined the Research Vessel Atlantis in Easter Island, the cruise ended 6 weeks later in Manzanillo, Mexico.

The scientific objectives of the cruise were to fully investigate discrete eruptive events along the crest of the southern East Pacific Rise. The primary tools employed were the DSL-120 sidescan sonar and the submersible Alvin with ABE operating in the evenings when the submersible was being serviced.

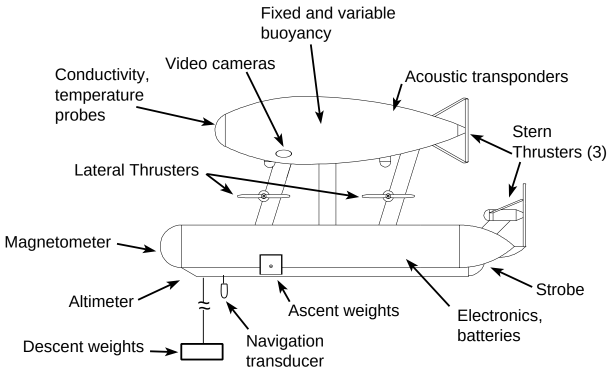


Figure 1. The Autonomous Benthic Explorer (ABE) is propelled by 7 thrusters and can manueuver in any direction or change heading over its entire operating range. A descent weight on a short mooring carries ABE to the seafloor, and it returns to the surface when the ascent weights have been released.

ABE deployments focussed on two areas of contrasting morphologies centered at 17°28.5'S and 18°14.7'S. The northern area is characterized by a broad, smooth axial dome whose apex is cleft by a narrow eruptive fissure (30-80 m wide, 5-12 m deep). The ridge crest in the area to the south is notched by a large trough (500-1000 m wide and 50-60 m deep) whose morphology is dominated by tectonism rather than eruptive volcanism. This large trough is bounded by an irregular staircase of escarpments each 10-20 m high, and its floor is sedimented and extensively fissured.

ABE made a total of 19 successful dives, obtaining detailed records of the bathymetry, magnetics, and water column properties as well as video snapshots of the seafloor. Results described in this paper were obtained from 3 dives over the trough area, results from other dives in the northern area are presented in [1].

2. The Autonomous Benthic Explorer, ABE

ABE can survey the near-bottom environment at depths to 5000 meters with a variety of sensors (figure 1). ABE's ability to maneuver independently in all three translational axes and heading at any speed makes it unique among the current crop of AUVs in use for science. These qualities are particularly well suited to near-bottom work in difficult terrain.

Our early deployments in 1995 and 1996 concentrated on precisely navigated magnetometer surveys over rugged terrain around active crustal spreading regions [2,4]. We demonstrated ABE's ability to follow pre-programmed tracklines using long-baseline acoustic navigation and terrain-follow over difficult terrain including steep scarps.

For the dives at 17°-18°S ABE carried a variety of scientific sensors. These included a video snapshot imaging system, conductivity and temperature sensors, a 3-axis magnetometer, an optical backscatter sensor, and a scanning sonar for cross-track bathymetric coverage.

2.1 Acoustic Navigation

ABE uses acoustic travel times from a network of up to 4 transponders moored to the seafloor to determine its position during its descent and while surveying. Before the first vehicle launch, we survey the transponders by interrogating them from vessel positions known from pcode GPS. The position fixes allow ABE to control its descent and to follow tracklines with precision.

Real-time algorithms determine ABE's position from two or more transponder returns and measured vehicle depth [1]. These routines eliminate spurious returns caused by noise through median filtering and utilize range gates to eliminate returns that have reflected off the surface (which are very consistent but will yield incorrect results unless carefully identified).

After recovering the vehicle we further process the data, recovering fixes that were rejected in real-time and refining the transponder survey by using the returns received at the vehicle.

