attack tactics were ineffective. Fire whirls were dramatic, as much as 800 m wide, crossing burned areas into unburned areas and causing spot ignitions ahead of the fire by as much as 1200 m. Pilots reported burning debris as high as 450 m above ground. Fire and heat from burning structures and ornamental vegetation were as much of a problem as any of the natural fuels.

Many forested areas that burned in October 2003 probably burned much more completely than they would have in the absence of successful fire suppression over the past century. Dense vegetation fostered the rapid spread of high-intensity fires in the forest canopy. Widespread die-offs of this vegetation may help to reduce the risk of canopy fires in the future. In recent years, large portions of southern California have experienced substantial vegetation mortality resulting from drought, insects, and disease [*Predictive Services*, 2003]. After the fine canopy fuels (needles, leaves, twigs, etc.) fall to the ground, the standing dead trees may be less prone to spreading fires in the canopy (Craig Allen, pers. comm.).

About 80% of the area burned in the October 2003 southern California fire siege, however, was in chaparral or grassland. Whereas healthy forests in southern California can sustain a low-intensity fire regime with regular surface fires in the absence of fire suppression, chaparral always experiences canopy fires that consume much of the vegetation. Not only does chaparral regenerate quickly, but a relatively small proportion of the areas with homes proximate to wildland vegetation actually burned—only about 5% of southern California's wildland-urban interface in total (S. Stewart, pers. comm.). Consequently, the risk of large regional-scale fires remains high.

Acknowledgments

Support for this research came from the U.S. National Oceanographic and Atmospheric Administration's Office of Global Programs. We thank E. Bainto for assistance with the graphics and C. Allen and M. Moritz for their comments.

References

Mensing, S.A., J. Michaelsen, and R. Byrne (1999), A 560-year record of Santa Ana Fires reconstructed from charcoal deposited in the Santa Barbara Basin, California, *Quaternary Research 51*, 295–305.

Mission-Centered Solutions (2003), *Southern California Firestorm 2003: Report for the Wildland Fire Lessons Learned Center*, 63 pp., Mission-Centered Solutions, Inc., Parker, Colo.; http://wildfirelessons.net/.

Predictive Services (2003), *Monthly Fire Weather/Fire Danger Outlook*, Southern California Geographic Area Coordination Center, Vallejo, Calif., November.

Pyne, S. J. (1997), *Fire in America*, 654 pp., University of Washington Press, Seattle.

Schlobohm, P. and J. Brain (2002), Gaining an Understanding of the National Fire Danger Rating System, *National Wildfire Coordinating Group Publication: NFES # 2665*, http://www.nwcg.gov.

Author Information

Anthony L. Westerling and Daniel R. Cayan, Scripps Institution of Oceanography, La Jolla, Calif.; Timothy J. Brown and Beth L. Hall, Desert Research Institute, Reno, Nevada; and Laurence G. Riddle, Scripps Institution of Oceanography, La Jolla, Calif.

Seabed AUV Offers New Platform for High-Resolution Imaging

PAGES 289, 294–295

A number of marine biological, geological, and archaeological applications share the need for high-resolution optical and acoustic imaging of the sea floor [*Ballard et al.*, 2002; *Greene et al.*, 2000; *Shank et al.*, 2002]. In particular, there is a compelling need to conduct studies in depths beyond those considered reasonable for divers (~50 m) down to depths at the shelf edge and continental slope (~1000–2000 m). Some of the constraints associated with such work include the requirement to work off of small coastal vessels or fishing boats of opportunity, and the requirement for the vehicle components to be air-shippable to enable inexpensive deployments at far-flung oceanographic sites of interest.

Over the last 2 and a half years, the Seabed Autonomous Underwater Vehicle (AUV) has been designed and deployed in support of such tasks off of Puerto Rico, Bermuda, Stellwagen Bank off Massachusetts, and the U.S. Virgin Islands.

