DESSC Recommendation to Incorporate ABE/Sentry into the NDSF

The operators of ABE requested DESSC to consider incorporation of ABE/Sentry into the NDSF. They have reviewed their request and associated documents and fully endorse inclusion of ABE/Sentry into the National Deep Submergence Facility (NDSF). Incorporation of ABE into the National Deep Submergence Facility (NDSF) would be concurrent with the removal of the towed systems DSL-120A and Argo II. DESSC also endorses the transitioning of the autonomous vehicle Sentry into the NDSF, and its replacement of ABE when Sentry becomes fully operational.

In support of the DESSC request, the following documents are provided for consideration at the next UNOLS Council meeting:

1) A letter of endorsement from DESSC

2) Support letters from the international science user community that include endorsements from:

Charlie Langmuir	Harvard University
Russell McDuff	University of Washington
Gretchen Fruh-Green	ETH-Zurich
Suzanne Carbotte	Lamont-Doherty Earth Observatory
Maurice Tivey	Woods Hole Oceanographic Inst.
Tim Shank	Woods Hole Oceanographic Inst.
John Sinton	University of Hawaii
Colin Devy	IFM-GEOMAR

3) Attachment 1 - The original ABE/Sentry white paper presented to DESSC by WHOI at their meeting in Woods Hole in May 2006.

4) Attachment 2 - A brief overview of the ABE vehicle, what it does, how - and its specifications.

5) Attachment 3 - Detailed information of the ABE data products that would be provided as standard as an NDSF vehicle.

UNIVERSITY OF WASHINGTON
Seattle, WA 98195

Peter Wiebe
UNOLS Council Chair
Woods Hole Oceanographic Institution
Woods Hole, MA 02543

June 12, 2006

Dear Peter:

The operators of the Autonomous Benthic Explorer (*ABE*) have requested the DEep Submergence Science Committee to consider incorporation of *ABE* into the National Deep Submergence Facility (NDSF) concurrent with the removal of the towed systems *DSL-120A* and *Argo II*. DESSC has reviewed the information package and proposal submitted by the *ABE* operators and fully endorses inclusion of *ABE* into the NDSF in as timely of fashion as possible. The replacement of the two older assets (*DSL-120A* and *Argo II*) by *ABE* will improve the mapping, imaging, and exploration capabilities of the NDSF and place the facility in a good position to meet future challenges associated with deep sea exploration and research. DESSC also endorses the transitioning of the autonomous vehicle *Sentry* into the NDSF, and its replacement of *ABE* when Sentry becomes fully operational.

The flexibility and reliability of *ABE* has made this vehicle a favorite of the community for mapping, exploration, and geophysical and water column studies and there is very strong community support for bringing *ABE* into the NDSF (please see supplemental letters of support that are included with this letter of recommendation). Missions flown by *ABE* are routinely highly successful. They have lead to the collection of 1) some of the highest resolution, highest quality seafloor bathymetry obtained within the ocean basins; 2) the discovery and efficient mapping of new hydrothermal vent fields (e.g. Lau Basin); 3) novel heat flow and geochemical studies of hydrothermal plumes; and 4) detailed photographic imagery of the seafloor that allows assessment of ecosystems. *ABE* is also well suited for flying in highly rugged terrain (e.g. vertical and overhanging ledges and 60 m tall chimneys at Lost City). Its synchronous use with Jason 2 and Alvin allow extremely efficient and cost effective use of ship time and it is an important asset to have on multidisciplinary cruises.

The demand for *ABE* has been high, with over 180 missions completed, and it is anticipated that this demand will only continue to grow. *ABE* has been the AUV workhorse for the science community and new technological developments incorporated into and planned for *Sentry* will help NDSF meet upcoming challenges associated with rapid response capabilities, ocean observatories, and a growing demand by biological oceanographers for detailed measurements and observations. Because of increased community demand for *ABE* and its proven track record it is important that *ABE* becomes incorporated into the NDSF in a timely fashion so that this facility can continue to meet community science needs now and in the future.

Sincerely,

Deborah S. Kelley

Deborah S. Kelley
Chair of DESSC

HARVARD UNIVERSITY

DEPARTMENT OF EARTH AND PLANETARY SCIENCES
20 OXFORD ST.
CAMBRIDGE, MA 02138
TEL. (617) 495-2351 FAX. (617) 495-8839

Debbie Kelley
Chair, DESSC
School of Oceanography
University of Washington

12 June, 2006

Dear Debbie:

I am writing to you in support of including an AUV in the National Deep Submergence Facility (NDSF). My recommendation is based on my experience with ABE during a cruise to the Lau Basin a year and a half ago, so I will start with a brief report on what ABE allowed us to do that led to a far more efficient use of valuable ship time.

The Lau Basin in the southwest Pacific is a distant location for US Ships, and therefore the development of this area as a Ridge2000 (R2K) integrated study site was logistically challenging. I was chief scientist of the second cruise of this four cruise program, with the aim to locate hydrothermal vents and carry out regional rock sampling along a ridge length of about 44km. How could this be most efficiently accomplished?

Through consultation with Chris German, then based in the UK, and Woods Hole colleagues, we came up with the idea of using ABE as the hydrothermal exploration tool. While the planning documents for R2K had envisaged the second cruise as localizing but probably not actually finding vent sites, we envisaged that with ABE we might be able to go from water column signals to actual vent field location, completion with photo-mosaics. Then, while ABE was diving and recharging batteries, we could do rock sampling from the surface, effectively doubling the efficiency of shiptime compared to a sequential series of rock sampling and plume sampling programs carried out from the ship itself.

We used ABE in three different modes. In Phase 1, ABE flew at the depth of the neutrally buoyant plume, which permitted us to map the plume well in two dimensions. Then based on this information we designed Phase 2 to fly 50-75 meters above the bottom, carrying out further water column work and obtaining sea floor bathymetry. Since ABE's depth and propeller usage were continually monitored by the vehicle, analysis of these data not only provided us with superb bathymetry far beyond what the ship was able to obtain, but also showed abrupt vertical changes in depth showing when ABE intersected the buoyant plume stem. These data then permitted Phase 3, 5-10 meters above the bottom when ABE was able to take color photography for the identification of specific vent fields and first order characterization of the biota. ABE was able to navigate through complex chimney terrain, even in areas that subsequently were viewed logistically challenging for Jason. Through this series of phased exploration, we were able to discover and characterize three new vent fields, and also provided the Japanese information that led them directly to the discovery of the Mariner field in the southern part of the study region.

While ABE was working and recharging, we were able to carry out the most intensive rock sampling program of any back-arc basin, making the Eastern Lau Spreading Center the best studied back-arc basin in the world.

ABE had three major advantages for us. First, it enabled a strategic and very successful approach to vent discovery, with unprecedented success over such a short period of time in a poorly known and tectonically complex area. Second, ABE provided an unparalleled data set-- three dimensional water column information over many square km, high resolution bathymetry, and photo-mosaics, all navigated on a common basis. Third, ABE enable far more efficient use of ship time, providing 50% more rock samples than would have been obtained otherwise.

This program was very expensive because ABE was included as a line item. It could be funded through the normal proposal process because this cruise was an essential part of the R2K program, with a long planning process and community mandate behind it. I would be very reluctant to propose such a program without such a background. It is one of the strange aspects of our funding system that even programs that allow more efficient use of our valuable and increasingly scarce shiptime can run into problems owing to the review process and the natural psychological sticker shock response. If ABE were to be included in the NDSF, such programs of exciting science and increased efficiency would be facilitated.

To conclude, I had not previously used an AUV, and I found the ABE capabilities and personnel professional, helpful and accommodating. They worked long hours to ensure the success of our program. I am confident that they would work well within a structure such as the NDSF, permitting wider use of this emerging and rapidly improving technology, and more efficient use of our ship resources. I strongly recommend the inclusion of ABE, and hopefully more advanced vehicles in the future, within the NDSF.

Sincerely,

Charles Langmuir
Professor of Geochemistry

UNIVERSITY OF WASHINGTON

SCHOOL OF OCEANOGRAPHY
Russell E. McDuff, Director

June 13, 2006

Dr. Deborah Kelley
UNOLS DESSC Chair
University of Washington
School of Oceanography
Box 357490
Seattle, Washington 98195-7940

Dear Deb,

I would like to add my strong endorsement to the ABE AUV (and eventually its successor Sentry) being added to the National Deep Submergence Facility in conjunction with the removal of older, less capable platforms.

This is a transition that I have advocated since 2000 and so I consider this a step that is long overdue. The cost effective conduct of many R2K studies has been impaired by the "free" availability of the Jason family versus funding ABE costs from science funds. ABE has primarily focused on mapping, but my own experiences demonstrate that it is a flexible vehicle, with top technical support for adaptation to other missions.

