FLUXES OF HEAT AND SALT FROM ENDEAVOUR SEGMENT VENT FIELDS: DISCRETE MEASUREMENTS AS A TEST OF THE SEA BREEZE "FLUX METER" HYPOTHESIS

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Project Summary

Intellectual Merit. Measurement of the fluxes of heat and materials that tie geological forcing to biological response is central to addressing the major questions posed in the Endeavour Integrated Study Site implementation plan. We propose to acquire two sets of complementary observations: the vertical fluxes of fluid mass, heat and salt rising from Endeavour Segment vent fields and the lateral transport of fluid mass within the axial valley. Taking advantage of the topographic constraints of the Endeavour Segment, we will use these observations to evaluate whether the mean subinertial component of the lateral fluid flux into the valley balances the upward, buoyancy-driven fluid flux from the vent fields–our "sea breeze" hypothesis. A strong correlation would provide a means of making continuous, remote proxy measurements of the integrated fluxes from the vent fields, thereby serving as a "flux meter." A variety of preliminary data indicate that lateral transport exists and is of the expected magnitude. In addition to testing the sea breeze hypothesis, the data would help address a number of other significant questions concerning the how the flux of heat from Endeavour Segment evolves, the rates of change associated with phase separation and segregation, fluxes of substrates used as energy sources by plume microbiota, and characteristics of the regional circulation relevant to larval dispersal.

The vertical fluxes from the vent fields would be measured by establishing appropriate control volumes around them and using the autonomous vehicle ABE, complemented by precisely navigated CTD observations and a nearby current meter mooring, to measure the temperature, salinity and velocity fields on their boundaries. Our survey of Main Endeavour Field in 2000 showed that in ~60 hours of dive time the total vertical flux from the field can be determined to within ~10%. The lateral fluid flux would be measured with a dense array of conventional current meter moorings and up-looking acoustic current profilers. This array would be deployed in summer 2003, serviced while conducting the ABE surveys in summer 2004, and recovered in summer 2005.

Broader Impacts. The project continues a long-standing collaboration with Canadian colleagues in this Canadian Marine Protected Area. The data collected would benefit a number of other programs proposed within the Endeavour Segment ISS. We would continue to provide research opportunities for graduate and undergraduate students. We would again host secondary school teachers, under the auspices of the REVEL program, on our 2004 cruise. REVEL provides opportunities for teachers to participate in research, to bring increased knowledge and excitement to their classrooms, to develop innovative curricular materials and to establish on-going partnerships with active researchers.

Results from Prior NSF Support

OCE-9872090: Precise measurement of heat flux from a hydrothermal vent system, R.E. McDuff, D.R. Yoerger, A.M. Bradley and R.E. Thomson, $423,028, 6/1/99-5/31/03.

The focus of the Flow Mow project was to measure, with substantially improved precision and accuracy, the flux of heat from the Main Endeavour Field (MEF), Endeavour Segment, Juan de Fuca Ridge. In an 18-*day RV Thomas G. Thompson* cruise we used the autonomous vehicle ABE, complemented by precisely navigated CTD observations and a nearby current meter mooring, to measure the temperature, salinity and velocity fields on the boundaries of a control volume established around MEF. The upper surface of the volume was placed ~75 meter above the plume sources, guided by results of a synthetic sampling of a model for rising hydrothermal plumes. This choice optimized the tradeoff, as a function of height of rise, between the increasing frequencies of encounters with rising plumes whose radius grows linearly versus the decreasing ratio of hydrothermal signal to noise in the core of the plume.

Vertical Flux. The upper surface was surveyed with 20-meter line spacing 12 times, during seven of which the velocity sensor on the vehicle worked reliably. These seven replicate measurements range from 304 to 615 MW, with a mean of 483 MW, a standard deviation of 103 MW and a standard deviation of the mean of 43 MW. This level of precision was as expected from the analysis of synthetic surveys; accordingly we believe the source flux is steady and the variation seen is mainly statistical. A surprise, when compared to historical observations, was the magnitude of thermal contamination of fluids filling the axial valley, about 0.05 C and showing substantial spatial and temporal variability. This variable datum represents an additional significant contributor to variance in the flux estimate.

Horizontal Flows. We placed a mooring of five current meters ~1 km south of MEF, with meters 50, 100, 150, 200 and 250 meters above the valley floor. Within the proposal body we will discuss the results in greater detail, but for now the currents are tidally-driven, with the deeper meters below the axial valley walls showing net transport to the north and the shallower meters, above the valley walls, showing net transport to the southwest. Within the valley, subinertial flow was steady and northward.

Horizontal Flux. We have integrated data from ABE transects on vertical walls around the field, from the current meter mooring and from precisely navigated, vertically oscillating, CTD casts and tows to put bounds on the corresponding horizontal flux of heat. This analysis of observational data has been complemented by development and application of a "puff" model for dispersion driven by oscillatory currents. As expected from this model, we observe a difference between the spatially and temporally averaged thermal anomaly north and south of the field, giving rise to a northward horizontal flux of order 10-100 MW.

Principal Conclusions. Because our measurements came after the 1999 earthquake swarm that resulted in significant changes in the behavior of the MEF, one must integrate these data with older data with some caution. From our data, in August 2000 the *total* flux of heat from MEF was ~500-600 MW, with 5/6 or more of this transported vertically into the overlying neutrally buoyant plume layer. Since the nature of our approach is to measure the flux across the surfaces of a control volume enclosing the vent field, this estimate integrates all heat emanating from the field, be it of focused, diffuse or conductive origin. As the smoker-style vents within MEF remain active, ~300 MW remains a reasonable estimate of the flux due to this mode of discharge [*Bemis et al.*, 1993; *Ginster et al.,* 1994]. *Johnson et al.* [2002] estimate diffuse flow from the field to be ~150 MW. Thus we conclude that the partitioning between focused and diffuse flow is ~1:1-3:1, substantially different from the canonical 1:10 value generally attributed to *Schultz et al.* [1992]. Past estimates of heat flux in the area based on steady-state analysis of observations in the neutrally buoyant layer range from 1 to 3 GW [*Baker and Massoth*, 1987; *Thomson et al.*, 1992; *Rosenberg et al.*, 1988]. Either these include significant contribution from other fields along the Endeavour Segment, a possibility consistent with the measurement techniques employed, or alternatively the output from the MEF has decreased in the past decade.

