Entrainment and bending in a major hydrothermal plume, Main Endeavour Field, Juan de Fuca Ridge

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We measure expansion rate and bending in a 23-hour time series of acoustic images of the lower 25 m section of a buoyant hydrothermal plume rising from Grotto vent in the Main Endeavour Field, Juan de Fuca Ridge. We then calculate entrainment coefficient, the constant of proportionality relating mean inflow velocity at the plume edge to maximum mean upward velocity within the plume. The plume section alternately bends southwest at relatively high inclinations (37°) and northeast at lower inclinations at irregular intervals twice during this time period, apparently driven by current reversals in the mixed semi-diurnal tidal cycle. The measured expansion rates (0.11–0.25 m/m) and calculated entrainment coefficients (0.07–0.18) are directly proportional to the degree of bending (R^2 = 0.75). The loss of buoyancy flux related to enhanced mixing in a stratified environment during bending may contribute to reduction of potential rise height consistent with predicted (∼400 m) and measured (300–350 m) plume tops. Citation: Rona, P. A., K. G. Bemis, C. D. Jones, D. R. Jackson, K. Mitsuzawa, and D. Silver (2006), Entrainment and bending in a major hydrothermal plume, Main Endeavour Field, Juan de Fuca Ridge, Geophys. Res. Lett., 33, L19313, doi:10.1029/2006GL027211.

1. Introduction

Submarine hydrothermal plumes are agents of dispersal of heat and matter transferred from the lithosphere into the ocean by sub-sea floor hydrothermal convection systems in amounts that are quantitatively significant. High-temperature solutions (200 to 400°C) discharge from point sources at mineralized chimneys. The chimney discharge rises as a plume with a stem and a cap. The plume stem comprises momentum-driven jets at the source vents, which become buoyant jets and plumes within the initial meters of rise. The buoyant plumes may rise up to hundreds of meters above the vents as a consequence of total weight deficiency per unit time (buoyancy flux) produced by the volume of lower density fluids [McDuff, 1995]. As the buoyant plume rises, it entrains seawater until it attains neutral buoyancy relative to the density stratification of the surrounding ocean. At its neutrally buoyant level, the plume spreads laterally as a cap on the stem [Morton et al., 1956; Turner, 1986]. Plumes are generally bent by cross flow of deep ocean currents, which blurs the distinction between stem and cap.

In this paper we apply acoustic methods to volumetrically image, visualization methods to reconstruct in 3D, and quantification methods to measure expansion rate and to calculate entrainment coefficients of a major hydrothermal plume [Bemis et al., 2002; Rona et al., 2002]. The plume discharges from a cluster of chimneys atop the north tower of the Grotto sulfide edifice, a mound 15 m long by 10 m wide by 10 m high, with base at a water depth of 2195 m in the Main Endeavour Field situated in the axial valley of the Endeavour segment of the northern Juan de Fuca Ridge [Delaney et al., 1992]. Our time series of 23 hourly acoustic images shows the lower part of the buoyant plume bending in reciprocal directions apparently in response to reversals in direction of prevailing deep ocean currents during a day of mixed semidiurnal tidal cycles (Figure 1 and Table 1). Our observations reveal systematic relations between expansion rate, entrainment coefficient, and bending (Figure 2).

2. Entrainment

The rate of entrainment of ambient seawater by a plume, buoyantly rising in a stratified water column from a seafloor hydrothermal field, influences the near-field dispersion of heat, chemicals, and biological material. The entrainment coefficient of a plume rising in the water column cannot be predicted theoretically and, therefore, must be deduced from laboratory or field measurements [Fischer et al., 1979]. According to the entrainment hypothesis [Morton et al., 1956; Turner, 1986], “the mean inflow velocity across the edge of a turbulent flow is assumed to be proportional to a characteristic velocity, usually the local time-averaged maximum mean velocity or the mean velocity over the cross-section at the level of inflow”. The constant of proportionality relating the mean inflow velocity at the edge of the plume to the maximum mean upward velocity within the plume is the entrainment coefficient α. Specifically, the entrainment coefficient α is defined so that the rate of entrainment of volume at a particular height is given by 2πb_eν_V_C(0) where b_e is a length scale (plume radius at 1/e of axial value for Gaussian profile) and V_C(0) is the time-averaged axial vertical velocity. The entrainment relation, with the additional assumption that profiles of time averaged vertical velocity and buoyancy force in cross-sections are of similar form at all heights, implies that even in a stratified medium the
radius of the lower part of the plume stem will spread linearly with height as \( b_g = cz \), where \( z \) is height and \( c \) is a constant that can be shown to be proportional to \( \alpha \), \( c = 1.2(6/5)\alpha \), when \( b_g \) is the radius given by the distribution of a conservative tracer [Turner, 1986].