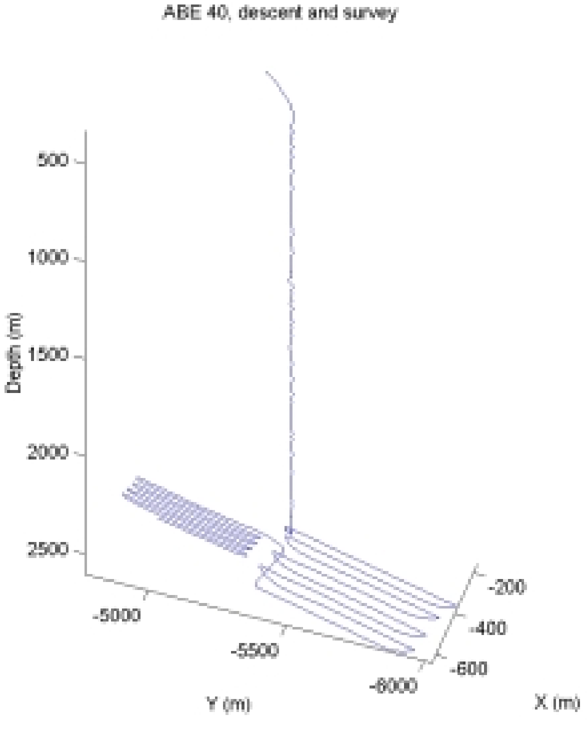


Figure 2. This plot shows ABE's track during a controlled descent to 2600 meters followed by preprogrammed tracklines over the seafloor.

2.2 Precise Descent and Trackline Following

After launch, ABE must descend to the desired starting location for the survey while using minimal battery power. While being pulled to the seafloor by its descent weight, ABE utilizes knowledge of its position, its forward glide, and its heading servo to spiral to the seafloor to a prescribed location, as shown in figure 2 [4]. Without active control, ABE would drift several kilometers due to currents and its body lift during its 2 1/2 hour trip to the seafloor. While descending, ABE draws less than 10% of the propulsive power used during level transit.

Precise descents are particularly important in bad terrain. Much of the terrain out on the ridge flanks is extremely hostile and obscured from the transponders due to the rugged topography.

After reaching the seafloor, ABE executes a series of tracklines. Each trackline specification contains details concerning which sensors to use and how to follow the bottom. For example, during video survey, ABE will follow the bottom within approximately 5 meters. During scanning sonar transects, the vehicle will travel about 20 meters off the bottom, and the video system and its flash will be turned off to save power. Low-powered sensors such as the water column sensors and the scanning sonar remain on during all transects.

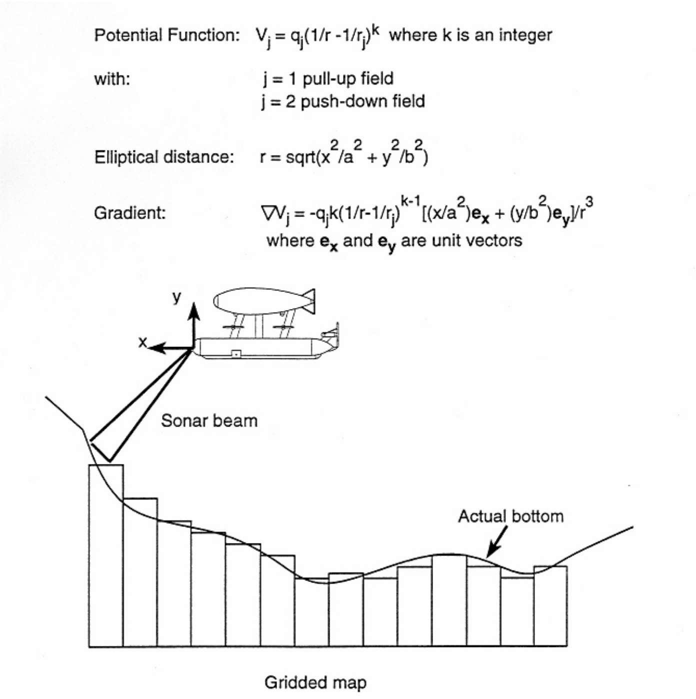


Figure 3 This diagram illustrates ABE's bottom-following algorithm. As the vehicle transits, it builds a map of the seafloor using an acoustic rangefinder pointed forward at 30 degrees. An asymmetric potential field is used to alter the vehicles forward and vertical speed.