I hope in the future DESSC adopts an approach to stewardship of NDSF such that these transitions occur in a more timely way.

Sincerely,

Russ

Russell E. McDuff
Professor and Director

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ETH

Eidgenössische Technische Hochschule Zürich
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Chair, Deep Submergence Science Committee
Prof. Deborah Kelley
University of Washington
School of Oceanography
Box 357940
Seattle, WA 98195

June 8, 2006

Inclusion of ABE in the National Deep Submergence Facility

Dear Debbie,

In anticipation of the up-coming recommendations to UNOLS about AUVs, I would like to express my support of the addition of the Autonomous Benthic Explorer (ABE) as part of the National Deep Submergence Facility. As you are aware, our experience with the use of ABE during the 2003 Lost City expedition was extremely positive and I was very impressed with its unique mapping and exploration capabilities.

I think it is important to emphasize to UNOLS that the bathymetric data collected from the Lost City field is truly astounding and has proven crucial to our understanding of this spectacular hydrothermal system. Our work with ABE produced a unique bathymetric map with a resolution at the meter scale, which has allowed us to recognize very small-scale geological features and has led to a much better understanding of how the Atlantis Massif was formed, what processes have led to the formation of Lost City, and why it is located where it is. In addition, our expedition in 2003 was the first time that ABE had flown in an extremely steep and complex terrain. It performed amazingly well and proved its flexibility not only in navigation but also in the mode of conducting sonar surveys – in addition to down-looking surveys, the possibility to have the sonar placed at a side-looking angle was invaluable to better image the steep cliffs along the face of the massif and the pinnacles and towers in the hydrothermal field.

I am convinced that other groups have experienced similar successful deployments of ABE and that a very broad marine community would benefit greatly if ABE were added as an official AUV of the National Deep Submergence Facility. The highly flexible and versatile operating conditions available with ABE and its potential for producing high quality, 3D bathymetric data open up numerous possibilities for mapping and exploring new areas of the ocean floor. In addition, the ability to couple ABE missions with other vehicles is a highly efficient way to conduct field programs like that at Lost City.

With best wishes

Gretchen Früh-Green

LAMONT-DOHERTY
EARTH OBSERVATORY
OF COLUMBIA UNIVERSITY
P.O. Box 1000 61 ROUTE 9W Palisades, NY 10964-8000 USA

Dr Deborah Kelley
Chair of DESSC
School of Oceanography,
University of Washington
(kelley@ocean.washington.edu).

June 12, 2006

Dear Dr Kelley,

I am writing in response to a request for a letter of support for adding the ABE-Autonomous Underwater Vehicle (AUV) to the National Deep Submergence Facility. Since it's development in the 1990's, ABE has been used for a number of unique seafloor and water column mapping studies that have provided new insights into fundamental crustal accretion and hydrothermal processes. In the coming years there is no doubt that AUVs like ABE will play an important role in observatory science and will be crucial for the event response studies envisioned under ORION. Adding the ABE AUV to the NSDF would facilitate wider use of this remarkably versatile vehicle for marine science and would encourage the further development of AUV technology for academic research. I am highly supportive of this proposal to transfer the vehicle to the NSDF.

My own experience with ABE is as a user of ultra-high resolution bathymetry survey data collected using this vehicle by Cormier and Ryan in 1999. During this program, ABE was configured with a variety of sensors enabling the collection of co-located and complementary data along pre-programmed tracks. My focus was the Imagenex bathymetry collected to provide a complete coverage of a portion of the southern East Pacific Rise at 18°14'S. The resolution of the seafloor bathymetry obtained with this system was unprecedented and provided for the first time seafloor maps comparable in resolution to the highest achievable on land.

The significance of this vastly improved spatial (3-5m) and vertical (< 1m) resolution for my study is that it enabled application of a fault restoration technique to assess the relative contributions of magmatic and tectonic extension to seafloor spreading and axial trough relief. A variety of mechanisms have been proposed for the crestal troughs found along portions of the fast spreading ridges including tectonic extension, volcanic collapse and subsurface magmatic movements. The complete coverage Imagenex bathymetry enabled us to fully characterize the tectonic displacement field associated with faults and vertical-offset fissures in the region and calculate the seafloor subsidence volume represented by the crestal trough. Comparison of the trough volume with typical seafloor eruption volumes, revealed that only a small subset of the frequent magmatic events which build the upper crust are needed to form the pronounced axial depression. A significant reduction in magma supply to the ridge crest, which is invoked in some models for axial troughs, is not required. This study would not have been possible without the ultra-high resolution data that can only be acquired with near bottom vehicles. The precise navigational capabilities of ABE were as important to the success of the mapping capability as the ability to operate a high resolution sonar near the seafloor.

From my involvement with Ridge2000 and MARGINS related science it is clear that there is increasing need for the high resolution mapping capability only achievable with autonomous underwater vehicles. ABE has proven itself to be a highly versatile platform of use for a variety of investigations. Operation of the vehicle as part of a national facility is now needed to stabilize support and facilitate the broader use of this unique capability.

Best Regards,

Suzanne Carbotte
Doherty Research Scientist
Carbotte@ldeo.columbia.edu
845-365-8895

WOODS HOLE OCEANOGRAPHIC INSTITUTION
Dr. Maurice A. Tivey, *Tenured Associate Scientist Department of Geology and Geophysics*

Dr. Maurice A. Tivey
phone (508)-289-2265
email: mtivey@whoi.edu

June 8th 2006.

Prof. Deborah Kelley
Chair – Deep Submergence Science Committee (DESSC)
Sch. Of Oceanography
University of Washington
Seattle, WA

RE: Incorporation of AUV ABE/Sentry into the NDSF

Dear Debbie

I would like to express my support for bringing an autonomous underwater vehicle into the National Deep Submergence Facility (NDSF) which is operated by Woods Hole Oceanographic Institution (WHOI). It is my understanding that the Autonomous Benthic Explorer or ABE vehicle will be initially used within the facility, but that ABE will be replaced with the second generation vehicle Sentry by the end of 2007 once that vehicle has been demonstrated to be equal to or superior to the ABE vehicle.

I was the first science user of ABE back in 1995 when I suggested that the ABE engineering team led by Al Bradley, Dana Yoerger and Barrie Walden could collect magnetic field data for me while testing their various subsystems. Since that time, ABE has gone on to log more than 180 science-driven missions collecting more than 3000 km of bottom tracks with remarkable success. The data ABE has been able to collect has both excited and inspired scientists and technologists alike. The funding agencies of the National Science Foundation (NSF) and the NOAA Ocean Exploration program were very supportive of science programs utilizing this new technology. This support was particularly impressive as the costs of the vehicle operations had to come out of the science funding portion of the programs. Scientists were willing to sacrifice increased bottom lines to their budgets because of the quality and high-resolution nature of the data and because the ultimate scientific insight one obtained from an ABE survey was simply unparalleled at the time. With tighter budgets becoming *de rigeur* it has been more difficult to sustain this. Many colleagues have asked me why such technology is not more widely available and part of the NDSF. The remarkable robustness of the ABE system, its compatibility with the navigational systems of other NDSF vehicles has meant that joint missions using ABE and Alvin or ABE and Jason have been remarkably successful. This synergy makes the idea of having ABE/Sentry part of the NDSF a no brainer in my book.

While the use and availability of AUVs has expanded tremendously over the last few years, the availability of deep ocean capable AUVs and also the ability to navigate and negotiate in typically rough terrain has been much more limited. ABE and its successor Sentry are specialized platforms for science which like other vehicles in the NDSF offer unique capabilities for research in the deep ocean. These capabilities, such as the ability to hover, or back up in rough terrain and to navigate using existing NDSF navigational infrastructure are a force-multiplier to the existing use of NDSF vehicles freeing up Jason or Alvin to concentrate on manipulator-intensive operations rather than having these systems “mow-the-lawn” for a portion of their operations. The additional capability of unattended AUV operation freeing the ship to pursue other science operations such as CTD casts or multibeam mapping or even dive the submersible Alvin means increased efficiency and cost-effectiveness of ship time for science.

In summary, I believe that having an AUV with the unique capabilities offered by ABE and its successor Sentry is a very positive step for the NDSF and one that will make the facility even more successful than it has been to date.