An equally intriguing result is the magnitude, several cm/s, and steadiness of subinertial currents confined within the walls of the axial valley. We believe that this low frequency component of flow is most likely driven by entrainment of fluid into buoyant hydrothermal plumes, a concept at the core of this proposal.

Broader Impacts. 1) Our data have been used by other Y2K observatory [*Tivey et al.*, 2000] collaborators to help interpret their findings. 2) This project has provided research experience for Scott Veirs who is expected to finish his Ph.D. degree program later this year. Fritz Stahr, a postdoctoral fellow with a physical oceanography background, developed interdisciplinary breadth. 3) We hosted seven participants in the REVEL program (http://www.ocean.washington.edu/outreach/revel/) on the *RV Thomas G. Thompson*. Our role was to help them learn relevant background, to provide fulfilling and interesting research experiences, and to keep them aware of our progress in interpreting the data they helped collect. REVEL provides opportunities for secondary school teachers to participate in and contribute to seagoing research, bringing increased knowledge of the deep sea and their own research experience back to their classes. 4) With modest supplemental funding we have developed a searchable metadata catalog for all Y2K observatory work that will be incorporated into the RIDGE 2000 data management system.

Publications and Data Dissemination

F.R. Stahr, R.E. McDuff, S.R. Veirs D.R. Yoerger and A.M. Bradley, Vertical heat flux from the Main Endeavour Vent Field on the Juan de Fuca Ridge, G^3, manuscript.

R.E. Thomson, S.F. Mihaly, A.B. Rabinovich, R.E. McDuff, S.R. Veirs, and F.R. Stahr, Plume-induced, topographically constrained circulation at Endeavour Ridge: implications for the colonization of hydrothermal vent fields, *Science*, manuscript.

S.R. Veirs, R.E. McDuff and F.R. Stahr, Magnitude and variance of horizontal heat flux at the Main Endeavour hydrothermal vent field, G^3, manuscript.

Yoerger, D.R., A.M. Bradley, F.R. Stahr and R.E. McDuff, Survey of deep-sea hydrothermal vent plumes with the Autonomous Benthic Explorer (ABE), In *Proceedings of the 12th International Symposium on Unmanned Untethered Submersible Technology*, 2001.

Related meeting abstract, posters, manuscripts, additional supplemental information and data sets can be obtained at http://bromide.ocean.washington.edu/flowmow/.

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Introduction

Measurement of the fluxes of heat and materials that tie geological forcing to biological response is central to addressing the major questions posed in the Endeavour Integrated Study Site implementation plan. Such measurements link the volcanic and tectonic processes important in controlling the evolution of heat transfer and chemical exchange deep in the crust with the seafloor manifestations of hydrothermal activity including sulfide mineralization, biological productivity, and the dynamics of the near-vent deep ocean environment.

We propose to acquire two sets of complementary observations: the vertical fluxes of fluid mass, heat and salt rising from Endeavour Segment vent fields and the lateral transport of fluid mass within the axial valley. Taking advantage of the topographic constraints of the Endeavour Segment, we will use these observations to evaluate whether the lateral fluid flux into the valley balances the upward, buoyancy-driven fluid flux from the vent fields–our "sea breeze" hypothesis [*Thomson et al.*, 2002]. A positive correlation would provide a means of making continuous, remote proxy measurements of the integrated fluxes from the vent fields, thereby serving as a "flux meter."

The Sea Breeze Hypothesis

We hypothesize that hydrothermal plume-induced circulation in the axial valley of Endeavour Segment is dynamically similar to the formation of the summer sea breeze in coastal inlets. Buoyant atmospheric plumes, formed during summertime heating of the land in proximity to a pool of relatively cold ocean water, give rise via entrainment to strong, up-channel surface winds [*Atkinson*, 1981]. In analogy with steep coastal inlets, the axial valley of the ridge confines the thermally driven currents on Endeavour Segment to be along-axis. Cold bottom water entering the truncated axial valley from the south and north is drawn inward, toward the buoyancy sources. Because the venting is "steady," near-bottom, subinertial currents in the axial valley also will be steady, disrupted only by temporal variations in the regional pressure gradients associated with low-frequency motions and eddy-like flow in the overlying water column. Modification of the local plume-driven circulation by mesoscale pressure gradients in the overlying water column would mimic the effect that synoptic-scale low pressure systems have on the sea breeze.