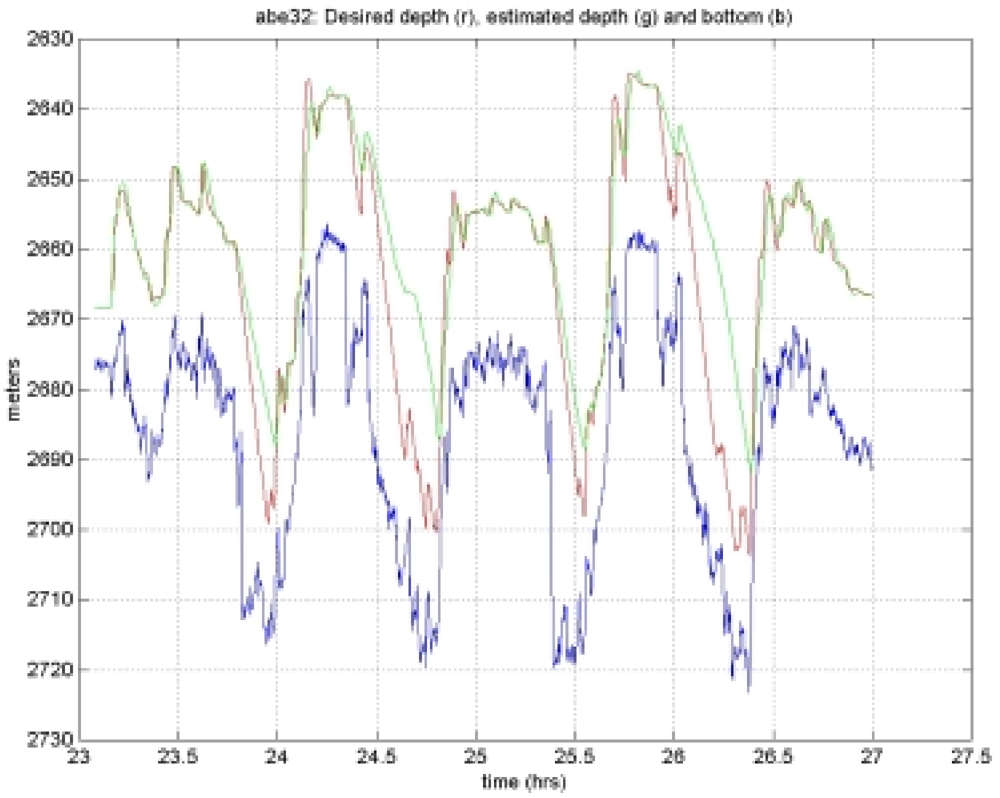


Figure 4. This plot shows the vehicle depth and the estimated bottom depth as functions of time during repeated crossings of a rift valley. The vehicle descends conservatively, but will slow down or even stop while ascending.

2.3 Bottom Following

Terrain surrounding the Mid-Ocean Ridge is very rugged, featuring steep slopes, scarps, and fissures. To obtain detailed magnetic and bathymetric data in these areas, ABE must survey close to the seafloor without risk of collision, maintaining a prescribed offset. Unlike most conventional AUVs which are controlled using surfaces located on the tail (like a torpedo), ABE's thrusters enable it to maintain controllability throughout its entire speed range. ABE can stop, drive directly up or down, and even back up.

ABE's control system takes full advantage of the vehicle's maneuverability. ABE carries an acoustic rangefinder in its nose that points 30 degrees forward. Data from the altimeter is first median filtered, then fed to a control algorithm that employs a one-dimensional map and a synthetic nonlinear elliptical force field[4], as shown in figure 3. Based on interaction between the map and the synthetic force field, the algorithm commands changes in the depth setpoint and forward thrust. The asymmetry in the design allows the vehicle to descend conservatively but ascend agressively. Also, the vehicle does not slow down during descents, but can slow down, stop, or even back up during ascents.