Sincerely,

Maurice A Tivey

Maurice A. Tivey

MS #24 ♦ Woods Hole, MA 02543 USA ♦ Phone: 508-289-2265 ♦ Fax: 508-457-2023 ♦ E-mail: mtivey@whoi.edu

WOODS HOLE OCEANOGRAPHIC INSTITUTION

To: Dr. Deborah Kelley
Chair, Deep Submergence Science Committee
School of Oceanography
University of Washington

June 10, 2006

From: Dr. Tim Shank
Associate Scientist
Biology Department
Woods Hole Oceanographic Institution

Re: Consideration of ABE into the NDSF- a biological perspective

Dear Debbie,

I understand the ABE (Autonomous Benthic Explorer) is currently being considered for inclusion in the National Deep-Submergence Facility. As a past user of ABE, I would like to provide you with my perspective, perhaps somewhat unique (but not for long) as I am one of the few biologists (actually perhaps the only one so far) who has used ABE repeatedly to conduct biological research. Over the past ~5 years, I have utilized ABE as part of five research programs (over 25 dives) and have witnessed enormous advances in the capabilities and field-readiness of the ABE's systems. ABE has been essential for rapidly and efficiently locating and mapping remote vent sites to investigate the composition and distribution of vent communities (e.g., from 2002- Galapagos, to 2004- Lau Basin, to 2006- South Atlantic) as well as to interact synergistically with partnered vehicles (e.g., Alvin and ROV Quest) to collect fauna and other data for a variety of detailed studies, including the pursuit of the evolutionary relationships among hydrothermal vent fauna around the world (e.g., discovery of vent sites in the South Atlantic and Lau Basin).

As you know, ABE conducts fully autonomous surveys of the seafloor and is especially well suited to working in the rugged terrain on the mid-ocean ridge crest. ABE has proven reliable for constructing micro-bathymatric maps of the seafloor as well as overlapping digital imagery for the critical characterization of seafloor fauna and their habitats prior to follow on bottom operations (e.g., Shank et al., 2003). Recently, ABE has been used for several biological programs in the Galapagos Rift, Lau Basin, New England Seamouts and the South Atlantic which have further proved its reliability as a high-resolution seafloor survey vehicle, and pointed to its unique characteristics not only to collect detailed, near-bottom geological, geophysical and ground-truthing data, but also detailed photographic imagery and subsequent mosaics that permit the characterization and assessment of organismal-habitat relationships.

The next five years of deep-sea biological research will utilize ABE and it's imaging capability for diverse biological objectives, including: 1) detailed mapping of the temporal and spatial changes in faunal community structure with repeat transect imaging surveys (observatory-type applications), 2) biologically mapping large continuous swath-like expanses of the seafloor (e.g., several degrees of latitude along a mid-ocean ridge, in concert with other AUVs) to document the patchy distribution of populations for developing metapopulation models; and 3) exploring under polar ice for potentially unique species and ecosystems. Actually, I am happy to let you know that each of these examples is already funded and underway, with biological hypotheses driving the use and need for ABE (and other AUVs).

Biological science applications in the future include the autonomous tracking of pelagic organisms (e.g., larvae, harmful dinoflagellates) and the fusion of autonomous delivery mechanims, adaptive sampling, and species-specific molecular probes to detect, characterize, and assess microbial community structure, the movements and behavior of larvae, phytoplankton, and zooplankton, and how their genes function in differing environments. These new perspectives on seafloor biological processes (and their scales) will revolutionize our ability to image the deep ocean and seafloor and have already fostered a paradigm shift in field techniques and measurements that will surely result in new perspectives for earth and biological processes.

ABE is currently at the forefront of being the scientific "workhorse" and has rightfully garnered this respect. Biological oceanographic research and AUVs are already in a courtship phase and together they will revolutionize biological approaches, measurements, and observations in the deep-sea for decades to come. Biological research will (and is already) synergistically driving the needs for the future development of AUV technology. ABE is a clear leader in the consistent delivery of scientific products, maintaining proven abilities, and meeting the challenges of rapidly-evolving hypotheses in deep-ocean science. I encourage you to consider including ABE as an autonomous underwater vehicle asset in the NDSF.

I would be more than happy to discuss any questions or thoughts regarding ABE and the future of deep-submergence science with you anytime. Thank you.

Sincerely,

Timothy M. Shank

Timothy M. Shank

Date: Tue, 13 Jun 2006 12:11:30 -1000
From: John Sinton <sinton@hawaii.edu>
To: kelley@ocean.washington.edu
Cc: cgerman@whoi.edu
Subject: ABE and the NDSF
Parts/Attachments:
1 OK ~41 lines Text
2 Shown ~50 lines Text

Dear Deb,

I want to express my support for the idea of including ABE into the NDSF. This is an extremely versatile vehicle that makes an ideal ancillary program for many deep submergence investigations. ABE was a night program during my 1999 STOWA cruise and this arrangement worked exceedingly well. Al and Dana even rigged up a mini wax corer on ABE, which gave us additional sampling sites! I know that there is now the possibility to use ABE concurrently with Alvin so it is becoming ever more attractive as a complementary vehicle. I have recently written proposals to use both ABE and Alvin on an investigation of lava flow fields of the Galapagos spreading center because the two data sets - visual observations and sampling from Alvin, magnetics, high-resolution bathymetry, sub-bottom profiler and potential for near-bottom photographs from ABE are a near-perfect combination for the scale and types of studies that are required for this project. I would think that there are many high-resolution geological investigations that would want to use this combination of capabilities and for this reason it simply makes sense to incorporate ABE into the NDSF. I would be happy to provide additional comments if you think it would be useful.

Regards,
John Sinton

Attachment 1

Introduction of a Deep-Diving, Multipurpose AUV into the National Deep Submergence Facility

C. R. German, B. Walden, D. R Yoerger (WHOI)

1. Overview

We propose to introduce an autonomous underwater vehicle (AUV) equipped for deep (up to 5000m), near-bottom operations as a natural complement to the HOV *Alvin* and ROV *Jason II* within the National Deep Submergence Facility (NDSF). Initially, we propose to add *ABE (Autonomous Benthic Explorer)* to the NDSF. *ABE* is a proven and reliable research AUV with more than 170 scientific dives. Incorporation of *ABE* into NDSF will bring new capabilities to the facility and offer investigators from a wide spectrum of disciplines greater flexibility in conducting a remarkable array of mid-water and near-bottom scientific investigations. Our vision is that *ABE* will be replaced by the new *Sentry* AUV by January 2008 once its operational and scientific capabilities have been demonstrated. *Sentry* will not only have improved capabilities over *ABE*, but because it has been designed as an operational vehicle it will be simpler and more cost-effective to operate than *ABE*. Estimated day rates for *ABE/Sentry* range from $7,250 (for 105 operational days/yr) to $9,050 (for 63 operational days/yr). In order to introduce an AUV into the NDSF with minimal impact on current NDSF operating budgets we recommend to DESSC that the *Argo II* and *DSL-120A* towed vehicles be removed from the NDSF. *Argo II* will be retired; the *DSL-120A* vehicle will continue to be available for scientific use outside of the NDSF.

2. Scientific Capabilities of an *ABE*-like AUV

In recent years *ABE* has proven its usefulness as a deep-diving AUV dedicated to scientific investigations near the seafloor - both as a complement to human- and remotely-operated vehicles and as a stand-alone vehicle-of-choice for novel investigations. During more than 170 dives, *ABE* has conducted a remarkable array of scientific operations for marine geologists and geophysicists, physical and chemical oceanographers and biologists. Specific examples include: high resolution geological and geophysical mapping at the EPR 9-10°N and 17°S (e.g. Carbotte et al., 2003), Juan de Fuca Ridge (Glickson et al., 2006) and Galapagos Spreading Center 86°W; detailed seafloor mapping even in extremely rough terrain (e.g. Lost City; Kelley et al., 2005; Karson et al., 2006; Ludwig et al., 2006); sub-seafloor geophysical investigations using high-resolution magnetics (e.g. northern MAR); comprehensive water column mapping of heat-flow from known hydrothermal fields (e.g. Juan de Fuca Ridge Thompson et al., 2005); detection of completely new hydrothermal systems in previously unexplored ridge-systems using chemical sensors and the first photo-reconnaissance of the ecosystems hosted at these sites (e.g. Lau Basin; southern MAR); and cable route surveying on the Juan de Fuca Ridge.

AUVs have greater maneuverability than towed vehicles used for the same purpose and can provide both higher quality data and improved survey efficiency compared to vehicles towed by a surface ship. Because an AUV is decoupled from the surface ship, its operations are less sensitive than towed vehicles to sea state except during launch and recovery. AUVs can also be operated simultaneously with other shipboard operations allowing more efficient use of ship time. Both *ABE* and *Sentry* can be mobilized worldwide from a single 20’ van and can be deployed from a range of non-specialized research ships (e.g. ships without a dynamic positioning system), facilitating rapid response efforts and exploratory research in new areas.