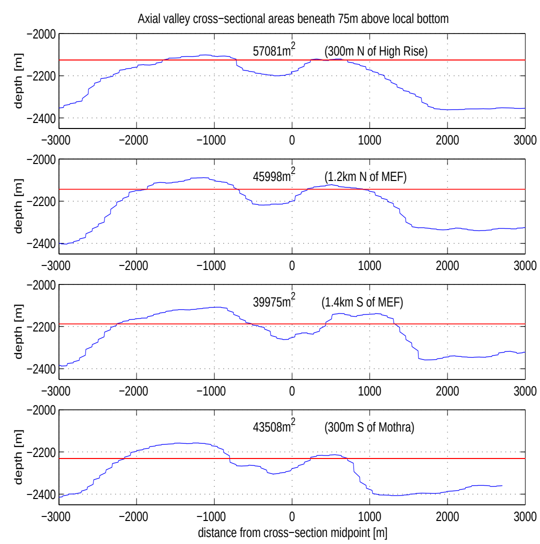
Based on the Flow Mow data set, the vertical flux of heat from the MEF is ~500 MW [*Stahr et al.*, 2002]. With a typical temperature of 360 C, this translates to a total flux of vent fluid from these sources of 0.33 m^3/s. With the regional hydrography of the northeast Pacific, plume theory suggests that while rising to the equilibrium level, ~4000 parts of adjacent ambient fluid will be entrained per 1 part hydrothermal fluid [*McDuff*, 1995], thus requiring an entrained flux of ~1350 m^3/s. This entrainment grows very roughly linearly with height of rise such that ~3/7 occurs within 75 meters of the seafloor, an elevation typically below the depth of the adjacent bounding ridge crests. Within the axial valley, fluid must converge toward the vent field to conserve mass. Both regional flow patterns and the presence of nearby fields will affect the proportions coming from the south and north. Our preliminary data suggest that most of the entrainment-driven flow enters the valley from the deeper region to the south. We can estimate the scale of the expected net flow as follows. Let F be the flux of hydrothermal fluid at the source, A be the cross-sectional area of a vertical section perpendicular to the strike of the valley and below the depth of the flanking walls and v be the speed of the along-axis flow. By mass balance and with an entrainment ratio of 3/7 x 4000:

$$Av = 1700F$$

$$v = \frac{1700F}{A}$$

From representative cross sections (Figure 1), the value of A below 75 m closure is ~50,000 m^2. From earlier, F is 0.33 m^3/s. Thus v due to MEF alone is ~1.1 cm/s. If all of the entrainment-driven flow is from the south, the multiple fields would produce a northward current of several cm/s at the southern end of the axial valley that would decay as it supplied the entrained fluid for each of the vent fields in succession.

Figure 1. Representative cross sections across Endeavour Segment at the locations shown in Figure 3. Lines with 75 m of closure are shown; the east wall is generally lower than the west and typically provides at least 75 meters of closure. The constrained cross-sectional area at this level is ~50,000 m^2. Progressing northward (bottom panel to top panel), the topography shoals, ~150 m over the 9 km from Mothra to the saddle between Salty Dawg and Sasquatch (Figure 3). The data are from a 1996 Hydrosweep survey conducted by D.S. Kelley and available at http://bromide.ocean.washington.edu/gis/).



Of equal interest is the temporal resolution of this approach. The time scale of horizontal replacement would be:

$$\tau = \frac{AL}{Av} = \frac{L}{v}$$

where L is the spacing of the major fields, ~2 km. Thus:

$$\tau = \frac{2\times10^5 \text{ cm}}{1 \text{ cm/s}} = 2\times10^5 \text{ s} \approx 2.3 \text{ days}$$

These scaling arguments provide a compelling basis for conducting a test of the hypothesis. The central premise of this proposal is that we can instrument the axial valley so as to "fence-in" the vent fields, determine the relationship between vent field fluxes and the entrainment-driven currents, and thereby establish a proxy time series for the enclosed vent output. The ability to affordably evaluate vent output over many years with temporal resolution of a few days would be of immense scientific value. Imagine that such an array of instrumentation would have been in place when the 1999 earthquake swarm occurred. The event (discussed below) brought about a variety of significant changes in the behavior of the MEF vent system [*Johnson et al.*, 2000] that are poorly understood because continuous measurements were so sparse.

Background

The Endeavour Segment of the Juan de Fuca Ridge

The locus of spreading on the Endeavour Segment consists of a 500 to 800 meter wide axial valley flanked by two linear volcanic ridges separated by ~1.5 km with inward-facing faults and outward-facing constructional volcanic surfaces. These are interpreted as the splitting of a once-intact volcanic ridge [*Kappel and Ryan*, 1986; *Tivey and Johnson*, 1987]. Closely-spaced water column surveys and detailed seafloor mapping indicate that the shoalest third of the segment has (at least) six hydrothermally active and several inactive sites of past sulfide deposition distributed over an along-axis distance of 15 km [*Delaney et al.*, 1991, 1996; *Kelley et al.*, 2001]. The Main Endeavour Field (MEF) is one of these and has been sampled and mapped through a number of ALVIN and ROPOS programs [*Delaney et al.*, 1992]. Another active, but less well-studied field, High Rise, is located 1.8 km north of the Main Endeavour field [*Robigou et al.*, 1993]. Salty Dawg (~3.5 km north of MEF) was first visited in 1995 [*Delaney et al.*, 1995] and Mothra Field (~2.8 km south of MEF) in 1996 [*Delaney et al.*, 1996]. An additional field, Sasquatch, ~5.6 km north of MEF was discovered in 2000 [*Kelley et al.*, 2001]. Also in 2000, a site of high temperature venting ~500 m north of MEF, Raven, was found by *Johnson et al.* [2002]; because its fluids have not yet been sampled it is uncertain whether it is an extension of MEF. These hydrothermal systems and their geological context have been described extensively in the literature [*Delaney et al.*, 1992; *Karsten et al.*, 1986; *Johnson and Holmes*, 1989; *Tivey and Delaney*, 1986; *Baker and Massoth*, 1987; *Kappel and Ryan*, 1986; *Stakes and Moore*, 1991; *Bemis et al.*, 1993; *Butterfield et al.*, 1994; *Schultz et al.*, 1992; *Thomson et al.*, 1992; *Robigou et al.*, 1993; *Fornari and Embley*, 1995; *Hannington et al.*, 1995; *Wilcock and Delaney*, 1997; *Johnson et al.*, 2000; *Kelley et al.*, 2001].

