SURVEYING DEEP-SEA HYDROTHERMAL VENT PLUMES WITH THE AUTONOMOUS BENTHIC EXPLORER (ABE)

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Abstract

We present results from a novel survey of heat flux from hydrothermal vent plumes using the Autonomous Benthic Explorer, ABE. In this survey, we used the fully autonomous robot to measure the total heat flux from the Main Endeavour Field on the Juan de Fuca Ridge as well as the surrounding bathymetry. The paper summarizes plume behavior and outlines difficulties in prior methods of heat flux estimation, which have produced over an order of magnitude disagreement. We outline an approach where the AUV measures components of heat flux (temperature, conductivity, and velocity) over the surface of a carefully chosen control volume surrounding the vent field. We present results from a series of 10 ABE dives showing how fields of vertical velocity, temperature, salinity, and optical backscatter compare and also how they change with time. The paper concludes with a discussion of how these results can help us plan fully autonomous missions to locate and survey new vent sites.

Introduction

Autonomous underwater vehicles (AUVs) provide unique capabilities for mapping hydrothermal plumes. In this paper, we present results from an AUV cruise to the Main Endeavour Field (MEF) on the Juan de Fuca Ridge (47N, 129W) in the N.E. Pacific during August 2000. The MEF lies along the crest of the Juan de Fuca Ridge, an active spreading center where tectonic plates diverge. Hydrothermal vents occur when volcanic and tectonic processes induce the circulation of seawater through the earth's crust (Figure 1). As a result, hot, chemically altered seawater is discharged, or vented, forming plumes that often rise hundreds of meters into the water column. These hydrothermal vent plumes contribute significantly to the heat and chemical composition of the world's oceans.

While the various parts of the MEF have been intensely studied using manned submersibles, remotely operated vehicles, and towed, moored, and bottom-mounted instruments, the published estimates of heat flux from prior studies vary by more than an order of magnitude. Using an AUV, specifically the Autonomous Benthic Explorer (ABE), we were able to measure the distribution of temperature anomalies, salinity changes, and vertical velocity, nearly synoptically over the whole field thus allowing total heat flux to be computed. In addition to the plume data, we also made a bathymetric map of the area. We called our study Flow Mow, as we conducted a systematic grid search or "mowed the lawn" to estimate the heat flow.

During this experiment, we also gained knowledge on how an AUV could be used to autonomously locate and survey plumes and vent sites. These lessons provide strategies for surveying known sites with more efficiency as well as for locating vents when their position is only known approximately (e.g., after an eruption or tectonic event).

Summary of the Autonomous Benthic Explorer (ABE)

The Autonomous Benthic Explorer (Figure 2) performs fully autonomous oceanic surveys to depths of up to 5000 meters. It determines its position by using acoustic returns from a set of transponders moored to the seafloor. Based