Components and Capabilities

In designing the Seabed AUV (see http://www.whoi.edu/DSL/hanu/seabed), a decision was made to incorporate standard oceanographic sensors as far as possible to minimize costs and allow for easy maintenance. It currently supports a 300-kHz side-scan sonar, a 1200-kHz Acoustic Doppler Current Profiler, a Seabird pumped Conductivity, Temperature and Depth sensor, a 675-kHz mechanically scanned pencil beam sonar, and a 12-bit (high dynamic range) camera system. A 2-kWhr lithium-ion battery pack provides an 8-hour endurance for Seabed running at speeds between 0.3 m/s to 1 m/s. Its size—each of its two torpedo-shaped hulls is 1.5 m in length—and weight of 250 kg permit easy deployment off small coastal or fishing vessels of opportunity, and it can be shipped by air at a very reasonable cost to most departure ports.

Optical Imaging and Navigation and Control

Seabed has been designed specifically to further the growing interests in the area of sea floor optical imaging; specifically, high-resolution color imaging and the processes of photomosaicking and three-dimensional image reconstruction. In addition to high-quality sensors, this imposes additional constraints on the ability of the AUV to carry out structured surveys, while closely following the sea floor. The distribution of the four thrusters, coupled with the passive stability inherent in a two-hulled vehicle with a large meta-centric height, allows the Seabed AUV to survey close to the sea floor, even in very rugged terrain.

Figure 1 illustrates vehicle performance in such challenging applications. The vehicle (top left) can follow steep gradients at constant altitudes; in this case, on a coral reef off the U.S. Virgin Islands, and follow a greater than 45° slope at 3 m (top center) while obtaining high-resolution imagery with good color fidelity.

Figure 2 shows an image obtained from the vehicle using its camera and lighting system at night in 65 m depth, in the absence of ambient lighting. The nonlinear preferential attenuation of different parts of the visible spectrum underwater led to images that are not color-balanced. However, the 12 bits of dynamic range provided by the camera allow us to compensate and color balance the imagery as shown in Figure 2 (bottom) by using methods including frame averaging and parametric surface fitting in the homomorphic domain.

To accomplish high-resolution, large-area surveys, the AUV is run under closed loop control [*Whitcomb et al.*, 2000]. Navigation in shallow water (down to a few hundred meters) is accomplished by using a doppler velocity log in combination with Global Positioning System data before and after the dive. Algorithms for bottom-following in rugged terrain also allow the AUV to carry out autonomous surveys in regions of high relief while running precise track lines. The results of such a task are illustrated in Figure 3. Here, the AUV was imaging a boulder pile with a series of closely spaced track lines, while maintaining a constant 3-m altitude off the bottom in an area where the relief was also of that order.

Photomosaicking Underwater Imagery

Photomosaicking underwater is a challenging task [*Pizarro et al.*, 2003]. The nonlinear attenuation of color underwater, the absence of uniform ambient lighting, an unstructured

---

By Hanumant Singh, Ali Can, Ryan Eustice, Steve Lerner, Neil McPhee, Oscar Pizarro, and Chris Roman