Results of an ABE dive over the trough are shown in figure 4. In this case, ABE was programmed to fly 20 meters off the seafloor. For video survey, the offset from the seafloor was set to 5 meters.

3. Survey Processing Methodology

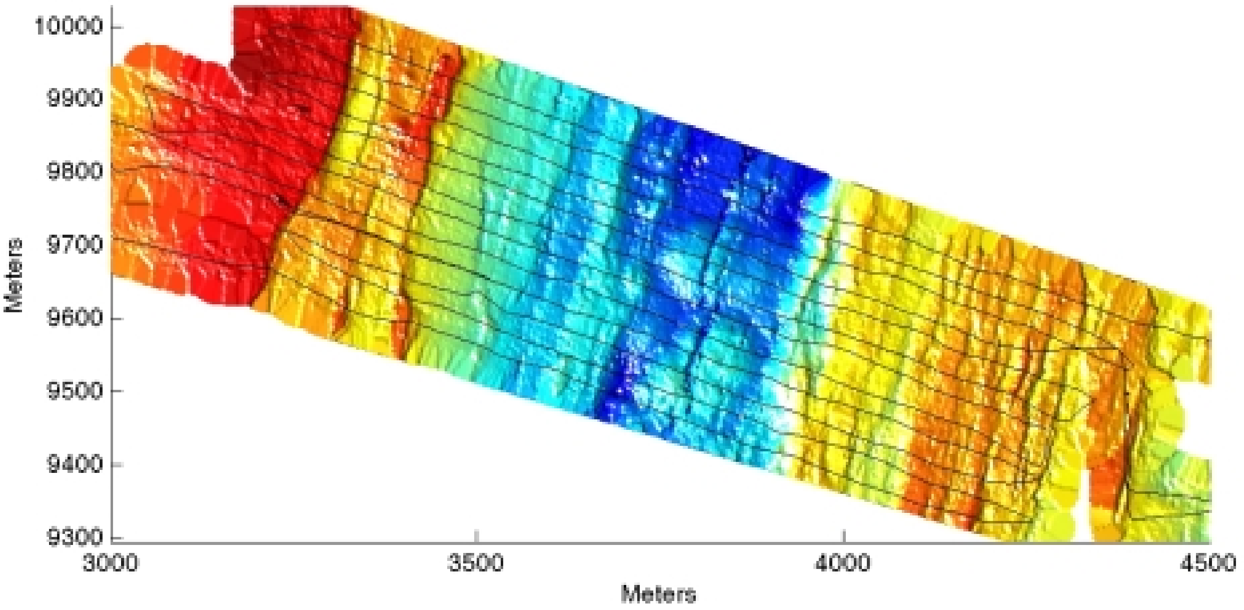
We used an Imagenix model 855 mechanically scanned pencil-beam sonar to collect range data. The unit operates at 675 khz, has a 1.9 degree conical beamwidth, steps in 0.6 degree increments, moves at approximately 2 steps/second, and can measure ranges out to 70 meters depending on the bottom type. We used fixed settings for the gain parameters. After making some adjustments between the first few dives, we obtained over 99% good returns with virtually no "flyers" or early returns.

In post-processing, we transformed the range and bearing measurements from the scanning sonar into a "dot cloud" of points registered in world coordinates. For the type of data gathered in these surveys, where the depth can be assumed to be a simple function of horizontal position, standard gridding routines [8] can be used to create a surface rendering. The sonar processing effort was greatly enhanced by the use of software developed to process data from the Jason ROV system[9]. This software had been used extensively for archaeological mapping on the Skerki Bank cruise[5] and the Edifice Rex effort[6]. Likewise, techniques for removing systematic biases in sensor data were also borrowed directly from the earlier Jason efforts. The methodology used to render the data and to eliminate systematic biases is described in more detail in the references [1, 7].