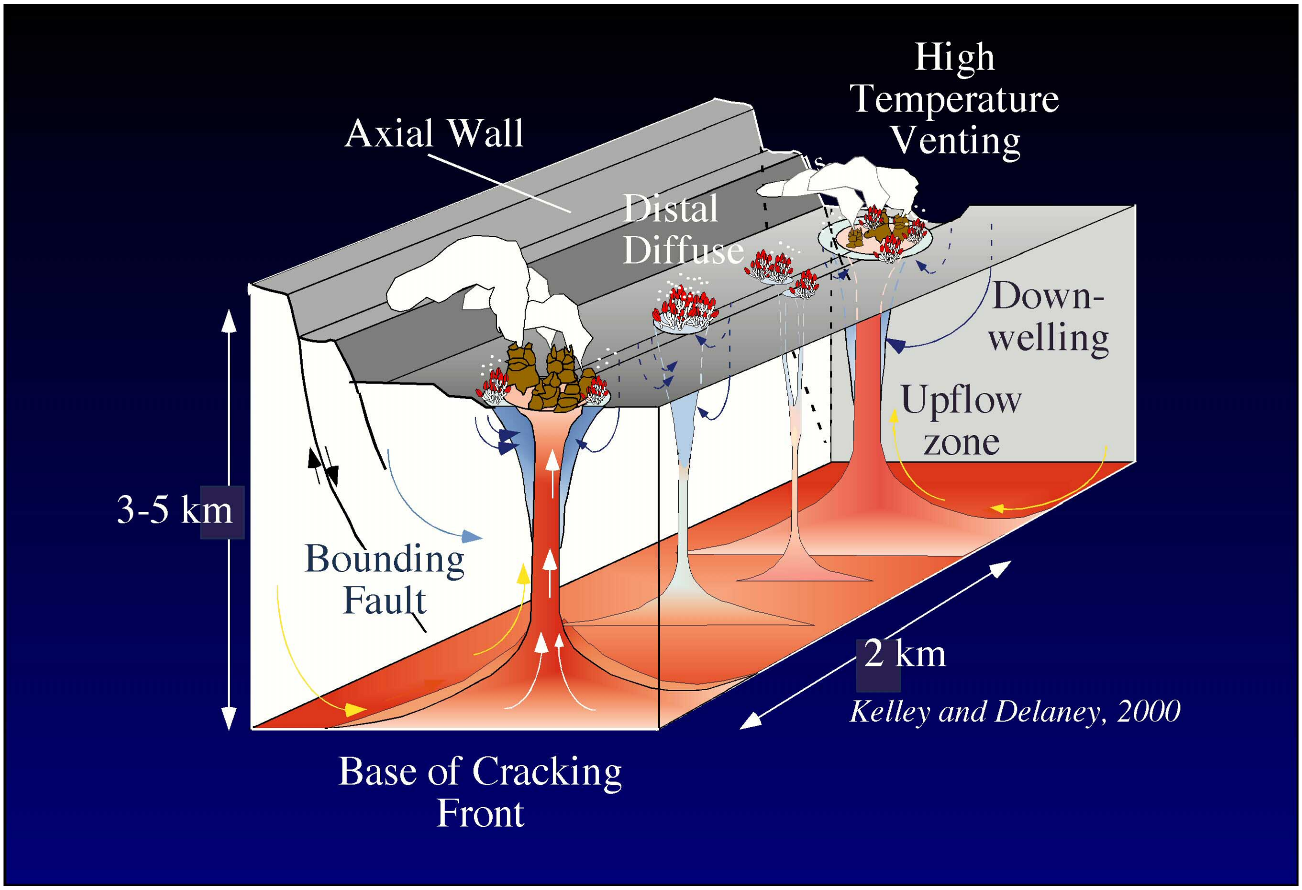

Figure 1. Hydrothermal plumes occur on the mid-ocean ridge. While water circulates through the crust, it is heated while giving up some constituents and gaining others. The vents occur in many forms, including vigorous "black smokers", cooler "white smokers" and weaker but more widespread diffuse vents.

on information from these transponders, ABE descends to the seafloor to a precise location and then executes a series of pre-programmed tracklines in the area of interest at a speed of about 50 cm/sec. ABE can survey at a uniform depth or it can follow bottom contours using returns from an acoustic ranging sonar along with an algorithm based on potential fields [Yoerger 1998]. ABE carries a variety of scientific instruments including mapping sonars, electronic cameras, a magnetometer, and various water property sensors including, conductivity, temperature, depth (CTD), and optical backscatter. To enable both the controlled descent and trackline following, real-time algorithms determine ABE's position from two or more transponder returns and measured vehicle depth. These routines eliminate spurious returns caused by noise through median filtering and range gates to eliminate transponder returns reflected from the sea surface. The "surface bounces" cause significant difficulty as they are typically very consistent but yield incorrect vehicle location unless carefully identified and eliminated.

Experiment Design and Results

Conceptually, hydrothermal plumes resemble steam plumes commonly seen rising from power plants in cold weather. At the top of the stack, the flow is fast and tightly constrained and the temperature is high. As we look higher, we see the plume broaden and join with plumes from adjacent stacks. As the enlarging plume rises even higher, cooling continues to reduce the buoyancy and finally the plume "turns over" and becomes the neutrally buoyant cloud often driven off by the wind.

Prior to our AUV survey, existing approaches for measuring the flux of heat from a hydrothermal system had strong limitations. Some previous estimates for the entire ridge segment used sparse measurements in the neutrally buoyant portion of the plumes, while most field-scale estimates extrapolated point measurements made at individual diffuse and "black smoker" sources to the whole field. These estimates vary widely, with the field-scale values of heat flux at the MEF varying from 360 to 9400 megawatts.