3. The Long-term Plan for the *ABE* & *Sentry* Vehicles Within the NDSF

ABE is now a reliable and proven research platform for scientific investigations near the deep seafloor with high demand from scientists across the U.S. research community. Its powerful capabilities, proven track record, and use by a wide range of investigators motivate us to propose that it be incorporated into the NDSF. *ABE* meets many of the criteria that DESSC has discussed for adding a new vehicle to the NDSF, including:

- the vehicle provides a unique capability to the deep submergence community in comparison to other available assets
- the vehicle has a proven track record of serving the deep submergence science community
- there is strong community demand for future use of the vehicle
- the vehicle complements other vehicles in the NDSF scientifically and/or operationally
- the vehicle would benefit from utilization of common personnel and infrastructure with other vehicles in the NDSF
- vehicle costs are affordable within the NDSF budget

WHOI's new AUV, *Sentry*, will soon offer improved scientific and operational capabilities to *ABE* and, hence, improved scientific opportunities to the U.S. community. Recognizing this, we plan to replace *ABE* with *Sentry* by January 2008 once the operational and scientific capabilities of the *Sentry* vehicle are demonstrated to users of the NDSF in 2007. At that point, the NDSF would then consist of three vehicles: an HOV (*Alvin*), an ROV (*Jason/Medea*), and an AUV (*Sentry*).

4. Timetable for Transition from *ABE* to *Sentry*

The first sea-trials of *Sentry* were completed in April 2006 with a series of dives progressing from 500m to 2500m in the North Atlantic off Bermuda. The results of these trials will be presented to DESSC at its meeting in May 2006. These trials were very successful and demonstrated that *Sentry* can operate autonomously following pre-programmed navigational instructions along pre-set courses and at fixed heights off bottom and/or survey depths in modes nearly identical to *ABE's*. All basic systems on the *Sentry* vehicle worked well. The heading control is good to about +- 1/2 degree and depth control to a few centimeters. Tests indicate *Sentry* will have a single dive range well in excess of 100 km (compared to 20-30 km along track per dive for *ABE*) at a speed of up to 1m/sec (~ 2 kts)

To transition from the basic *Sentry* vehicle tested in Bermuda to one equipped and ready for scientific operations, comparable to *ABE*, will require three additional steps:

- Completion of final vehicle system engineering, including surface radio-control, work-van, and purchase of seagoing spares.
- Equipping the vehicle with the existing *ABE* sensor suite (CTD, optical back-scatter and Eh sensors, magnetometer, near-bottom multibeam mapping tool, and a digital camera/strobe system for imaging)
- Interfacing of the vehicle with long-baseline navigational systems used by *Alvin* and *Jason*.

We estimate that the above efforts will require a total of ca. 7 person-months of effort (as listed below) and can be implemented readily, including sea-trials aboard R/V *Tioga*, during the remainder of calendar year 2006:

May-July 2006: Completion of vehicle system engineering (4 months total effort)
July-Aug 2006: Interfacing with science sensor suite (2 months)
Sept-Oct 2006: Completion of LBL interfacing and sea-trials aboard *Tioga* (1 month)

WHOI has committed $500K of institution funds for the completion of *Sentry* development. This work will provide a science-ready vehicle complete with a dedicated transport/work-van and a set of the most critical operational/sea-going spares.

During calendar year 2007 we plan to operate *ABE* and *Sentry* side-by-side within the NDSF facility to demonstrate the operational and scientific capabilities of *Sentry* to science users. By January 2008 at the latest, and possibly earlier in 2007, we envisage *Sentry's* operational capabilities to be similar or superior to that of *ABE*. Once these capabilities are confirmed, *ABE* will be withdrawn from NDSF service and the transition will be complete.

Milestones:

- June 2006: *ABE* enters NDSF: announcement pre-Aug 15th NSF grant deadline.
- Aug. 2006: *Sentry* vehicle engineering complete.
- Oct. 2006: Science sensor suite and LBL capabilities for *Sentry* implemented.
- Jan.-Dec.2007: *Sentry* operated alongside *ABE* to demonstrate its capabilities
- Jan. 2008 (at latest): *ABE* withdrawn from NDSF; *Sentry* becomes dedicated NDSF AUV.

5. Removal of DSL-120A and ARGO from NDSF and Plans for Providing Sidescan and Photo-imaging to Science Users

It is our belief that the deep submergence community in the U.S. would be best served by the introduction of a deep-diving AUV like *ABE/Sentry* into the NDSF. Technologically, AUV are supplanting towed vehicles like *Argo II* and *DSL-120A* because of their superior versatility, maneuverability, and surveying efficiency. This transition is reflected in the usage of these vehicles over the past few years. For example, *ABE* had 104 'at-sea' days in 2004, 47 days in 2005, and 70 days in 2006. By comparison, usage of *DSL-120A* was 75 days in 2004, 51 days in 2005 and none in 2006; *Argo* was not used at all during the 2004-2006 period. In order to introduce an AUV into the NDSF with minimal impact on current NDSF operating budgets we recommend to DESSC that the *Argo II* and *DSL-120A* towed vehicles be removed from the NDSF. *Argo II* would be retired; the *DSL-120A* will continue to be available for scientific use outside of the NDSF.

In the case of the *Argo II* deep-towed camera system, we anticipate that future deep submergence community needs for real-time seafloor imaging can be met by the upgraded *Medea* vehicle (in the NDSF) or the Tow-Cam system that is operated as part of the MISO shared-use facility (outside the NDSF). *Medea* (which was upgraded in 2005) currently provides a stand-alone, real-time imaging system utilizing a fiber-optic cable that can be used for the same high-altitude (~10m) reconnaissance surveying that *Argo II* was used for. For imaging applications that don't require real-time data, AUVs are rapidly developing photo-mosaicing capabilities that are supplanting that of towed vehicles. During 2007, as the capabilities of *ABE* are transitioned to *Sentry*, a high-resolution, seabed photographic capability will be implemented on *Sentry*.

High-frequency, near-bottom side scan sonars remain an important tool for the deep submergence community especially for large-scale tectonic and reconnaissance mapping. Although we are recommending that the *DSL-120A* be taken out of the NDSF, it would still be available for use in deep submergence studies as shared-use equipment similar to the Tow-Cam. If the *DSL-120A* becomes shared-use equipment, in the future PIs will have to include the cost of using the *DSL-120A* in their proposals (as they do now for *ABE*). The day rate for the *DSL-120A* for two month-long field programs each year is estimated to be roughly comparable to the expected day rate for *ABE/Sentry* (see below). Thus the replacement of the *DSL-120A* with *ABE/Sentry* will not place a significant additional financial burden on NDSF.

There are several options for the delivery of high-resolution sidescan to the deep submergence science community in the future that DESSC may wish to discuss:

(1) The *DSL-120A* vehicle can continue to be supported by WHOI's Deep Submergence Laboratory

(DSL), with the operational assistance of the University of Hawai'i's HMRG group (as it has for the past 6 years). This is the most likely mechanism to support the only funded *DSL-120A* program scheduled for 2007 (Klein EPR program). This arrangement will facilitate the coordination of *DSL-120A* operations with those of other NDSF vehicles operated by WHOI.

(2) The *DSL-120A* vehicle could be migrated to the HMRG group at the University of Hawai'i. Members of this group are intimately involved in the operation of this vehicle and they are also the sole operators of the newer, complementary, *IMI-30* deep-tow vehicle, already offered as a separate facility at the University of Hawai'i. There may be costs savings by the management of the *DSL-120A* and the *IMI-30* vehicles by a single operational team.

(3) In the longer term, *Sentry* could be upgraded with an equivalent 120kHz sidescan system if there were community support (and funding) to do so. The advantages in terms of vehicle stability, speed and maneuverability make this an interesting option to explore in the longer term. As noted above, the April 2006 trials have confirmed that *Sentry* will be able to achieve a range significantly in excess of 100km at a cruising speed of 1.5 knots (maximum survey speeds typical for any deep-tow vehicle+cable combination, due to drag). With this range an AUV becomes an attractive, cost-effective option for seafloor mapping operations. For example, our preliminary calculations show that *Sentry* could achieve a ca.15% saving in shiptime for conducting "exploratory" type mapping operations over ca.200km range (e.g. Martinez et al., 2004; Lau Basin) where AUVs are least favored. Savings closer to 50% in shiptime could be achieved in surveys that require multiple parallel swaths (hence vehicle turns) such as past studies of the slow-spreading MAR (Humphris et al., 2002) and future studies such as off-axis mapping of the East Pacific Rise, process studies along an active ocean margins, and thorough characterization of ocean observatory sites.