Over the nearly two decades of hydrothermal studies on Endeavour Segment it has been generally considered to be a robust, slowly changing system, in a tectonically-dominated phase of the volcanic-tectonic cycle advanced by *Kappel and Ryan* [1986]. This view was changed dramatically by observations made after a swarm of earthquakes occurred on June 8, 1999, with the main shock registered on the PNW regional network and ensuing events recorded by the northeast Pacific SOSUS array [*Johnson et al.*, 2000] Shortly thereafter, temperatures of a number of diffuse vents, spanning 2 km along strike, increased. These investigators suggest that fluid flow may have increased as well, at least temporarily, by ~10x. Anecdotally, submersible divers consider the waters around the vent fields to now be more turbid, and the spatial patterns of vent temperatures and salinities within MEF have changed compared to the relatively stable situation observed from 1984 through 1998 [*D. Butterfield and M. Lilley,* personal communications].

Finally, while not yet widely-disseminated, another recent finding that will significantly change our view of the Endeavour Segment has emerged from the July 2002 MCS studies of the Juan de Fuca Ridge: the central portion of the segment is underlain by an unusually deep (~2-2.5 km) AMC reflector extending over 15 km along-axis [*R. Detrick*, personal communication].

Heat Flux

Endeavour Segment is one of the best studied portions of the mid-ocean ridge with respect to heat output from hydrothermal systems. Prior to our work, a variety of approaches had been applied to estimating the heat flux from vent systems: 1) measurements of plume thermal content and time-series of currents to estimate the net export of heat [*Baker and Massoth*, 1987; *Thomson et al.*, 1992], 2) measurement of thermal content using ^{222}Rn as a radioactive clock [*Rosenberg et al.*, 1988], and 3) extrapolation of estimates made at individual vents [*Bemis et al.*, 1993; *Ginster et al.,* 1994; *Schultz et al.*, 1992]. These estimates range from ~100 to ~10000 MW. Two likely causes of the wide range are that there are uncertainties inherent to each of these approaches and that there are distinct differences in each of the approaches such that different kinds of fluxes were being measured. An unlikely explanation is that this range represents temporal variability. In more detail:

- Tidally induced variability in deep currents makes it very difficult to provide a well-constrained estimate of the heat flux from measurements in the neutrally buoyant, laterally spreading portion of a plume. The error analysis in *Thomson et al*. [1992] indicates that a six-month current meter record is only sufficient to constrain the net transport within an order of magnitude at equilibrium depth.
- There is reasonable agreement of the estimates, 1-3 GW, made from data from the neutrally buoyant plume. The radon-based value is somewhat higher than the other two and may reflect a significant component of radon entrained from diffusely venting fluids (Rn/heat ratios are much higher in low temperature discharge). While the location of the maximum anomalies suggest a strong source at MEF, the continuity of anomalies at this level and the spatial scale of the measurements make it likely that the estimates include heat from other adjacent vent fields.
- The 10 GW estimate in *Thomson et al*. [1992], the "instantaneous" value, depends on a mechanistic interpretation of the intersected plume cross section as being a horizontally deflected upflow. If this is not the case, then it represents a significant overestimate, consistent with our Flow Mow results.
- As expected, the two estimates based on measurements at discrete smoker-style vents only, ranging from 70-360 MW, are the lowest values. The *Bemis et al.* [1993] estimate excludes plumes that have coalesced and so is an underestimate by some unknown quantity. The methodology applied may or may not include entrained diffuse flow; we are unaware of any model that would let us answer that question. The *Ginster et al.* [1994] data extrapolate measurements made on 31 smokers. The range of strengths of individual sources shows enough variability that the uncertainty in the integrated estimate is about a factor of three. Both of these studies are limited by the lack of knowledge of the substantial number of vents in the SW portion of the field; at the time only vent 8E was known.

- The older direct estimate of diffuse flow is the point measurement reported by *Schultz et al.* [1992]. This estimate extrapolated to the vent field yields a flux of 9400 MW. The contrast between the estimates from discrete smoker sources and in the neutrally-buoyant layer suggest a strong component of entrained diffuse flow, but about a factor of ten smaller than inferred by extrapolating this single point measurement to the entire vent field. *Johnson et al.* [2001] have since made a direct estimate of ~150 MW for the diffuse flow component.

As described in our results from prior support, we believe that through Flow Mow we have significantly improved our knowledge of the heat flux from MEF. We now have a reliable estimate of the heat flux that is unambiguously associated with this particular field and it suggests that focused and diffuse flow support fluxes of similar magnitude. However it is significantly lower than past estimates for MEF and two possible explanations emerge: either MEF has decreased in thermal output over the past decade, or our suggestion that the neutrally buoyant plume estimates include heat fluxes from other Endeavour Segment vent fields is correct.

Physical Oceanography

Currents at Endeavour Ridge consist of oscillatory flow superimposed on a slowly varying mean background flow. The oscillatory flow is primarily in five major frequency bands corresponding to distinct physical forcing mechanisms. In order of decreasing variance in the current, these bands are: 1) the semidiurnal band, principally the M_2 and S_2 tidal constituents with periods of 12.4 and 12.0 hrs, respectively; 2) the episodic, ~16-hr period, inertial band with frequencies "blue-shifted" by several percent above the local Coriolis frequency, f ($\approx 1.08\times10^{-4}$ s^{-1}); 3) the diurnal band, principally the K_1 and O_1 tidal constituents with periods of 23.9 and 25.8 hrs, respectively; 4) the low-frequency synoptic band with periods of days to weeks, with a broad spectral peak in the range of 4-6 days [*Cannon and Thomson*, 1996; *Lavelle and Cannon.*, 2001]; and (5) the high-frequency band consisting mainly of energy arising from nonlinear interactions at inertial and tidal frequencies, including the $2f$, M_4, and fM_2 frequency bands [*Mihaly et al.,* 1998].