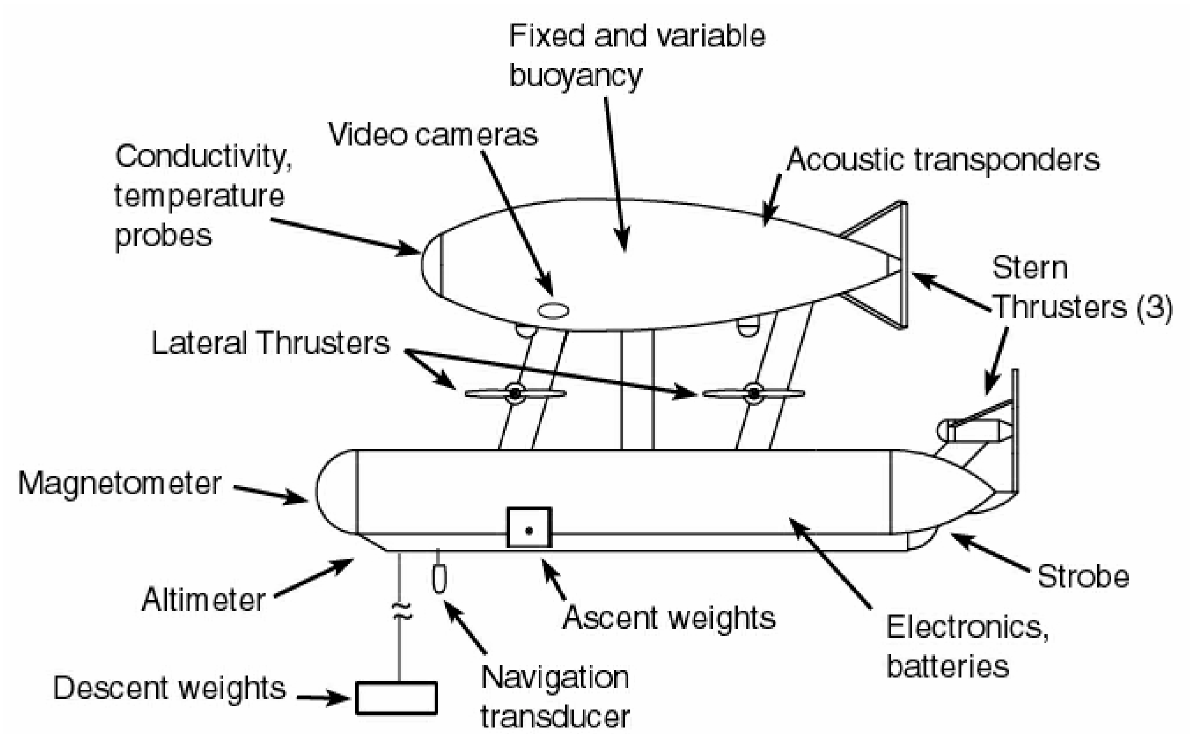

Figure 2. The Autonomous Benthic Explorer, built and operated by the Woods Hole Oceanographic Institution, is a fully autonomous robot designed to survey the deep seafloor and the surrounding water column. ABE 's unusual shape and thruster configuration provides excellent stablity, moderate drag, and permits the vehicle to maintain control throughout its speed range.

Using an AUV allows a more comprehensive approach by which we measure the flux across the walls of a control volume around the whole vent field. In doing so we integrated all heat emanating from the field, whether of focused, diffuse or conductive origin. In the MEF, over 150 discrete smoker vents have been identified in addition to substantial areas of less vigorous diffuse flow. By characterizing the heat content of the rising portion of the plumes, we took advantage of the natural integration of all these sources into rising "patches" of heat that we could measure with the AUV.

We carefully chose the height above the vents for our survey based on a physical understanding of plume behavior. In general, the strength of the plume signature decreases with height but the plume cross section grows as it rises. Modeling and simulation showed that a height of about 75 meters optimally balances this tradeoff. A Monte Carlo model of the survey strategy incorporating the operating characteristics of ABE and its sensors, the known locations and approximate strengths of the major vents showed that data from a single dive could yield acceptable uncertainty in the heat flux estimate (of order +-10%, 1 sigma, Stahr 2000). During the actual observations, we found plumes that were both broad (enabling us to space the vehicle tracklines at 20 meters) and with a strong signals (temperature changes of tenths of a degree and vertical velocities up to 25 cm/sec).

Heat flux through a fixed area in a horizontal plane over the field is determined by measuring and combining two particular properties: increased heat content of the plume water compared to ambient background water (i.e., potential temperature anomaly), and the vertical velocity of the rising plume water. We measured the former by comparing temperature and salinity data from our ABE surveys to that from the same depths at a background station far from the field [McDougall, 1990]. We measured the vertical water velocity in one of two ways, either by summing the vehicle's velocity with the relative water velocity or by using a dynamic model of the vehicle's response to estimate the water velocity of the rising plume. Combining and integrating these measurements over the whole field area produced heat flux estimates for each survey and combining many of those provided a robust average heat flux estimate for the entire vent field.

The primary measure of vertical water velocity was obtained by combining relative water velocity from an acoustic current meter called MAVS-2 [Williams 1998] attached to ABE along with the vehicle's absolute vertical velocity obtained from its precision pressure transducer (Paroscientific). The MAVS-2 is a high-performance acoustic current meter employing a differential travel-time measurement technique. The current meter takes travel-time measurement across 4 paths to provide true vector averaged velocity in 3 axes. MAVS measures velocities in the range of 0.03 to 300 cm/s, making it an ideal sensor for this experiment where velocities up to 60 cm/s were anticipated. Post-survey, the pressure data were differentiated and both data sets were smoothed and combined to yield absolute vertical water velocity.

The secondary measure of vertical velocity came from a model based on ABE's vertical thruster response to rising plume water. When ABE transverses a plume with water rising at high speed, its vertical thrusters try to push it back down to its pre-programmed depth. (When not externally influenced, ABE is capable of holding depth to within ~10 centimeters.) After conducting a system test away from the vent field, a model was created that combined thruster command data and pressure data to provide an estimate of the vertical water velocity pushing ABE off depth. This model was applied to surveys when relative water velocity data was not available from the MAVS-2 and provided a high-quality estimate of actual vertical water velocity. Details of this model are provided in a related Flow Mow publication [Yoerger 2001].

Over the course of 10 dives in the Flow Mow experiment, ABE covered 225 km of bottom tracks in 114 hours. ABE collected bottom bathymetry, temperature, conductivity, vertical velocity, optical backscatter, magnetic, and electrochemical potential data over repeated surveys. The longest dive yielded nearly 30 hours of data, encompassing two full tidal cycles, and covering almost five full passes over the entire vent field in 59 kilometers of track. Data products included gridded maps of potential temperature anomaly and vertical velocity from which heat flux was calculated. The overall mean heat flux from MEF was found to be about 600 MW.

Bathymetric Mapping

During the experiment, one dive was dedicated to bathymetric mapping. As ABE followed its assigned tracklines, it measured the depth of the underlying seafloor in two ways. First, the fixed-beam sonar used for bottom-contour following provided range measurements