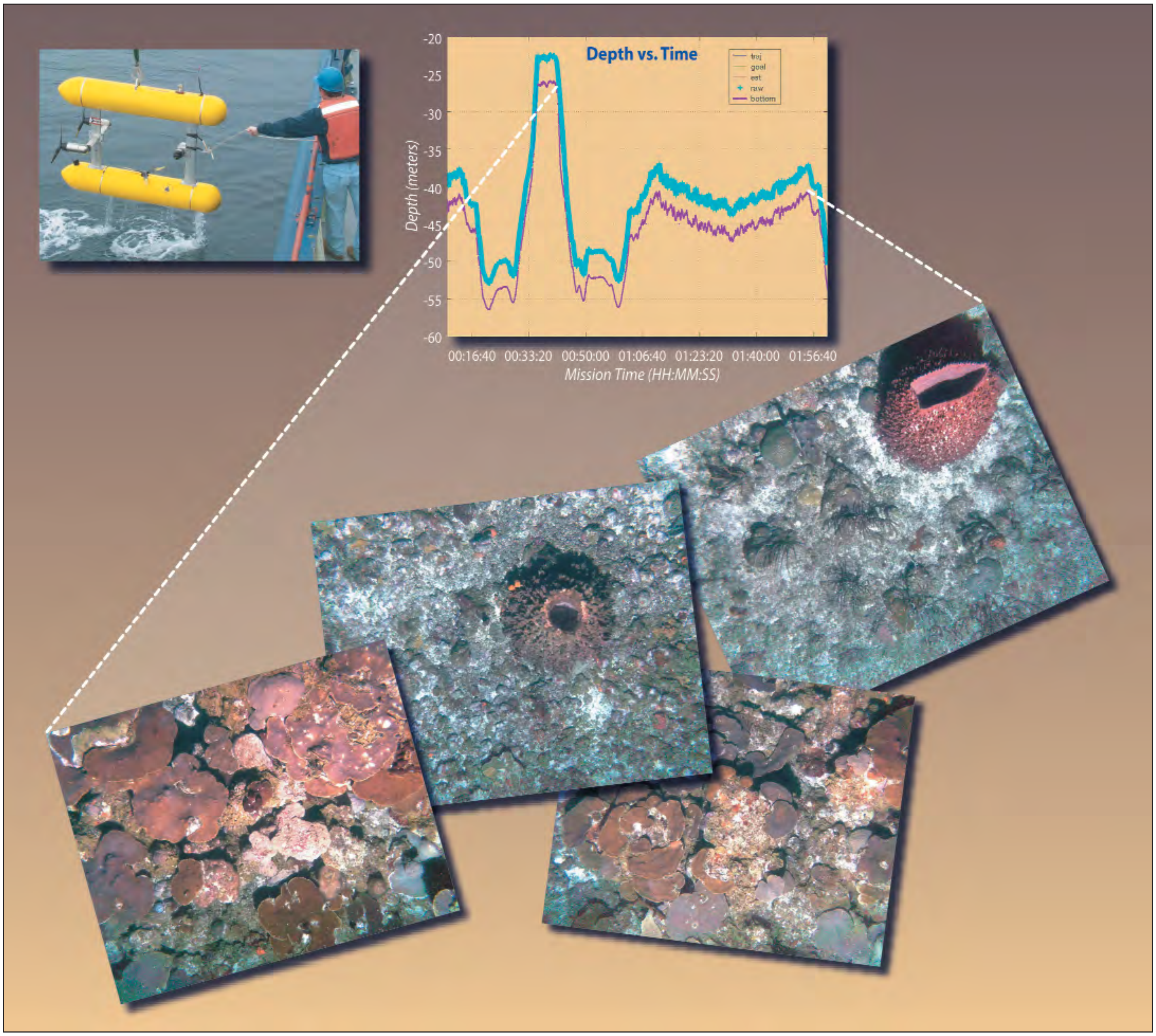

Fig. 1. The Seabed AUV (top left) has been designed for high-resolution imaging close to the sea floor. It is capable of working very close to the sea floor, as illustrated by the mission depth profile (top center) at a coral reef in the U.S. Virgin Islands. During this mission, it followed the sea floor bathymetry at a height of 3 m across a steep cliff in varied terrain. Even in such challenging environs, the Seabed AUV can obtain high-resolution, high-quality color imagery (bottom row).

terrain, and backscatter from the water column all combine to make image registration underwater a difficult task. Our systems-level solution to the problem (as described above) has been to use a combination of technologies to collect color-balanced images that can be coupled with precision navigation and closed loop control associated with the vehicle, to allow automatically constructed photomosaics, such as the 27-image mosaic shown in Figure 3.