6. Management of the NDSF AUV

- The management plan for an AUV in NDSF will follow the model already successfully implemented for both *Alvin* and *Jason II* by having a dedicated point-of-contact manager who is directly responsible for the AUV.
- During the first year (2007), when *ABE* is introduced into the NDSF and its capabilities are transitioned to *Sentry*, the AUV manager will be Dana Yoerger. Dana has been intimately involved in the development of both the *ABE* and *Sentry* AUVs. Yoerger, like Foster (*Alvin*) and Bowen (*ROV*) would report directly to the Chief Engineer for Deep Submergence (Walden) and scientific aspects of AUV use would be overseen, just as they are for *Alvin* and *Jason*, by the Chief Scientist for Deep Submergence (German).
- In managing the AUV facility, Yoerger would also receive administrative support from experienced staff at WHOI who are already familiar with NDSF operation (Offinger and Chandler). After this first transitional year, Yoerger would step down as manager but continue to provide shore-side engineering support for the NDSF AUV. A junior engineer/manager will be hired who will assume day-to-day management of the AUV.

7. Operational plan

- Ashore, *ABE* will be maintained and upgraded as required by Yoerger and Bradley. For *Sentry*, Yoerger, Catanach and Bradley (or Bradley's replacement upon retirement) will continue to be intimately involved in shore-side vehicle maintenance and development.
- At-sea operations of the AUV will require a three-person team: a mechanical engineer who also oversees all shipboard launch and recovery operations and coordinates with the ship's crew and officers; an electrical engineer to maintain the health of the vehicle systems and batteries and a software engineer to over-see mission programming, vehicle navigation and data manipulation/delivery to science. *Sentry* has been designed to not require senior engineering

support at sea. A team of experienced and qualified AUV operators will be established to meet increasing at-sea demands. In anticipation of this, we currently have 5 personnel active in DSL or NDSF being trained to support *Sentry* and/or *ABE* at-sea.

- The NDSF Data Manager (Vicki Ferrini) will develop scripts to assess the quality of AUV navigation and sensor data (e.g. C, T and optical back-scatter sensors, magnetometer, SM2000 and Imagenix, digital still camera). A list of standard *ABE* data products is described in an accompanying document.

Representative ABE Publications

Carbotte, S.M., W. B. Ryan, W. Jen, M.-H. Cormier, E. Bergmanis, J. Sinton, and S. White. 2003, Magmatic subsidence of the EPR at 18°14S revealed through fault restoration of ridge crest bathymetry. Geochem. Geophys. Geosyst, 4(1).

Cormier, M-H., W. B. Ryan, A. M. Bradley, D. R. Yoerger, A. Shah, J. Sinton, R. Batiza, and K. Rubin. 2003, Variable extrusive emplacement mechanisms in the axial region of the East Pacific Rise. Geology, 31(7).

Glickson, D., D.S. Kelley, and J.R. Delaney. 2006, Geological and hydrothermal evolution of the Mothra Hydrothermal Field, Endeavour Segment Juan de Fuca Ridge, *in prep.*

Karson, J.A. E.A. Williams, G.L. Früh-Green, D.S. Kelley, D.R. Yoerger and M. Jakuba. 2006, Detachment Shear Zone on the Atlantis Massif Core Complex, Mid-Atlantic Ridge 30°N. *Geochemistry, Geophysics, Geosystems in press.*

Kelley, D.S. J.A. Karson, G.L. Früh-Green, D.A. Yoerger, D.A. Butterfield, J. Hayes, T. Shank, M.O. Schrenk, E.J. Olson, G. Proskurowski, M. Jakuba, A. Bradley, B. Larson, K. Ludwig, D. Glickson, K. Buckman, A. S. Bradley, W.J. Brazelton, K. Roe, M.J. Elend, A. Delacour, S. M. Bernasconi, M.D. Lilley, J.A. Baross, R.E. Summons, S.P. Sylva. 2005, A serpentinite-hosted submarine ecosystem: The Lost City Hydrothermal Field. *Science*, 307, 1428-1434.

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Shah, A. K., M.-H. Cormier, W. B. Ryan, W. Jin, J. Sinton, E. Bergmanis, J. Carlut, A. M. Bradley, and D. R. Yoerger. 2003, Episodic dike swarms inferred from near-bottom magnetic anomaly maps at the southern east pacific rise. J. Geophysical Research, 108(B2).

Thompson, W.J., R.E. McDuff, F.R. Stahr, D.R. Yoerger, M. Jakuba. 2005, Heat flux from the Endeavour Segment of the Juan de Fuca Ridge, Eos Trnas. AGU Fall Meeting T31A-0489.

Tivey, M.A., A. Bradley, D. Yoerger, R. Catanach, A. Duester, S. Liberatore and H. Singh. 1997. Autonomous underwater vehicle maps seafloor, EOS, 78, 229-230.

Tivey, M.A., H.P. Johnson, A. Bradley, and D. Yoerger. 1998, Thickness measurements of submarine lava flows determined from near-bottom magnetic field mapping by autonomous underwater vehicle Geophys. Res. Lett., 25, 805-808.

Veirs, S.R., R.E.McDuff and F.R.Stahr, 2006, Magnitude and variance of near-bottom horizontal heat flux at the Main Endeavour hydrothermal vent field. *Geochemistry, Geophysics, Geosystems* 7, doi. Q02004.

Estimated Operating Budget

Transition period
As described above, the *ABE* AUV will be initially introduced into the NDSF in 2007. Existing NSF funding, coupled with WHOI institutional support, will be used to transition the *Sentry* vehicle to operational status. Following this transitional period *ABE* will be removed from the NDSF and *Sentry* will become the operational AUV in NDSF. Undoubtedly we will discover problems and improvements that will need eventual attention, but it should be possible to address critical issues using the suggested "baseline" support. The remainder can be the subject of future proposals

Routine Operations following transition period

<u>Baseline Support:</u>
3 person-months for AUV manager
6 person-months of engineering/technical support
1 person-month of administrative support
$10,000/yr: normal & expected parts & supplies
$50,000/yr: major modifications (science equipment installations/upgrades)

Total: $278,000

<u>Operational costs (per cruise):</u>

Normal Cruise:
Mobilization: 2 person-week of technician support
Cruise: 3 technicians door-to-door
Travel: 3 persons RT - $4,500
De-mobilization: 1 person-week of technician support
Expendables: $250 per dive, 1 dive/day
Insurance: $1,500
Shipping: 20' van RT - $20,000

Daily rate – Assume three 3-week cruises per year

Base	$278,000
Cruises	<u>$291,750</u>
Total	$569,750

63 operational days (door-to-door cruise days)
Daily-rate = $9,050

Daily rate – Assume three 4-week cruises & one 3-week cruise

105 operational days (door-to-door cruise days)
Daily-rate = $7,250

High level support personnel (e.g. Bradley, Yoerger)
Technical support personnel (e.g. Catanach, Billings, Duester)
Administrative support (Offinger/Chandler)

Attachment 2

The Autonomous Underwater Vehicle *ABE*

1. Overview

The *Autonomous Benthic Explorer* (*ABE*) is a fully autonomous underwater vehicle used for exploring the deep ocean up to depths of 4500 meters. *ABE* produces bathymetric and magnetic maps of the seafloor and has also been used for near-seabed oceanographic investigations, to quantify hydrothermal vent fluxes. Most recently, *ABE* has been used to locate, map, and photograph deep-sea vent sites following preliminary work by towed and lowered instruments. *ABE* has taken digital bottom photographs in a variety of deep-sea terrains, including the first autonomous surveys of an active hydrothermal vent site. To date, ABE has completed 181 dives in the deep ocean over 16 cruises, covering more than 3000 km of survey tracks at an average survey depth greater than 2000 meters.

2. Vehicle characteristics

ABE is a three body, open frame vehicle that utilizes glass balls as flotation in two free-flooded upper pods while the single, lower housing is host to the batteries that power the vehicle and all of its electronics. This separation of buoyancy and payload gives a large righting moment that simplifies control and allows the vertical and lateral thrust propellers to be located inside the protected space between the three, faired bodies. ABE has five thrusters allowing it to move in any direction. It can travel forward at a cruising speed of 0.6m/sec but one of ABE's most unique characteristics is that it can also hover and reverse – characteristics that are particularly valuable in the rugged terrain routinely encountered when investigating the deep seafloor. The navigation system onboard ABE consists of two proven and complementary navigation systems. For general use, ABE uses long "baseline" transponders, identical to those used by the research submersible *Alvin* and ROV *Jason*, and these allow deep seafloor surveys over distances of ca.5km to be carried out. In addition, however, ABE also carries an acoustic doppler velocity log (DVL) which provides short-range, high-precision navigation. With these navigation systems, ABE has the ability to follow tracklines with a repeatability of order 10m or better.