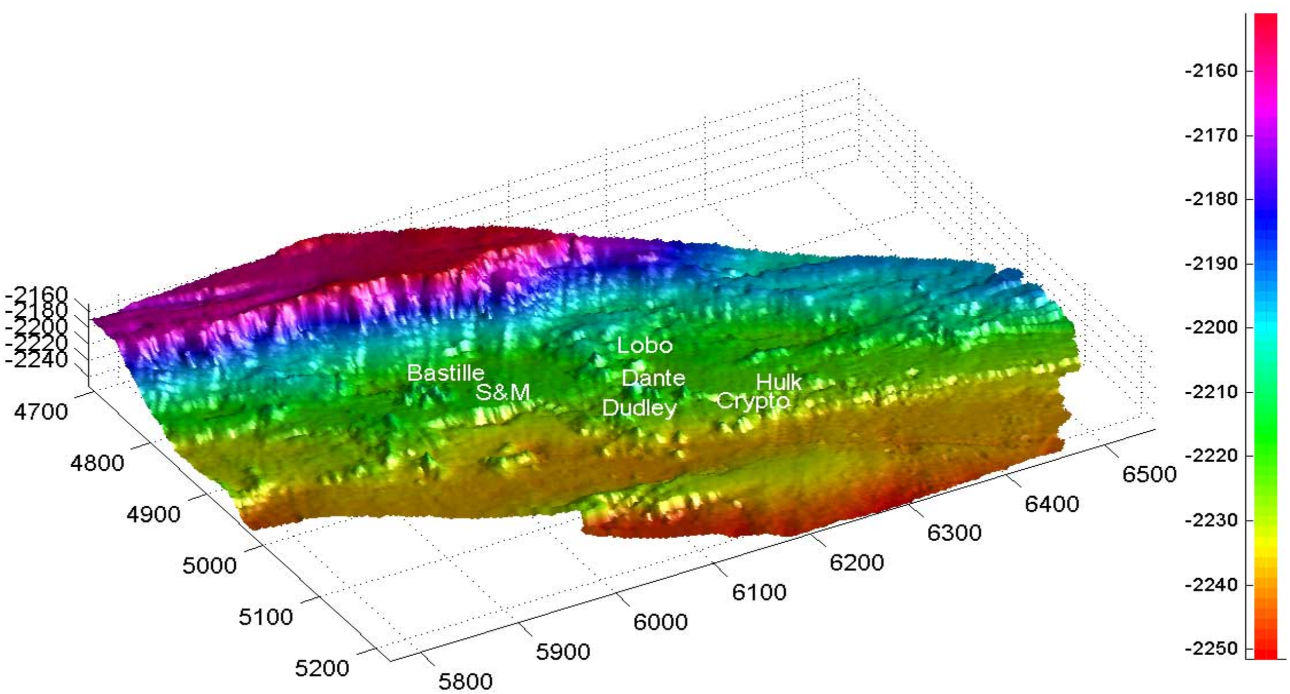

Figure 3 . This bathymetric map of the Main Endeavour Vent Field on the Juan de Fuca Ridge was acquired using ABE (Autonomous Benthic Explorer) during the Flow Mow cruise, August 2000. Some of the known high-temperature vents are indicated by name.

recorded at one-second intervals. These were combined with vehicle position and depth to produce high-resolution along-track sections of the terrain. Second, a mechanically scanned pencil-beam sonar mounted in ABE collected bottom range data in the cross-track direction. The Imagenix model 855 operates at 675 kHz with a 1.9 degree conical beam width, steps in 0.6 degree increments, and moves at approximately 2 steps/second depending on range. Each sonar return was interpreted as a digitized sample of sea-floor surface. The assemblage of all such returns was placed into world coordinates using the vehicle position and attitude data as well as the offsets between the navigational sensors and the sonar head. The resulting “dot cloud” consisted of 45,000 individual points in the survey area, which were then gridded at 2.5 meter spacing using a gaussian kernel with a characteristic length of 1.25 meters.

Figure 3 shows a perspective view of the resulting bathymetric map of our study area, the axial valley where active hydrothermal venting occurs (the east ridge is not included). Note especially the steep wall and relatively flat top of the western ridge rising in the upper left of the image. At the base are the active vents and associated sulfide mounds of the Main Endeavour Field, along with inactive mounds and talus slopes (accumulations of rock debris). Some of the faults in the middle of the axial valley are also easily visible. These features correspond well to previous maps of the MEF made through submersible observations and compiled by hand [Delaney et al., 1992]. However, this map covers more area, shows more details and gives far more precise relative positions of the features.

Heat Flux Mapping

To derive heat flux, we employed different sampling strategies on different surveys. On some dives, we surveyed an entire control volume around the field, covering the top and each of the sides. The dives were timed with some knowledge of the tidally induced currents in the axial valley to attempt to capture heat being transported out of the field across the sides of the control volume. Figure 4 shows ABE tracklines from a survey (dive #50) where it covered the top twice and each of the sides once. The survey took 20 hours and all sensors functioned well for the entire run. In other surveys, we used the AUV to perform as multiple surveys of the top (sometimes at varying levels) as possible as most of the heat flux is vertical. Figure 5 shows the vehicle tracklines from the dive #51, which provided nearly five full passes over the top of the field spanning almost 30 hours. During this run, we measured parameters of the neutrally buoyant plume as it crossed the upper sides of the “control volume” above ABE using a conductivity-temperature-depth (CTD) package lowered from the ship simultaneously. This demonstrated one of the significant attributes of AUV operations: the ship is free to conduct other surveys synoptically.

Surfaced contour plots of the vertical velocity measured by the primary technique (MAVS-2 and pressure data) during dive #51 are shown in Figure 6. There are six panels, one for each pass over the field and the locations of known high temperature vents are annotated on each plot. The surfaces were generated by gridding the data at 10 meter spacing using a gaussian kernel with a characteristic length of 10 meters. These plots show the time-varying nature of the plumes. This variability makes multiple surveys over the same area critical to creating a robust average of heat flux (or any parameter) for the whole field. One of the principal advantages of using an AUV is that such near-exact repeat surveys can be made easily and quickly. Figure 7 shows four different quantities measured during the second pass of dive #51. Three of these, vertical velocity, potential temperature and salinity were used to determine heat flux, while the fourth, optical backscatter, provides another traditional measure of plume locations. Combining parameters measured simultaneously on an AUV, and nearly synoptically for the whole field, allows a better understanding of plume variability than previously available with any technique. This variability has significant impact on the quality and certainty of heat flux estimates, as well as for any field-scale parameter.