The M_2 tidal currents, which can exist as both barotropic and baroclinic modes of oscillation, are aligned approximately along ridge (020) with speeds diminishing from ~5 cm/s at the depth of the ridge crest to ~2-3 cm/s within the confines of the valley. Noticeable along-axis realignment of the M_2 current ellipses takes place within the valley due to the steering effects of the valley walls. Inertial currents–highly energetic clockwise circular rotary currents at the low-frequency limit of the allowable internal wave band in the ocean–have amplitudes of 3-4 cm/s at the depth of the ridge crest and near-zero amplitudes within the valley. Inertial motions originate as wavelike wind-driven surface oscillations [*Thomson et al.*, 1990; *Pashinski*, 1998] that propagate downward to the ridge crest where they are amplified by a factor of 1.2 to 1.7 within several hundred meters of the seafloor through interaction with the sloping ridge flank. Bursts of inertial kinetic energy have durations of ~1 week (bandwidth $\Delta\omega \approx 0.007$ cph) and are confined to the frequency band 0.996-1.079f. During winter, these motions are the most energetic component of the flow variability in the vicinity of Endeavour Ridge, except within the axial valley [*Thomson et al.,* 1990]. Because the diameter, $d = 2|\boldsymbol{u}|/f \approx 1$ km of these near-circular, clockwise rotary, horizontal currents matches the width of the valley, inertial currents are annihilated by the walls of the valley. Diurnal tidal currents are significantly amplified with proximity to the ridge crest and highly attenuated within the confines of the valley. Diurnal currents above the ridge crest are rectilinear and oriented cross-ridge, but become increasingly clockwise rotary near the top of the ridge. The combination of increased amplification and rotary behavior is indicative of topographically induced, bottom-trapped subinertial motions over the ridge flanks [*Allen and Thomson*, 1993]. Within the valley, diurnal currents become increasingly rectilinear and directed along axis. The exception is the broad topographic saddle ("flats") at the northern end of the valley where the motions remain clockwise rotary. Low-frequency (synoptic or weather-band) motions are marginally enhanced with increased proximity to the ridge crest and strongly attenuated within the valley. The statistically significant spatial coherence of these motions over distances of 100 to 1000 km along Juan de Fuca Ridge [*Cannon and Thomson*, 1996] suggests that the motions are either wavelike propagation of wind-forced subinertial currents trapped over the ridge flank or a broad oceanic response coupled to the inherently large spatial scales of oceanic wind stress fields.

Of greatest significance to this proposal are the steady, slowly varying background flows, obtained by low-pass filtering the hourly time-series (Figure 2). At elevations exceeding ~75 m above the valley, the slowly varying background flow has speeds of 1-2 cm/s. Although the background flow is generally parallel to the ridge crest, at upper levels periods of marked cross-axis velocity are common. Below ~75 m elevation, the near-bottom background flow increases to ~2-4 cm/s and becomes generally steady and unidirectional up-valley, albeit with a significant cross-valley component at some

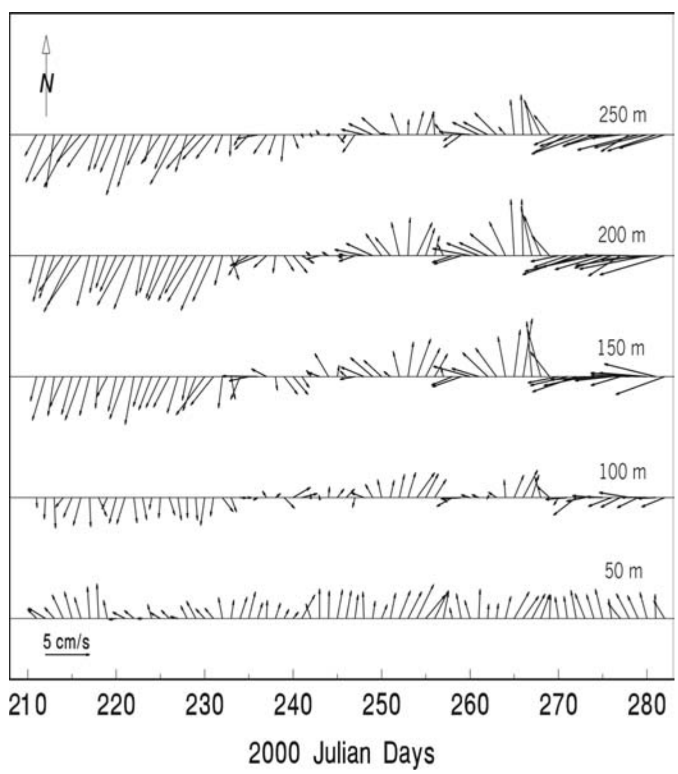


Figure 2. A feather time-series of the mean flow on the five current meters deployed ~1 km south of MEF in 2000. The mean flow depicted is the original hourly record filtered with a low pass Kaiser-Bessel filter with 32 hour cutoff *period [Emery and Thomson*, 2001]. Vertical patterns are similar in two current meter moorings deployed in 2001, one near this location and one near Salty Dawg.

sites. There also are event-like flow reversals when the mean currents are directed to the southwest at all depths within the axial valley. The up-valley background flow is strongest at the southern end of the valley, where hydrothermal venting may be most intense, and weakest at the relatively wide and flat northern end of the valley, where hydrothermal venting is diminished. Up-valley flow of 2-4 cm/s also has been identified in measurements obtained in the 1980s from the southern end of the valley and from the vicinity of the MEF [*Thomson et al.*, 1990]. However, because of the limited (>1 km) navigational accuracy of LORAN-C at the time, it was thought that the flow was related to the effects of nearby topographic features. Among older current meter records collected at the ridge site between September 1984 and September 1986, those from near-bottom depths from the southern end of the valley and near the main vent field indicate persistently northward flow.