The data processing proceded in the following steps:

1 The navigation was reprocessed, recovering some transponder returns that had been rejected in real-time

Figure 5. This plot shows the gridded bathymetry and the vehicle tracklines for 3 dives, ABE30-ABE32. Each dive covered approximately 10km of tracks. This area comprises the ridge crest, which notched by a large trough (500-1000 m wide and 50-60 m deep). This large trough is bounded by an irregular staircase of escarpments each 10-20 m high, and its floor is sedimented and extensively fissured. The trough is much steeper on the east side than on the west.



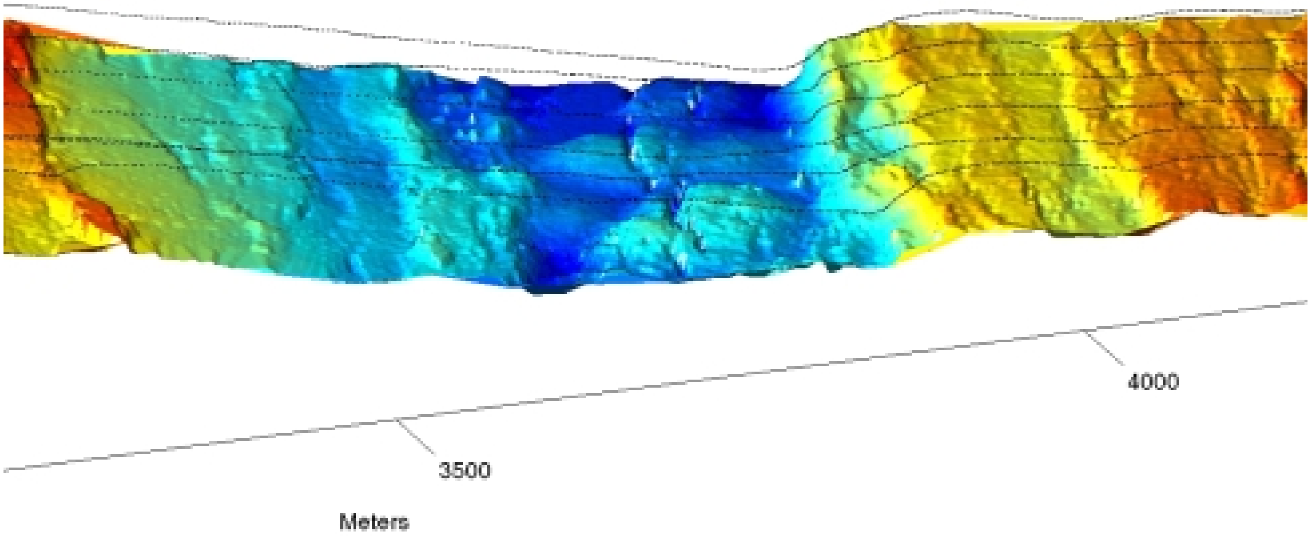


Figure 6 This plot shows the trough and the vehicle tracklines for which the vehicle was travelling from west to east. The shaded bathymetry shows the floor of the trough, including two split volcanic structures.The moderate, stepped slope can be seen on the left, while the steeper slope can be seen on the right.