Implications for AUV-based Plume Searches

While our surveys during Flow Mow all used a pre-programmed “lawn mower” pattern to obtain an estimate of the heat flux, we have often considered the possibility of using an AUV to search for plumes in a more adaptive mode. This experiment provides us some knowledge to create search strategies that may enable precise location of hydrothermal vents by finding and surveying their plumes.

Vent searches usually begins at a large scale using bathymetric maps, dredged rock samples and sometimes earthquake data to find sections of mid-ocean ridge that might have vents. However, these sections are usually tens to hundreds of kilometers long while vent fields are typically only hundreds of meters and individual vents only one meter. Once the general search location is determined, a ship-based survey is conducted using a CTD and optical backscatter device. During these surveys, the ship steams very slowly forward while the sensor package is oscillated up and down through the range of depths which might contain a neutrally buoyant plume. This survey pattern is known as a “vertically oscillating tow”- VOT or “tow-yo”. If a plume signature is detected in density or particulate matter, then water bottles are tripped to obtain samples which are analyzed after recovery for chemical plume signatures such as

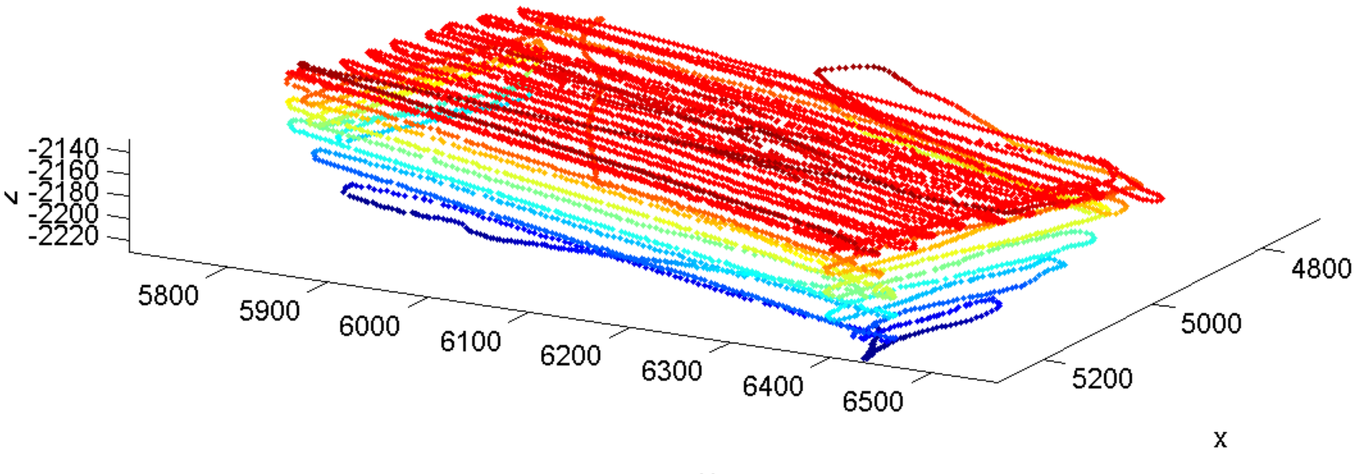

Figure 4. This plot shows tracklines from a single dive, ABE50. These tracklines formed a control volume around the entire field. Each of the four sides was covered once, and the top twice.