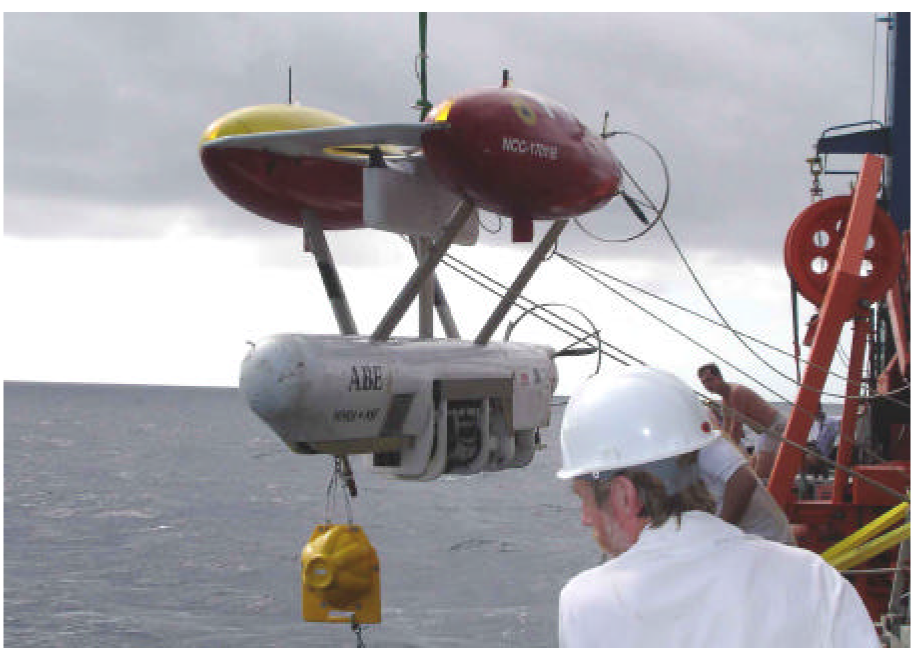

Fig.1 The ABE vehicle during at-sea deployment (Mid-Atlantic Ridge, 2005)

3. ABE Specifications

Dimensions:	Length = 3 m, width = 2 m, height = 2.5 m
Weight:	550 kg
Operating range:	20-40 km (14-20 hours)
Energy:	Lithium Ion batteries (5 kWh)
Consumption:	Hotel load: < 50W
	Total: 210-300W (depending on mission type)
Recharge time:	Maximum of 12 hours (80% recharge in ~6 hours)
Bus power:	42-60 Volts DC (for sensors)
Survey speed:	0 to 1.4 kt (top speed)
Descent time:	1000m/hour (expendable weights for descent and ascent)
Navigation:	Long baseline acoustic transponders
	Doppler Velocity Log
Sensor suites:	The standard science and engineering suite for ABE is detailed on the following page.

4. How ABE Works

ABE operates autonomously from the support research vessel. It has no tether, and is controlled in real-time by onboard computers using its own rechargeable batteries for all power. Upon launch, ABE descends to the seafloor through the use of a descent weight that is released after safe arrival at the seafloor. Throughout any dive, ABE uses acoustic long-baseline transponder navigation together, when close enough to the seafloor, with bottom-lock acoustic doppler measurements to determine its position and velocity over the seabed. ABE descends at 15-20m/minute following a controlled spiral trajectory to ensure that it reaches the desired starting point while consuming minimal energy.

After reaching the seafloor and performing a series of checks, ABE releases its descent weight to become neutrally buoyant and begins its pre-programmed survey. A dive can consist of any mix of water column investigations (e.g. hydrothermal plume surveys) at constant water depths, seafloor geophysical investigations at fixed heights above the seafloor (anywhere from 50-200m off depending on the application: e.g. magnetics, high-resolution bathymetric mapping) and digital photography at a height of just 5 meters above the seafloor. ABE usually surveys until either it reaches the end of its programmed survey or its batteries are depleted (typically between 20-30km along track and 15-30 hours of survey time, depending on sensor payload, survey type, and terrain). At the end of its dive, ABE releases two ascent weights to become positively buoyant and return to the surface at 15-20m/minute.

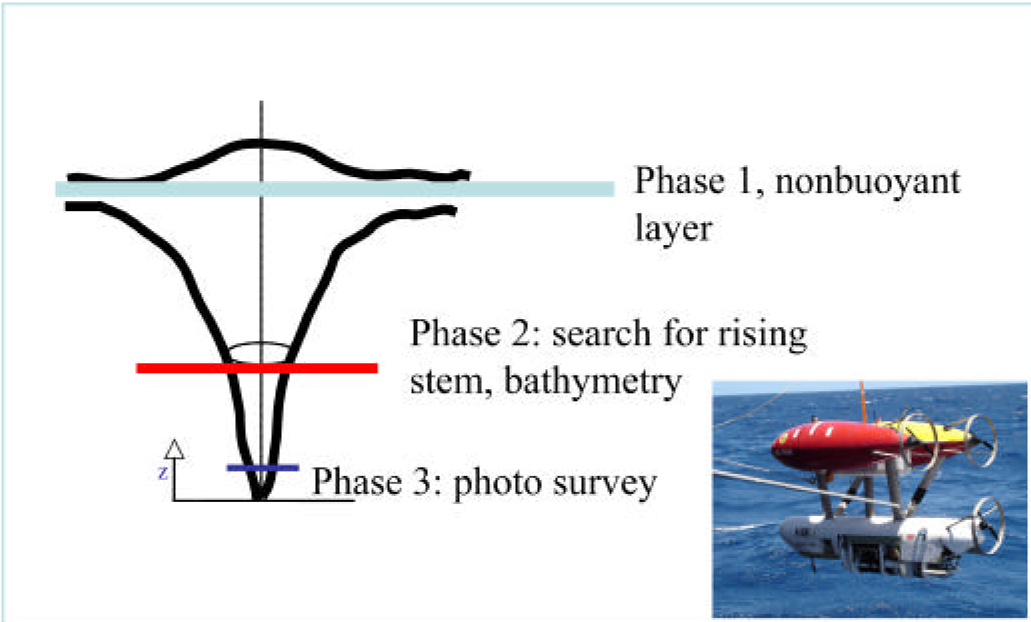

Fig.2 Schematic illustration of one recent use of *ABE* (2004-2006) - to locate new sites of hydothermal activity in the Pacific and Atlantic Oceans. Phase 1: oceanographic (physical/chemical) sensors are used to locate the centre of a dispersing effluent plume 100-300m above the seabed. Phase 2: SM2000 or Imagenex system is used to map the seafloor at high resolution; simultaneously, oceanographic sensors detect when the *ABE* vehicle intercepts the stem of the rising plume. Phase 3: digital still imaging is conducted of the seafloor at and around the vent-site to reveal the detailed geologic setting of he new vent-site and the nature of any associated chemosynthetic ecosystem.

5. Standard Science Sensor-Suite on ABE

ABE is equipped with a standard suite of science and engineering sensors (see below). In addition, ABE is a sufficiently flexible platform that additional sensors can be interfaced by PIs according to their specific interests and scientific needs.

Engineering sensors:
- ParaScientific pressure sensor, rated to 4500m
- Attitude sensors (pitch, roll, heading)

Geophysical sensors:
- SIMRAD SM2000 200kHz multibeam sonar, rated to 3000m
- Imagenex 675kHz scanning sonar, rated to 4500m
- 3-component Develco fluxgate magnetometer, rated to 4500m
- EdgeTech CHIRP (6-18kHz) sweep sub-bottom profiler, rated to 4500m

Oceanographic sensors:
- 2 sets of C, T sensors SeaBird models SBE3 & SBE4, rated to 4500m
- SeaPoint optical backscatter sensor (OBS) rated to 4500m

Seafloor photography

- a 1024 x 1024 pixel 12-bit digital still camera, rated to 4500m

Project-specific sensors interfaced to ABE by PIs during recent cruises

- Eh electrode (redox sensor) – Dr.Koichi Nakamura, Japan
- Fe(II) and Mn sensors – Prof Chris German, NOC, United Kingdom

NB All sensor data are stored on the vehicle and retrieved upon recovery.

Attachment 3

ABE Data Products

Precise navigation, robust control, and co-registered sensors permit ABE to characterize the seafloor and the near-bottom environment on the meter-scale through complementary sensing modes. Consequently, there are four different kinds of data and, hence, data products that can be expected routinely from *ABE* operations.

1. Navigation data

The most fundamentally important data-set for any *ABE* operation – a requirement for all *autonomous* vehicles if missions are to be achieved successfully – is accurate seafloor navigation.