Similar mean flows have been observed in hydrothermally active, topographically constrained segments on the MAR. *Murton et al.* [1999] attribute near-bottom transport into an enclosed axial valley primarily to conductive heating, while *Thurnherr* [2000] argues that along-axis mean flow is generated through diapycnal mixing near sills, rather than by hydrothermal entrainment.

With present data, we cannot rule out the possibility that enhanced diapycnal mixing over the rough topography of the axial valley is a primary cause for the intensified, unidirectional background flow observed within the deeper half of the axial valley [*Thurnherr and Speer*, 2002]. However, given the widespread extent of vigorous hydrothermal venting within the valley and the apparent confinement of the inflow layer beneath the neutrally buoyant plumes, it is more likely that the inflow is a dynamic response to the entrainment of cold (~2 °C) ambient bottom water by hydrothermal plumes in accord with the scaling arguments presented earlier.

Scientific Rationale

In the context of this overview of past work, the observations and related modeling we propose would help address several outstanding question regarding fluxes from these and other hydrothermal systems and their interaction with the regional oceanography.

What is the heat flux from Endeavour Segment? We simply have no idea whether MEF dominates the heat flux from Endeavour Segment or contributes on a proportional basis. Only by directly measuring the heat flux from the other fields along Endeavour Segment will we have a context for the role of MEF.

The existence of an AMC adds an interesting new dimension to resolution of the "Lister problem", the question of how to supply heat at the power levels observed and at the same time maintain a body of melt [*Lister*, 1983; *Wilcock and Delaney*, 1997]. One key part of the data that will be required to constrain this problem is knowledge of the heat flux from each of the Endeavour Segment fields and how it evolves with time.

What is the flux of salt from Endeavour Segment? A distinctive characteristic of all Endeavour Segment vent fields is the imprint of phase separation and segregation on vent fluid chemistry. For example all of the active vents within MEF have salinities below seawater and so salt must be stored in the subsurface. While the 1999 earthquake perturbed the spatial pattern, this condition has existed for at least 18 years. While we have much less chemical data for Salty Dawg, its name derives from it having a salinity above seawater. Of interest is the extent to which salt is stored in brine reservoirs [*Bischoff and Rosenbauer*, 1989; *Butterfield et al.*, 1994; *Schoofs and Hansen*, 2000] and how these reservoirs might change through time. Having establishing the heat and fluid flux from each vent field, the salt flux is easily derived using discrete measurements by others and the hydrographic signatures of the rising plumes as measures of the salt content. This basic information would help us understand how interconnected the various Endeavour Segment vent fields might be. In this regard Wilcock is proposing a theoretical study of the role of salt in fluid convection in the segment and these data would help constrain his efforts.

Similarly fluxes of all important chemical constituents can be constrained, information important to understanding issues like the organic carbon fluxes in the overlying water column and the deposition of hydrothermally-derived sediment on the ridge flanks.

How stable are these fluxes? For MEF we now have a reliable baseline measurement, but no well-constrained idea of how it might be evolving through time. We will obtain a second data point in the field-specific portion of our work. *Johnson et al.* [2000] suggested that the flux from diffuse vents may have increased substantially following the 1999 earthquake, but if such a response took place, our observations suggest that it had likely decayed away by summer 2000 or alternatively that the diffuse flux prior to the earthquake swarm was very small.

With our current meter arrays and the CTD observations we will make in 2004 we can replicate the earlier steady-state flux calculations for the neutrally buoyant plume. When compared to our direct measurements from the Endeavour Segment vent fields, these replicates will help establish what the older measurements imply about temporal variability.

In a more general context we hope to develop a robust proxy measurement that will help establish the character of temporal variability on a continuous basis for at least MEF and possibly also for Mothra and High Rise. However, even if the sea breeze hypothesis is falsified, we still will have established a baseline heat flux estimate for all (known) major fields on the segment.

What is the regional circulation? The current meter mooring we placed in 2000, now supplemented with additional deployments by Thomson in 2001, have revealed the strong shear that exists between the southwest flows above the ridge crests and the rectified flow within the axial valley. This is an important step toward providing a more comprehensive description of the circulation that will bear on issues like larval dispersal, patterns of microbial oxidation within plumes, and how off-axis sediments might be best used to study the history of hydrothermal activity on the segment. Thomson's group, in collaboration with Marina Subbotina of the P.P. Shirshov Institute of Oceanology, has initiated a program to adapt the Princeton Ocean Model to examine high-resolution (0.1 km scale) density-dependent, segment-scale circulation on Endeavour Segment. In particular they are examining topographic effects on the current structure and the character of entrained flow into the axial valley driven by hydrothermal buoyancy sources. Our data would contribute significantly to model verification, at which point the model would become a valuable tool in other interdisciplinary studies.