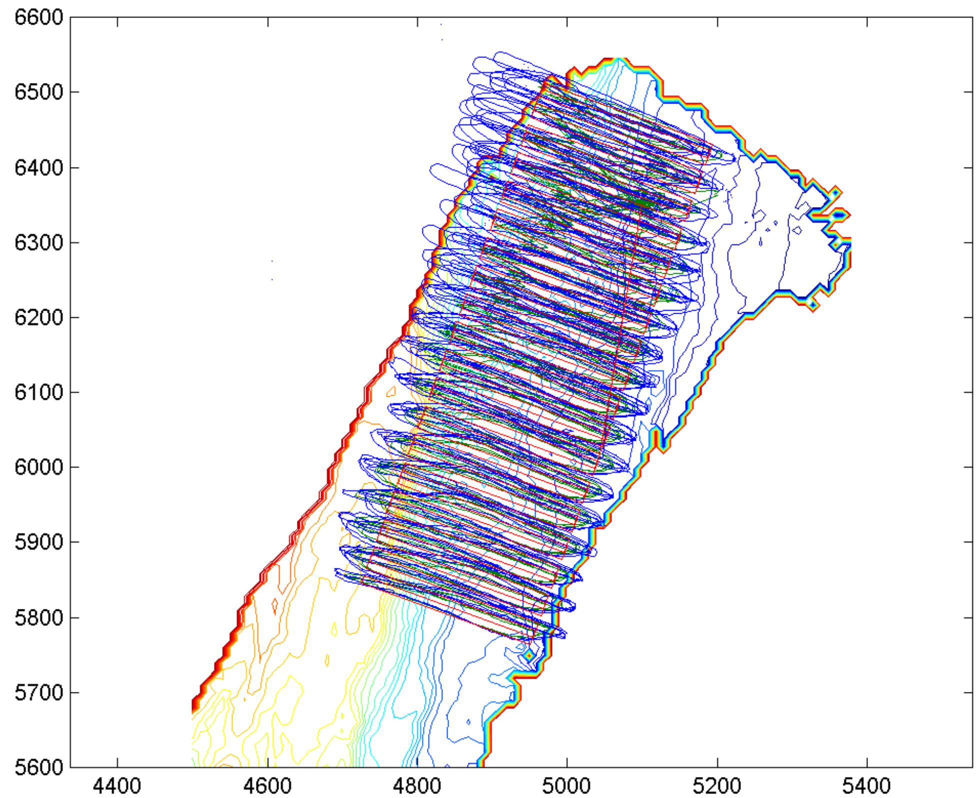

Figure 5. This plot shows the tracklines from the final dive, ABE51, superimposed over a contour rendering of the bathymetry. ABE covered the top of the field 5 complete times of 30 hours, covering nearly 60 km of tracklines. This survey allowed the heat flux to be mapped over two full tidal cycles.

iron, manganese, methane and hydrogen. Some of these constituents, (e.g., hydrogen and iron) are only found very close to the original vent source so they can be used to determine the plume's distance from its source. However, plume density signatures persist for long periods and are often advected far from their source. This makes the next step, a close-in survey, more difficult. Performing wide area vent surveys with an AUV is a viable and useful alternative to ship-based CTD search patterns. While in-situ evaluation of the chemical signatures is not currently available with instruments suitable for an AUV (development efforts for all the items listed above are ongoing), AUV-based measurement of the density and particulate properties can be done now, as shown clearly in Figure 7. Using a combination of real-time data and stored patterns,,an adaptive search strategy could prove far more efficient than a preprogrammed search.

Once a neutrally buoyant (NB) plume has been located and confirmed, the search for its source on the sea-floor begins. The location of vents is usually marked by stongly rising buoyant plumes as seen in Figure 6. Surveys to find the vents are sometimes conducted using the VOT method and sometimes using a remotely operated vehicle (ROV) or tow sled in the water above the bottom but below the originally detected NB plume. Once buoyant plumes are detected, then the search shifts to the sea-floor using an ROV or a human-occupied submersible. AUVs are excellent at water-column surveys as shown by the Flow Mow experiment. Further, we now have gave strong insight as to which parameters are best to build an adaptive search strategy around and the expected range of natural variability.

Figure 7 allows us to draw some simple conclusions and plots from other surveys of the MEF confirm these. For finding sea-floor vents, the vertical water velocity provides the broadest signal that corresponds to actual location on the sea-floor directly below. The vertical velocity is measurable even without an attached current meter as demonstrated in our vehicle dynamics and pressure data model [Yoerger 2001]. Detecting the presence of vertical flow is especially easy if the plumes are strong enough to overcome the vehicle's depth controller. Temperature anomalies also correspond well to the vent locations, but the peaks are narrower than those of velocity, as shown in Figure 8. Salinity varies, but has a narrow dynamic range and does not correlate well with actual vent location. Optical backscatter is easily measured, varies strongly, but does not correspond uniquely to vent locations as particles often accumulate in neutrally buoyant plumes and persist in the area for a long time.

In summary, the Flow Mow experiment confirmed that AUVs can carry out the needed measurements for both large-area plume searches and for locating sea-floor vents via their characteristic buoyant plumes. Further, it is easy to envision how an AUV could transition between a large-area and a close-in search to quickly narrow in on a vent field or even an individual vent. Part of the efficiency of this approach stems from the added capacity an AUV brings to an experiment by freeing the ship to conduct other surveys simultaneously as we did during dive #51. Developing robust adaptive sampling strategies will be the key to making use of AUVs for plume and vent searches.

Conclusions

In an experiment to measure heat flux from a hydrothermal vent field, an AUV demonstrated its capability to map vent plumes quickly and accurately. The Autonomous Benthic Explorer measured a multitude of properties in and around the Main Endeavour Field on the Juan de Fuca Ridge. From repeated surveys of the whole field, heat flux estimates (and all parts thereof) were calculated and spatially mapped within the field. Further, we gained information on how an AUV might be used to locate and survey plumes and vent sites without apriori knowledge of their location. Development of adaptive sampling strategies for AUVs could provide high-quality and efficient surveys over sections of mid-ocean ridge suspected of having un-discovered hydrothermal vents. Expanding present vent search capacity would benefit the oceanographic community as new vent sites continue to yield new insights into crustal and oceanic processes previously unknown or unobserved.