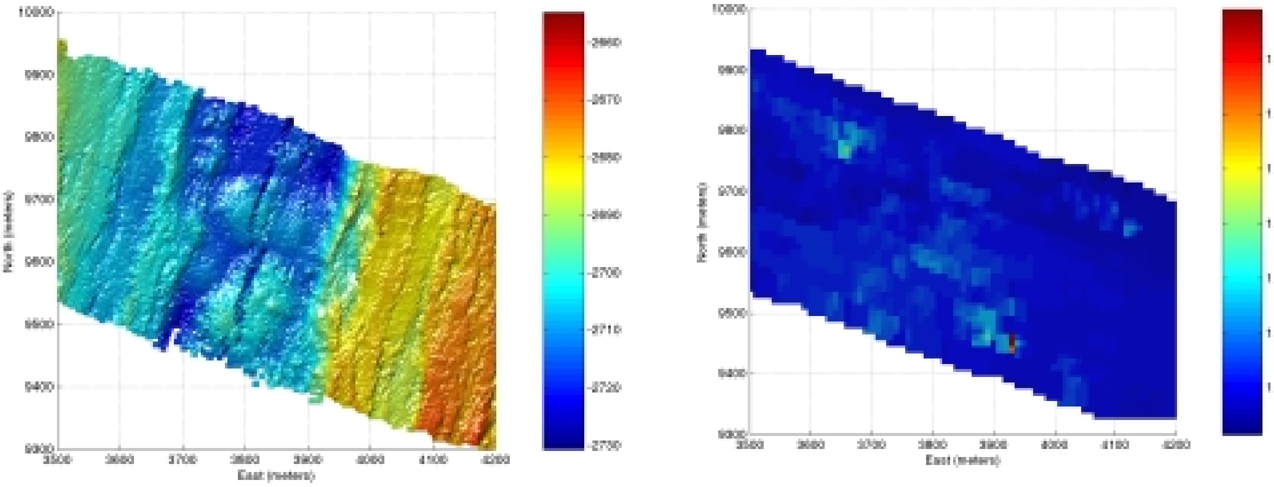


Figure 7. These plots show closeup views of the trough. The left plot shows the shaded bathymetry. The right plot shows the gridded temperature data. Two substantial temperature anomolies can be seen, which are likely associated with active hydrothermal vents.

and using improved transponder location estimates based on acoustic returns received at the vehicle.

2 Heading corrections were made using both ABE's magnetic compass and free gyro. These corrections reduced compass calibration errors and help mitigate the effects of magnetic anomolies [1,4].

3 Angular alignment errors for the sonar head were reduced by examining the bottom profiles when the vehicle was at reciprocal headings over a fixed location. A nonlinear minimization technique was employed to determine the value of the roll bias that produced the most consistent composite profile using scans from both reciprocal headings.

4 The dot cloud was rendered by combining the reprocessed vehicle position and attitude with the sonar range and bearing data.

5 The data was gridded onto a triangular grid spaced at 2.5 meters using a gaussian blending kernal.

4. Survey Results

Figure 5 shows a shaded rendering of the bathymetry along with the vehicle tracklines. Similar results for the larger area to the north can be found in [1], which also shows video imaging and mosaicking results.

Figure 6 shows a closeup 3D view of the bathymetry as well as the vehicle tracklines. This view emphasizes important details of the floor of the trough, including two split volcanic structures. Details of the bottom following performance can be seen as well.

Figure 7 shows a closeup of the gridded bathymetry of the floor of the trough along with a gridded represention of temperature.Temperature is consistent between tracklines and make sense geologically.

5. Conclusions

We employed an autonomous robot to gather a high resolution near-bottom dataset of bathymetry, magnetics, temperature, optical backscatter, and conductivity across the active tectonic and neovolcanic zone of the southern East Pacific Rise (18°S). ABE's pencil-beam scanning sonar provided an echo-sounding capability unprecedented at this scale in tight coverage (2.5 m^2 footprint) and the detail of measured relief. Gridded contours at 50 cm resolution produced a convincing picture of individual fault scarps, fissures, lava mounds, collapse pits, summit troughs, breached lava tubes, open-lava channels and lava pillars. The lack of trackline artifacts attest to the internal integrity of the data sets.

These results depended on a number of critical techniques. These included:

- A reliable vehicle capable of withstanding the rigors of launch, recovery, and prolonged survey in the deep ocean

- Precise, robust acoustic navigation combined with reliable track following control

- Reliable bottom-following in rugged terrain, enabled by a near-flawless acoustic altimeter and an appropriate control algorithm coupled to a maneuverable vehicle.

- Measurements from scanning sonar, temperature, and optical backscatter sensors well suited to completely autonomous operation.

- Software and related calibration techniques that permit detailed bathymetric renderings to be produced shortly after each dive.

Currently, we are preparing for several upcoming cruises with ABE. These efforts will continue our geological mapping and will expand our capabilities for mapping hydrothermal plumes. We are also designing a new vehicle that will feature improved endurance while retaining high maneuverability.

Acknowledgements

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