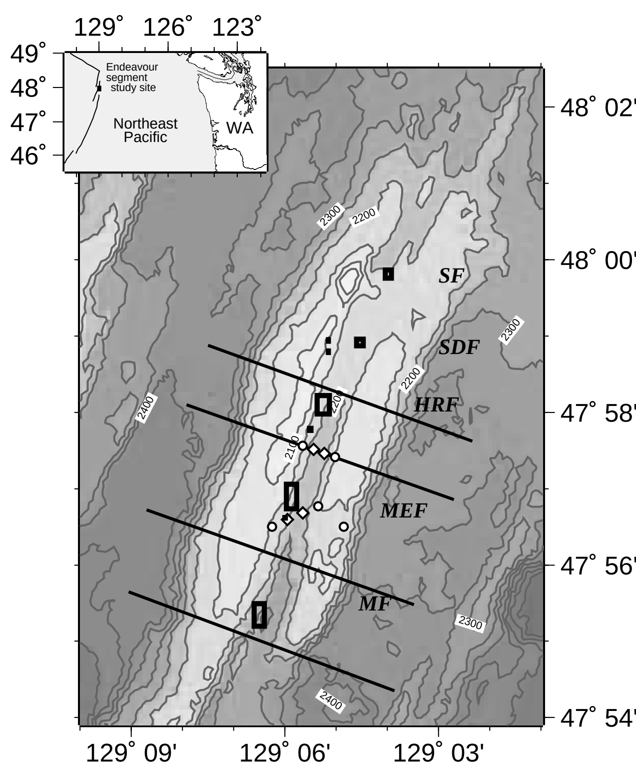
Proposed Program

We propose to acquire two sets of complementary observations: vertical fluxes of fluid mass, heat and salt emanating from vent fields and lateral transport of fluid within the axial valley, in order to test the sea breeze hypothesis and to contribute to addressing the other independent questions just outlined. While the scaling arguments presented earlier provide strong motivation for the proposed remote sensing approach, there are a number of issues that need to be addressed to build confidence in the meaning of such a time series. These issues motivate the following experimental design.

Topographic Considerations

A central feature of the sea breeze hypothesis is that the valley walls channel flow in a significant part of the depth range in which entrainment is occurring. Figure 3 shows the vent field locations superimposed on the topography. Along strike northward from Mothra, the segment shoals ~150 meters. Along the valley, the walls rise above 100-150 meters with the west wall generally higher than the east. Just south of Mothra and north of Salty Dawg, the relief of the east wall diminishes, so that the valley becomes poorly defined. An additional concern is the gap in the east wall just south of MEF. Given this topography we will initially focus our observations around MEF, and then seek to expand them to encompass Mothra and High Rise.

Figure 3. Topography of the Endeavour Segment showing major vent fields (the open boxes; from south to north Mothra, Main Endeavour, High Rise, Salty Dawg and Sasquatch) and areas of diffuse venting (small closed boxes). Topographic data as in Figure 1. The open symbols on the sections north of MEF, obliquely across the valley south of MEF and in the saddle on the east ridge wall show locations for the first year deployment of instrumentation; diamonds are upward-looking ADCPs, circles conventional moorings. Depending on analysis of these data the instrument may remain in these locations for a second year or be redeployed along the four sections which bound the three southern vent fields (see text).



A related issue is that this topography may lead to some acceleration of flow over the saddle near 47°59.5'. Because of the many sources of buoyancy, we cannot say whether the isopycnals remain parallel to the seafloor or parallel to geopotential surfaces.

Modeling

The success of Flow Mow relied on a careful analysis of synthetic data to verify the observational strategy. We anticipate that Thomson's group will have completed their initial development of the adaptation of the Princeton Ocean Model (POM) to the local environment before our first field work. An important application of the model will be for optimizing the deployment strategy for the current meter arrays by synthetic sampling of the model in ways testing specific array configurations. Sufficient work with the model has been completed for us to know that the relative source strength of the major vent fields is a key variable, so that the field work will be done in a sequence allowing continual improvement in the experimental strategy as additional observational and modeling results become available.

Field Work

To make our set of observations, we would conduct a series of four cruises in order to achieve a specific set of objectives.

In summer 2003 we would use *CCGS John P. Tully* in a 10 day cruise to deploy two cross-valley arrays of instrumentation north and south of MEF and one additional instrument suite in the gap on the east wall (Figure 3). Each array would consist of two conventional moorings with three to four meters each and two upward-looking ADCPs configured with 4-6 m depth bins and thus capable of finely resolving the depth structure of the currents. Together these would provide a detailed view of the cross valley shear and the possible role of flow at higher levels from the east. The goal would be to evaluate whether one could develop a predictive model of the flux of fluid across one of these fences, so that with this calibration a less dense array could provide sufficiently precise estimate of along valley flow. The limited set of measurements conducted by *Hautala et al.* [2002] using an upward-looking ADCP mounted on the Jason ROV and a towed downward-looking ADCP suggests that this is a realistic possibility.

In early summer 2004 we would conduct a 30-day *RV Thomas G. Thompson* cruise to accomplish several tasks. We would recover the instrument arrays and begin a series of short deployments to look at along-axis variability and the question of effects of the shoaling topography on flow. This would include an ADCP deployment within MEF itself. The arrays would be placed in another configuration at the end of the cruise, guided by our first look at the first year of data. These activities would require 10 days on station. We would conduct a series of ABE dives at each of the five major vent fields giving us ~60 hours of "mowing" over each surface. Based on our Flow Mow results this should be sufficient to determine the heat flux within a ~10% standard deviation of the mean. This would be combined with ~48 hours of precisely navigated CTD observations to constrain background hydrographic conditions at each of the fields. Some of the CTD work could be done in parallel with the ABE dives, as was accomplished during Flow Mow, so that this amounts to 18 cruise days. Adding two days of transit yields a 30 day cruise. (We are assuming that in general support of ISS activities that a suitable set of transponders will be in place, but given our need for this to be an early summer cruise it may be necessary for us to deploy these as well.)

Summer 2004 would be an intense period of data analysis. We would perform a preliminary analysis of both types of data to provide a basis for deciding whether we would be best served by continuing with a dense array around MEF or whether we would have confidence to use available instrumentation to separately fence Mothra, MEF and High Rise. One key element of this decision-making process would be to incorporate the heat fluxes of each of the fields into the POM circulation model, for we already know that the relative strengths of the five fields has a strong influence on the character of the flow in the axial valley. In late summer 2004, we would reconfigure the current meter arrays reflecting this data analysis on a 10-day *Tully* cruise for a second year-long deployment.

Finally in summer 2005 we would use a 10-day *Tully* cruise to either service or recover the array depending on the success of, or reaction to, a February, 2005 proposal built on the results from the first year of data.