The navigation used for *ABE* is a long-baseline (LBL) system augmented with doppler velocity logging. For LBL, *ABE* uses between 2 and 4 seafloor transponders, which are identical to those used by *Alvin* and *Jason*. The techniques used to set, survey, and recover the transponders are also identical. Presently, *ABE* uses 4 fixed frequencies, although plans are in place to expand this to eight and to allow the frequencies to be selected in software. *ABE* interrogates the transponders on a 10 second cycle. These interrogations are also heard at the vessel, which allows *ABE* to be tracked from the ship with only occasional interrogations from the ship to keep clocks synchronized. *ABE* does not depend on these interrogations from the vessel, however, so if the vessel leaves the site *ABE*'s navigation is not impacted.

In real-time, *ABE* uses the round-trip travel times, the vehicle depth measurement, and the local sound velocity profile to compute slant ranges. Based on vehicle and transponder depths, these slant ranges are projected into the horizontal plane and a fix computed using either a deterministic (two transponders) or least-squares (3 or more transponders) solution. *ABE* uses a series of filters to eliminate incorrect ranges caused by surface reflections and noise. The fixes are combined with the dead-reckoning solution from the doppler navigator and compass to produce the real-time position estimate, which is typically repeatable within a given transponder array to about 2 meters.

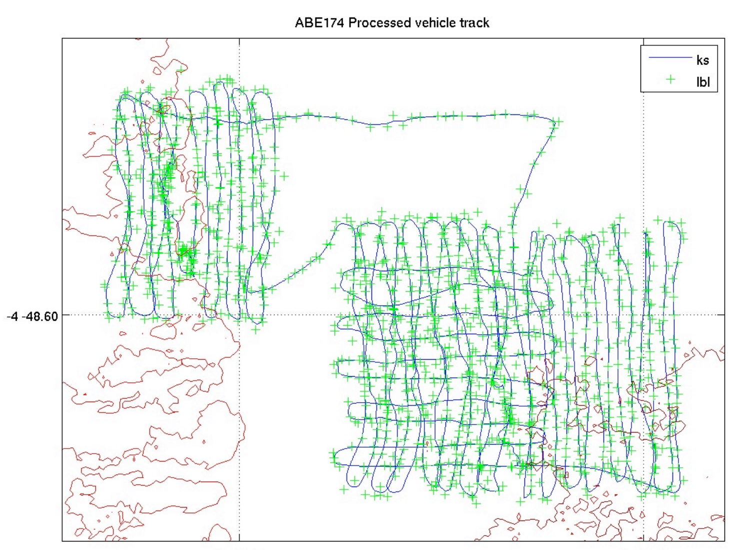

Fig.1 Example of processed post-dive navigation data (blue line) as derived from within-dive LBL fixes (green crosses) from an *ABE* near-bottom (5m off) photographic survey on the Mid-Atlantic Ridge – see Fig.3 for an example of a color photograph so obtained (C.German & D.Yoerger, WHOI).

At the end of each run, the data is postprocessed to produce a more accurate track. On the first dive in each area, the compass is recalibrated using magnetometer and compass data from slow spins during descent. Acoustic travel times are refiltered to recover as many good fixes as possible. For the first run in a new net, the transponder positions are adjusted to minimize the least-squares error for fixes with three or more ranges. Finally, the refined fixes, the recalibrated compass, and the doppler navigator data are recombined using a kalman smoother. The final processed navigation data is reported in Latitude and Longitude in decimal degrees (suitable for importing into, e.g., GMT amongst other mapping tools) and is embedded within the time-stamped scientific data file for each dive (see later).

2. Bathymetric data

Using either the SM2000 multibeam system (to depths up to 3000m) or the Imagenex scanning sonar, high resolution bathymetric data (precision ~1m, accuracy ~2-3m) can be obtained over an area of, typically, ≥2km^2 per dive depending on (i) height off bottom/line-spacing selected for the survey and (ii) choice of mapping instrument used (multibeam vs scanning sidescan). The bathymetric data products generated will be made available to the science user in three forms suitable for different science user needs:-

- raw x, y, z bathymetry data files that can be re-processed by the scientist, as required.
- gridded (5m) data files in .grd format which can readily be imported by the scientist into generic software such as *GMT* or *Fledermaus*, whether at sea or for post-cruise analysis.
- processed map *images* in .tif format that can be used by the science party for immediate visualization of the gridded data set, further dive planning while at sea and post-cruise report generation and publications.

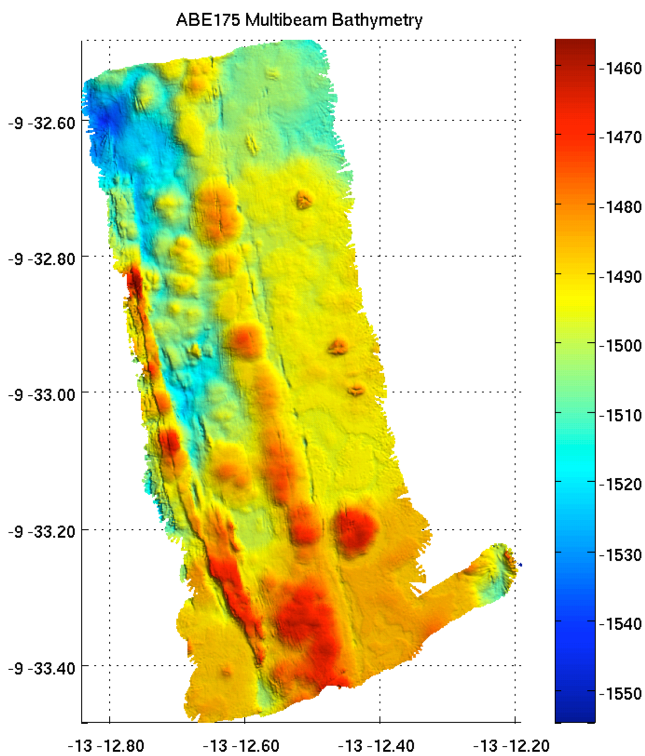

Fig.2 Example of a bathymetric map image generated at sea in May 2006 at 9°30'N on the Mid-Atlantic Ridge using the SM2000 multibeam system (C.German & D.Yoerger, WHOI).

3) Photographic Images

Using a dedicated high dynamic range (12-bit) 1024 x 1024 digital still camera, color photographs can routinely be obtained from ABE. At an altitude of 5m above bottom, each image measures approximately 3m x 3m. A fresh image can be captured every 5 seconds from ABE which, at a programmed survey speed of 0.4m/sec, generates a 33% overlap between adjacent images. The standard photographic data product generated by ABE will be a series of processed, time-stamped, color JPEG files. Together with the navigation, heading and altitude (height-off-bottom) data included in the science sensor data files (below) this will provide all the material necessary for interested scientists to generate photo-mosaics of areas of particular interest. (Under the auspices of the NDSF data manager, Dr.Vicki Ferrini, users will free access to software suitable for generating such photo-mosaics just as is already the case for Alvin and Jason photographs).