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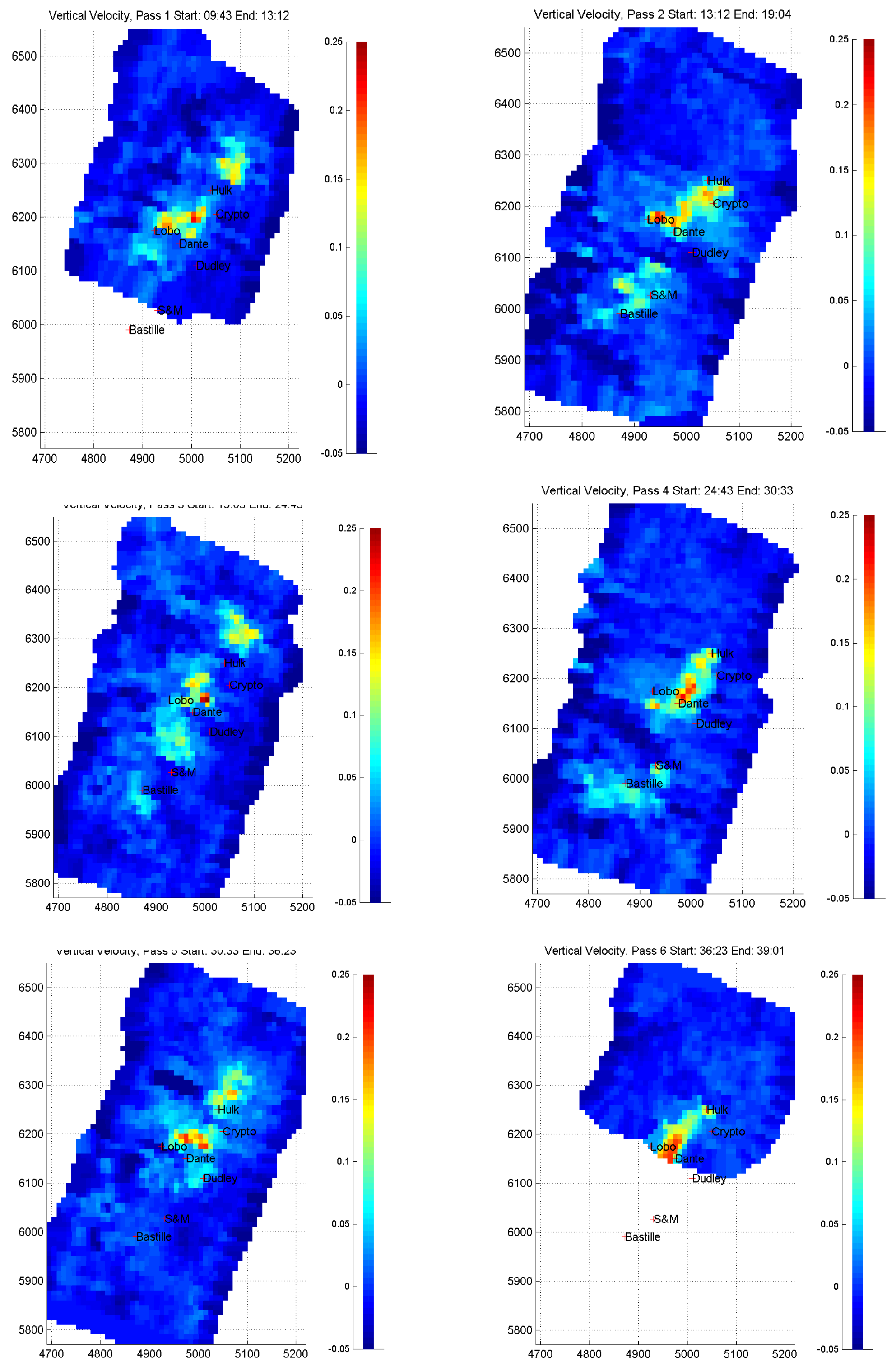

Figure 6. These six panels show the contoured and surfaced vertical velocity of each pass over the top of the MEF during ABE dive #51. The locations of some of the field's named high temperature vents (black smokers) on the seafloor 75 m below is noted in each panel. The panels are successive in time (spanning almost 30 hours) and show the changing nature of the fluid flow through the top of the control volume. The fluctuations in strength and location of vertically moving water is probably a function of changing currents in the axial valley induced by the tides, as well as changes in the entrainment of surrounding water and coalescence of individual plumes