Typically, overlapping imagery with a structured survey is collected, and after color compensation of each image, features based on the Harris corner detector are extracted, and they are encoded individually using Zernike basis functions. Features in Zernike space can then be compared across an overlapping image pair to estimate the transformation for that pair of images. In a sequential manner, image topologies can thus be generated, and in a final step, combined into a single photomosaic [*Shank et al.*, 2002].

These efforts highlight the possibilities associated with such work for underwater imaging platforms in general. Small AUVs, such as Seabed, are necessarily constrained in the amount of light available for optical imaging. They are also constrained by their size, to having a limited camera-to-light separation. Our ability to provide high-color fidelity and resolution for imagery obtained from a small AUV highlights the possibilities associated with optical imaging from other platforms such as the *Jason* ROV and the DSV *Alvin*. A number of these imaging technologies have been successfully transitioned to other assets within the academic community, including the *Jason* ROV and the *Abe* AUV. Efforts are also currently underway to make these photomosaicking technologies widely available for academic users.

Further details about the Seabed AUV can be found at Web site: http://www.whoi.edu/DSL/hanu/seabed. Our efforts with regard to the use of this asset are continuing through funded work on the engineering aspects as well as through scientific research cruises. The low costs associated with using this AUV make

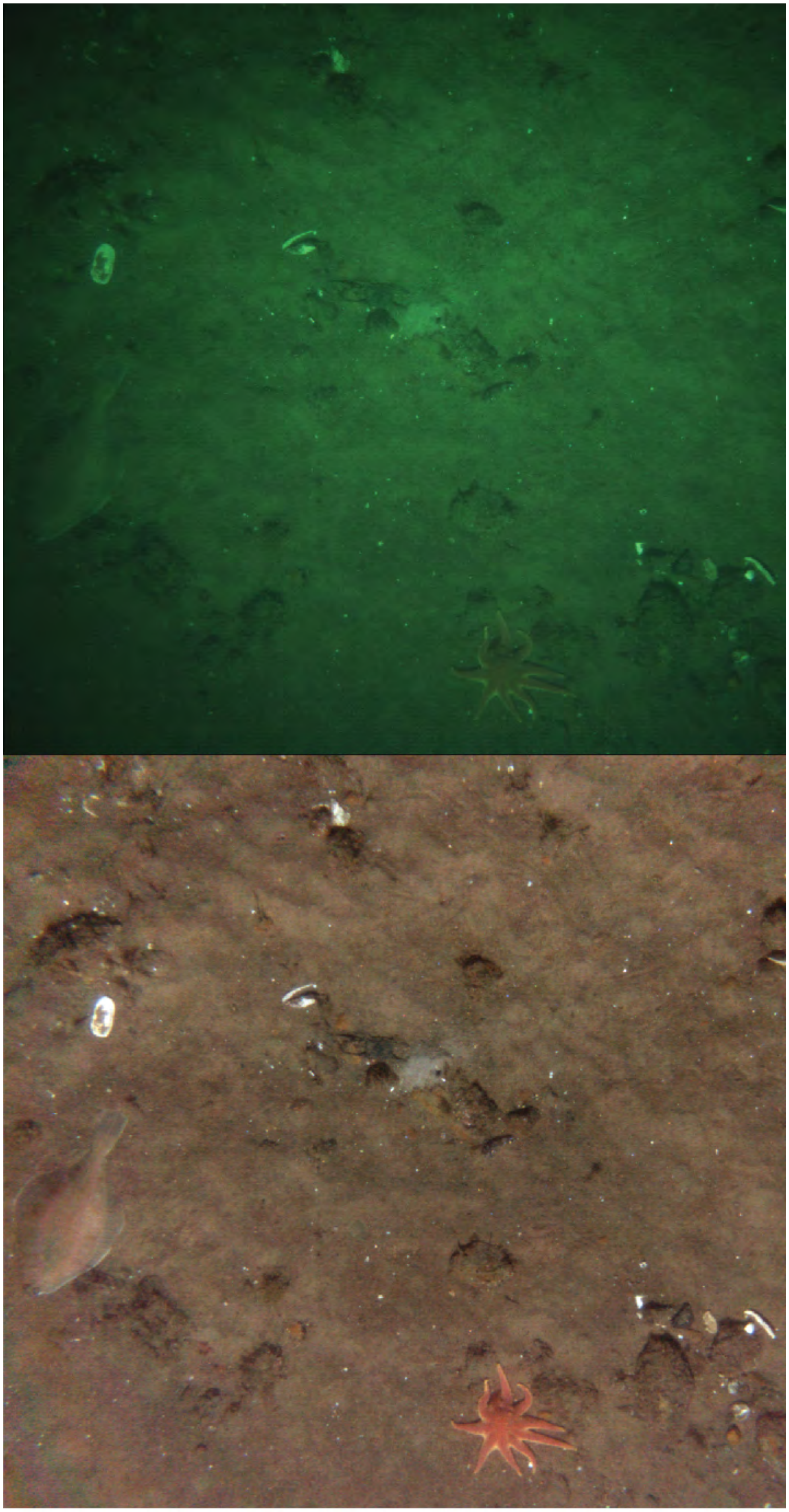

Fig. 2. A typical raw (top) and color-compensated (bottom) image obtained by using the Seabed AUV off Stellwagen Bank in 65 m of water. The image footprint covers an area of approximately 3 m x 3 m.

it an ideal platform for conducting long-term, repeatable time series surveys at sites of interest. Collaboration with those interested in using this asset is encouraged.