Instrumentation

ABE. Our work in 2000 with ABE showed it to be a highly effective platform for making vent-field scale measurements of the flux of heat. With the improvements in the battery system made that summer, it is routinely capable of dives in excess of 24 hours, greatly improving the duty cycle at which ABE can be operated during a cruise and providing the ability to collect quasi-synoptic data. While we experienced some early difficulties, we resolved all technical issues involving the interfacing of high precision CT sensors and the MAVS current meter to ABE and so will have a series of productive dives.

Current Measurements. IOS will make available from their extensive inventory current meters, both conventional (Aanderaa RCM 5, 7 and 8) and acoustic (Sontek ACM, Aanderaa RCM11 and Nortec Aquadop), acoustic releases and SEACAT CT packages, to have four moorings with three meters each deployed continuously in the two years of study. We would acquire four RDI 75 kHz Long Ranger ADCP instruments that have a range of 200 m in broadband mode and low power or 320 m in narrow band mode at high power. We would collect 10 minute ensemble averages based on 150 pings per ensemble with 6 m vertical bins yielding ~1 cm/s standard deviation. The off-the-shelf instrument is rated to 3000 meters and would be equipped with an additional external battery pack for the year long deployment. The IOS suite of analysis programs would be used to conduct the spectral and time-series analysis of the observations [*Emery and Thomson*, 2001].

CTD. With a relay transponder on the CTD cage and using dynamic positioning, we were able to position the CTD cage in known configurations relative to individual vent structures. We would again place pairs of CT sensors to be vertically separated. We found this to be a sensitive tool for identifying water column instabilities characteristic of rising hydrothermal plumes [*Veirs et al*., 1999].

Responsibilities

McDuff will lead the NSF-funded portion of the study. He will be responsible for coordination of the various program components, be chief scientist on the 2004 *Thompson* cruise, conduct the heat flux measurements from ABE, and coordinate, with Thomson, the deployment of the ADCPs to be acquired by UW. Yoerger and Bradley will be responsible for ABE operations and will work with the UW group to re-integrate their sensors with the ABE system. Thomson will be responsible for coordinating and analyzing the current measurements and be chief scientist on the three *Tully* cruises. McDuff and Thomson will work jointly to integrate the results of the two major observational components, to prepare publications and to make data submissions complying with the RIDGE 2000 data policy.

Synergy with RIDGE 2000 Programs and Other Broader Impacts

This project continues our long-standing collaboration with Thomson's group at IOS. His institute has pledged half the ship time needed to complete the project, two months of effort per year from Thomson, additional scientific and technical support, and access to ~$600k of equipment with the cost of maintenance and deployment mutually shared. A unique aspect of the Endeavour ISS is that it lies in Canadian waters within a Marine Protected Area. As a community we will have the best access when there are a number of on-going, mutually beneficial research programs.

Our suite of current meters would represent an important community resource. Thomson is collaborating in a similar fashion with the proposed Cowen et al. program which concerns cycling of organic carbon. If both projects are funded, some of the now separate moorings will be designed to meet the needs of both programs (and when budgets are negotiated there will be appropriate adjustments made to reflect these savings.) Tidal modulation of vent-specific time series is well known, but it is still unresolved whether this is due to interaction of currents with hydrothermal phenomena at the seafloor or tidal pumping of the subsurface hydrogeologic system. Our data would help to provide a context for interpreting vent-specific measurements. Overall, the array would be a rich data set for considering the role of currents in dispersal of larvae as is being proposed by Hautala et al. Finally it would enable some very exciting physical oceanographic experiments comparing topographically modified flows in the axial rift valley, with its buoyancy driven upwelling, to its neighbor to the west in which topographic effects are similar but where buoyancy sources are expected to be substantially smaller. We are discussing proposing such an experiment with Kevin Speer and Andreas Thurnherr at FSU.

The project will provide the core research experience for a Ph.D. student at UW. Within the UW School of Oceanography we have a special focus on experiential education for undergraduates and we would also recruit a student early in their program to be a long-term participant in our research team.

As a group we are active in connecting our research to education at all levels. *McManus* [2002] speaks to the importance of helping students follow diverse paths and McDuff is proud to have mentored several advisees who have focused their careers in education and continuing to participate in our research on a part-time basis. As we did in 2000, we will again host REVEL participants on our 2004 cruise and continue to work with them post-cruise as use their experiences in teaching and community outreach. McDuff and Yoerger frequently lecture to public school classes to help engender interest in science and engineering.

A Long Term Perspective

Flow Mow as funded represented a compromise between our ambitions and reviewer-induced caution. We wrote in the successful version of the proposal:

> "The collective advice from two earlier submissions of this proposal was to collapse its scope to a single field season, focusing on heat alone and without making related chemical measurements. The outcome of the field program will be to have measured heat output that represents, geologically, a single point in time. Though the field program covers a period of almost a month, we will not have determined if the heat flux of this system is steady, oscillatory, or evolving with time. We view this initial program as a critical demonstration that hydrothermal fluxes can be measured with sufficient precision so that conducting time-series measurements would be of value."

In this context, a natural path would be to simply propose a series of repeat Flow Mow-style measurements while extending the geographic focus to other Endeavour Segment vent fields. This proposal builds a path toward developing a much more powerful yet ultimately affordable approach. Proxy measurements will never replace high precision ones, but one will provide a suitable context for knowing when to make the other. With Canadian NEPTUNE funded and extremely likely to reach to Endeavour Segment within the next several years, a successful test of our proxy approach would provide ability to initiate and design event response activities not only around SOSUS-detected earthquakes. Having multiple independent indicators of change will help make better decisions concerning when to mount event responses. As we envision ABE or its predecessors integrating with NEPTUNE, these indicators would be a key determinant of how AUV operations might be prioritized between volcanic and hydrothermal research objectives.

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