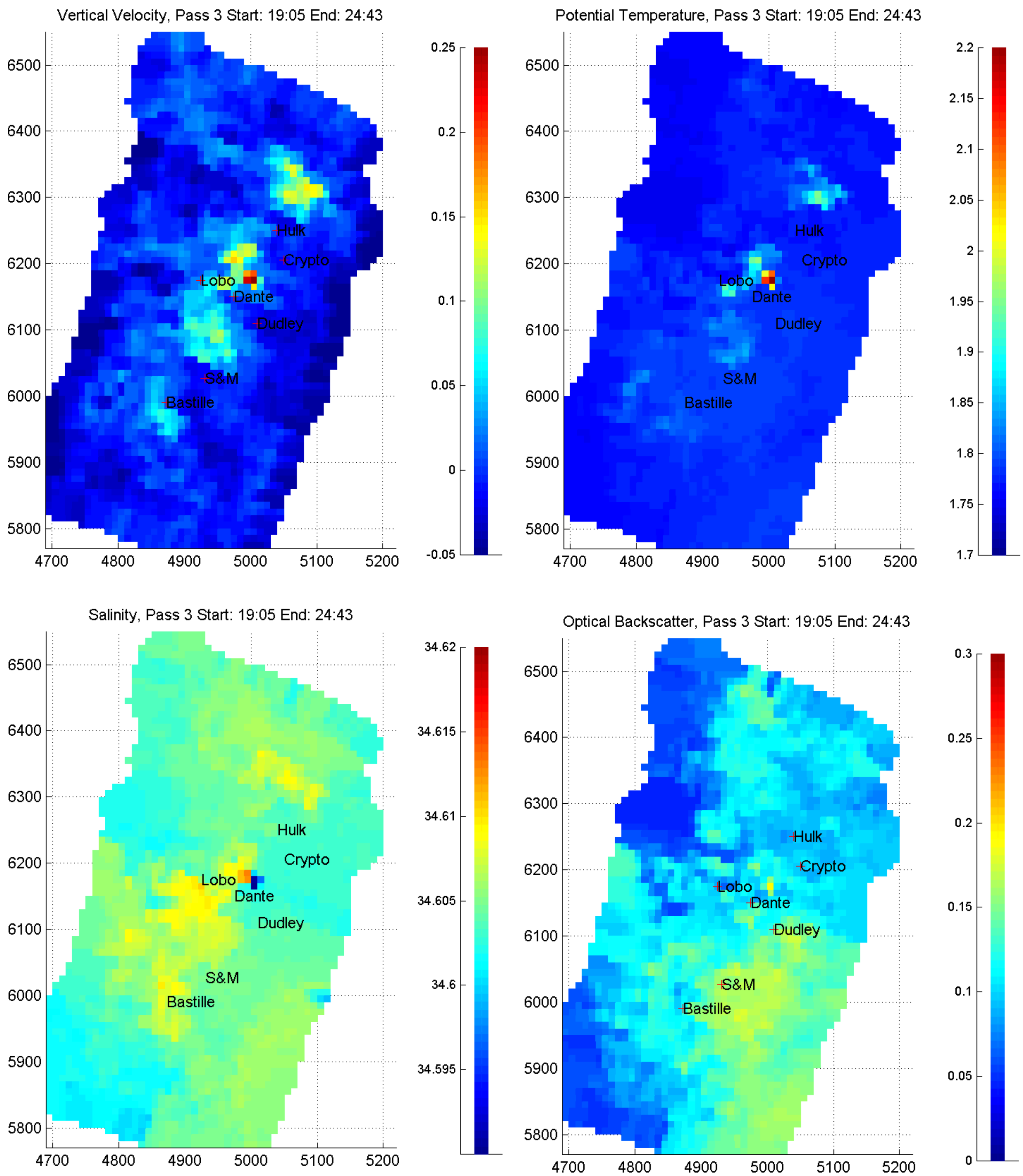

Figure 7. These panels show, clockwise from upper left, potential temperature, vertical velocity, optical backscatter, and salinity. The locations of both temperature and vertical velocity anomolies correspond well to vent locations, while salinity and optical backscatter provide a broader signal. While the full range of salinity measured was quite narrow, the optical backscatter differences were very easy to detect.

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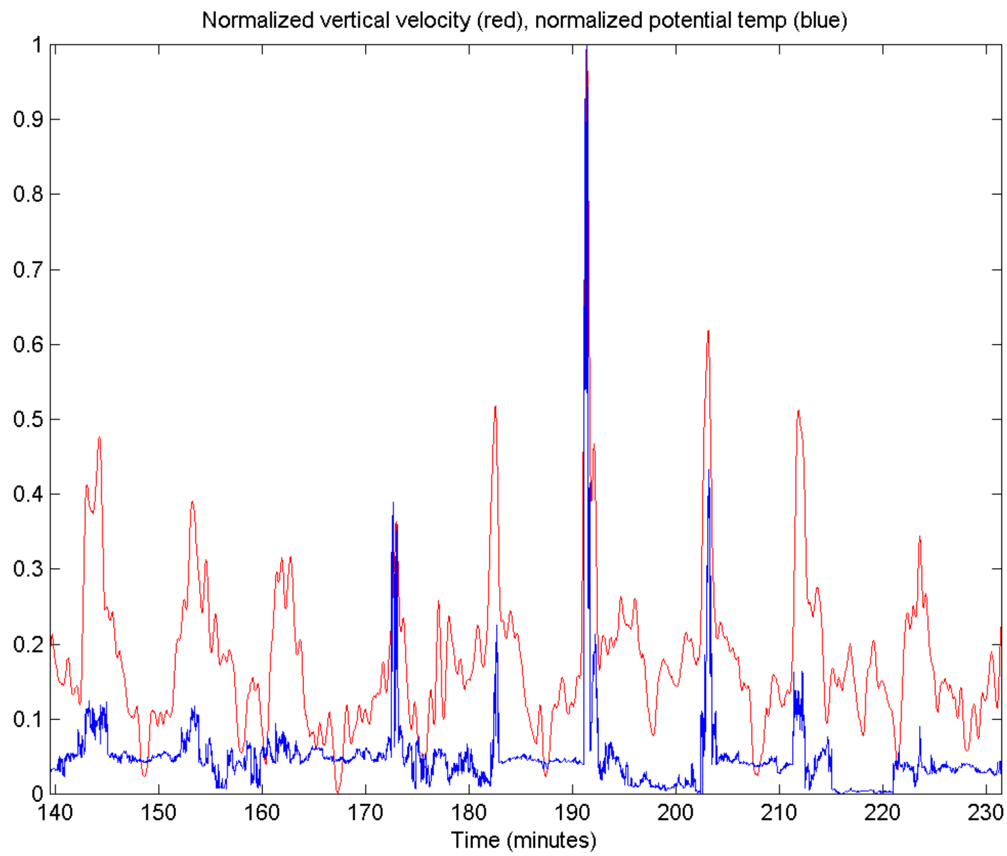

Figure 8. This plot shows normalized values both vertical velocity (red) and potential temperature (blue) as a function of time as the vehicle passes repeatedly through the plumes. The vertical velocity has a more consistent magnitude and broader peaks, making it a better candidate for locating the rising plumes than temperature. Also, vertical velocity can be easily detected by perturbations of the vehicle dynamics.