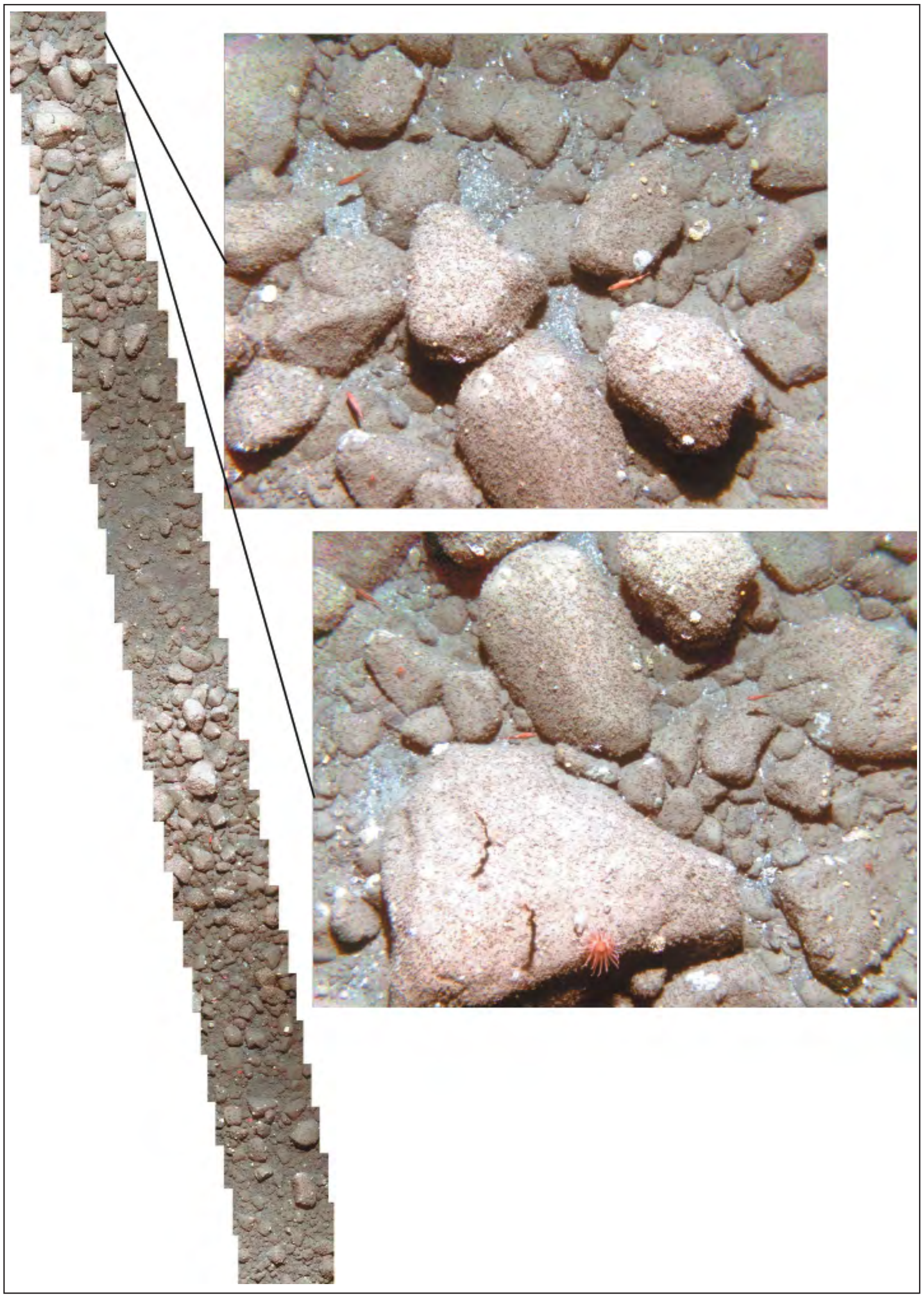

Fig. 3. A 27-image photomosaic of a rock pile in Stellwagen Bank, off of the Massachusetts coast, along with two of the original color-equalized images that went into constructing it. Each image encompasses an area of 3 m x 3 m, with the total mosaic spanning 35 m in length.

Acknowledgments

This work was funded in part by the Office of Naval Research under grant #N00014-01-10310, in part by the Censsis Engineering Research Center of the U.S. National Science Foundation under grant EEC-9986821; and in part by the Woods Hole Oceanographic Institution, through a grant from the Penzance Foundation. We thank D. Fornari and R. D. Ballard for their invaluable suggestions and comments regarding this manuscript. We also thank Rob Reves-Sohn, Page Valentine, James Lindholm, Ken Foote, Roy Armstrong, and Rick Nemeth for their support during our initial cruises.

References

Ballard, R. D., et al. (2002), The discovery of ancient history in the deep sea using advanced deep submergence technology, *Deep Sea Res., 1(47)*, 1591–1620.

Greene, G. H. et al. (2000), *Mapping and Classification of Deep Sea floor Habitats,* ICES 2000 Annual Science Conference, (CITY), Bruges, Belgium, September.

Pizarro, O. and H. Singh (2003), Towards large area mosaicing for underwater scientific applications, *IEEE J. Ocean. Eng. Underwater Image and Video Proc., 28 (4),* October.

Shank, T. et al. (2002), Time-series exploration and biological, geological, and geochemical characterization of the Rosebud and Calyfield Hydrothermal Vent Fields at 86°W and 89.5°W on the Galapagos Rift (abs.), *Eos, Trans. AGU, 83(47),* Fall Meet. Suppl.

Whitcomb, L. L., et al. (2000), *Advances in Underwater Robot Vehicles for Deep Ocean Exploration: Navigation, Control and Survey Operations,* The Ninth International Symposium on Robotics Research, Springer-Verlag, London.

Author Information

Hanumant Singh, Ali Can, Ryan Eustice, Steve Lerner, Neil McPhee, Oscar Pizarro, and Chris Roman

For additional information, contact Hanumant Singh, Deep Submergence Laboratory, Woods Hole Oceanographic Institution, Woods Hole, Mass.; E-mail: hsingh@whoi.edu.