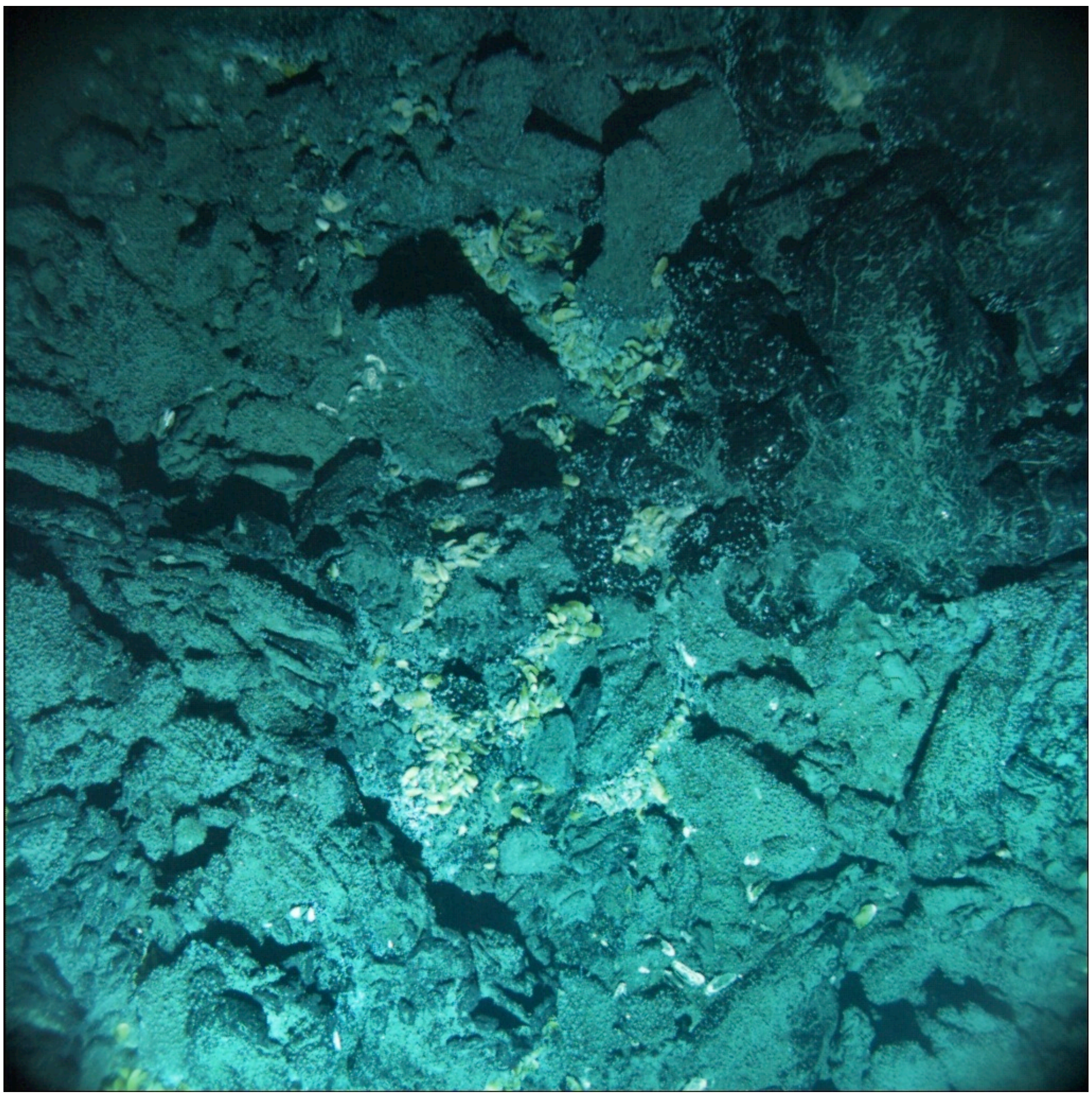

Fig.3 Example of a color photograph generated at sea in May 2006 on the Mid-Atlantic Ridge using ABE's 12-bit 1024 x 1024 pixel Digital Still Camera during ABE dive 174 – see Fig.1 (C.German & D.Yoerger, WHOI).

4) Standard 3-D navigation & science (geophysical and oceanographic) data arrays.

In addition to bathymetry and photographic data, numerous other sensors are routinely deployed on ABE and their data acquired. These are compiled at the end of each dive into a single scientific data file that is made available as a comma-separated-variable (.csv) text file. This is a format that can readily be imported into numerous data-analysis programs such as MatLab or other software appropriate for handling large data-files (e.g. Kaleidagraph - Mac OSX).
[NB: although .csv format files make for easy accessibility, the volumes of data collected by ABE on any given dive are large. Consequently, some non-specialist software (e.g. Microsoft Excel) which only allow files of up to ca.65,000 lines of to be opened, cannot be relied upon for routine usage. Science users wishing to take advantage of ABE will need to come to sea ready to take full advantage of the wealth of data that they will generate from their funded projects!]

The science data in each .csv file are organised into columns with labelled headings that cover time, processed navigation (vehicle position given in latitude and longitude in decimal degrees), depth, pressure (the primary variable from which depth is derived), height off bottom and heading (both essential for photo-mosaicing). Oceanographic data included in the same file include conductivity and temperature from each of the two C,T pairs mounted on the vehicle and optical backscatter output from the Seapoint OBS instrument. Geophysical data collected routinely on all deployments (in addition to the bathymetric data discussed previously) includes 3 components of magnetic field data. CHIRP sub-bottom profiler data can also be acquired if requested. For these geophysical data to be processed, a further .csv file is also provided that is typically used just buy the ABE group for engineering purposes: it includes pitch and roll data in addition to the heading data provided routinely to all science users (Table 1).

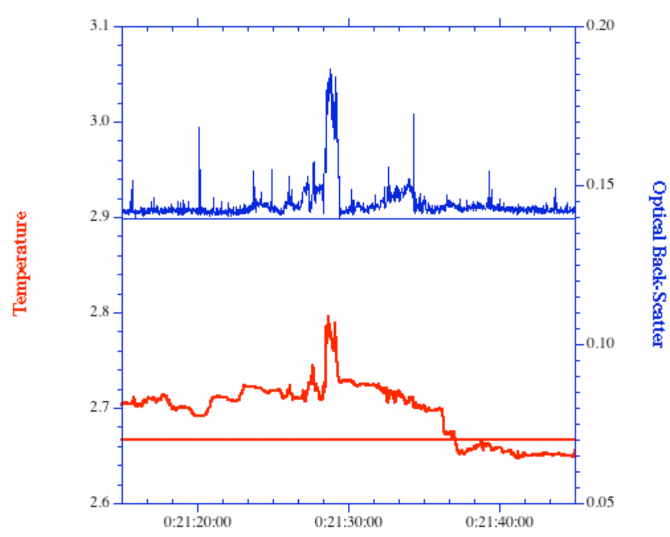

Fig.4 Plot of temperature and optical backscatter data recorded by ABE when intercepting a buoyant hydrothermal plume near 8°S Mid-Atlantic Ridge, May 2006 (C.German & D.Yoerger, WHOI).

Table 1: Example of Science Data routinely geenrated by ABE (ABE dive 175; May 2006)

Date	Time (h:mm:ss)	Latitude	Longitude	Depth	Pressure	Heading	MagX	MagY	MagZ	OBS	T1	C1	T2	C2	Height
15/5/06	5:48:58	-4.810074	-12.37186	2964.3	3005.8	7.23	2.0822	3.434	3.2894	0.1266	2.6021	3.2482	2.6009	3.2479	5.09
15/5/06	5:48:59	-4.810071	-12.37186	2964.3	3005.9	7.09	2.0822	3.4354	3.29	0.1268	2.6042	3.2484	2.601	3.2479	5.09
15/5/06	5:49:00	-4.810067	-12.37186	2964.2	3005.9	7.01	2.0818	3.4362	3.2906	0.1272	2.6049	3.2483	2.601	3.2479	5.09
15/5/06	5:49:01	-4.810062	-12.37186	2964.2	3005.9	6.95	2.0818	3.4378	3.2904	0.1266	2.6033	3.2483	2.6011	3.2479	5.09
15/5/06	5:49:02	-4.810058	-12.37186	2964.2	3005.8	6.94	2.0834	3.4404	3.2902	0.1268	2.6032	3.2483	2.6012	3.2479	5.09
15/5/06	5:49:03	-4.810054	-12.37186	2964.3	3005.9	6.92	2.0856	3.4428	3.2904	0.1262	2.6028	3.2483	2.6012	3.2479	5.27
15/5/06	5:49:04	-4.81005	-12.37186	2964.3	3005.9	6.96	2.086	3.4438	3.2912	0.1266	2.6036	3.2483	2.6012	3.2479	5.46
15/5/06	5:49:05	-4.810046	-12.37186	2964.3	3005.9	7.02	2.085	3.4444	3.2916	0.1266	2.6042	3.2484	2.6014	3.2479	5.48
15/5/06	5:49:06	-4.810041	-12.37186	2964.3	3005.9	7.06	2.084	3.4452	3.2916	0.1266	2.6035	3.2483	2.6013	3.2479	5.39
15/5/06	5:49:07	-4.810036	-12.37186	2964.3	3005.9	7.05	2.0824	3.4468	3.2902	0.1272	2.6044	3.2484	2.6013	3.2479	5.47
15/5/06	5:49:08	-4.810032	-12.37186	2964.3	3005.9	7.01	2.0802	3.4486	3.2884	0.1268	2.605	3.2484	2.6014	3.2479	5.48
15/5/06	5:49:09	-4.810028	-12.37186	2964.3	3005.9	6.91	2.08	3.4506	3.2872	0.127	2.6072	3.2487	2.6014	3.2479	5.39
15/5/06	5:49:10	-4.810023	-12.37186	2964.3	3005.9	6.81	2.0806	3.451	3.288	0.126	2.6093	3.2489	2.6014	3.2479	5.28
15/5/06	5:49:11	-4.81002	-12.37186	2964.3	3005.9	6.75	2.0816	3.4516	3.2886	0.1262	2.6093	3.2488	2.6015	3.2479	5.15
15/5/06	5:49:12	-4.810015	-12.37186	2964.3	3005.9	6.74	2.0822	3.4526	3.288	0.1264	2.6098	3.249	2.6016	3.2479	5.15