3. Acoustic Method

[5] We mounted a sonar system (Kongsberg Simrad SM2000; frequency 200 kHz) on a remotely operated vehicle (ROV Jason) modified to scan a plume in azimuth and elevation from a fixed position on the seafloor [Rona et al., 2002]. Three-dimensional acoustic images are formed by a combination of time gating for resolution in range (0.2 m to 2.0 m at distances from origin of 15 m to 50 m and 0.5 m in the perpendicular direction), digital beam forming for resolution in azimuth, and mechanical scanning for resolution in elevation (beam width 1.4°). The system scans a plume in 2 minutes and is calibrated to record absolute backscatter intensity.

[6] Our acoustic images of hydrothermal plumes are based primarily on intensity of Rayleigh backscatter from metallic mineral particles precipitated from high-temperature hydrothermal solutions and suspended as “smoke” in the plumes [Palmer, 1996] and turbulent density discontinuities. The particles are small (microns) relative to the wavelength of the acoustic frequencies used (≈1 cm at 200 kHz). At sufficiently low particle concentrations, backscatter intensity is directly proportional to concentration of suspended particulate matter as the product of total particle load and a factor dependent upon average particle mechanical properties, including density and bulk modulus [Palmer, 1996]. Particle behavior provides an approximate proxy of the size and shape of the buoyant plume because turbulent fluid velocities generally exceed settling velocities of the particles [Feely et al., 1994].

[7] We reconstruct a plume by interpolating 2D acoustic images (each from a single ping) cutting at multiple angles (−10° to 80°) through a buoyant plume onto a 3D rectangular grid (0.25 m spacing) averaging over 6 successive scans (12 minutes) [Rona et al., 2002]; we refer to this 3D grid as the plume volume. The averaged data are converted to differential scattering cross-section per unit volume. This quantity has units of inverse length and is proportional to particle concentration in the weak scattering limit in which acoustic self-shadowing is negligible. The averaged, gridded data are displayed as concentric surfaces of equal backscatter intensity using standard visualization software. The iso-intensity surfaces converge upward (Figure 1), while the actual boundaries diverge as the plume expands upward. The time-averaging reduces turbulent fluctuations through smoothing and relates our measurements to time-integrated models of buoyant plume behavior [Morton et al., 1956].

[8] We construct a centerline as the center of mass (backscatter intensity) to measure the distribution of properties of the plume in cross-sectional profiles [Rona et al., 2002]. Laboratory measurements of buoyant plumes have shown that the time-averaged rise velocity, temperature, and concentration of the buoyancy flux have a 2D Gaussian distribution about the centerline of the plume [Papanicolaou and List, 1988]. The assumption of self-similarity, which implies that the profiles of mean vertical velocity and mean buoyancy forces have the same mathematical form in cross-sections at each height in a buoyant plume, allows us to compute the expansion rate of the plume from the 3D distribution of differential scattering. We measure the increase of plume radius based on construction of cross-sections with height of the plume, defined as the distance from the centerline to the point where the backscatter intensity decreases to 1/e (0.4 or 37%) of that at the centerline [Bemis et al., 2002; Rona et al., 2002]. The 2D cross-sections are constructed perpendicular to the centerline at each height in the plume to measure...
undistorted radii for accurate determination of plume expansion rates [Frick et al., 1994].

4 Results

[9] In our July 2000 experiment, we used the sonar system mounted on ROV Jason to record a 23-hour time series (1900 GMT 26 July 2000 to 1900 GMT 27 July 2000) of acoustic images of the buoyant portion of the plume emanating from a cluster of black smoker vents atop the north tower of the Grotto sulfide edifice. We recorded from a fixed position on the west wall of the rift valley (latitude 47°56.95'N, 129°56.94'W; UTM coordinates 492611 m E, 5310654 m N) at a water depth of 2187 m with the sonar oriented northeastward at a nearly horizontal slant range of 20 m to the vents at 2185 m. Our deep-towed in situ video and temperature survey of the top of the north tower revealed five black smokers discharging 359°C effluent at a flow rate of about 1 m/s from chimneys 2 m high within a 3 m by 3 m area. The discharge coalesced into the main plume at a height of about 5 m above the vents. Diffuse flow and a few other black smokers overlooked by our survey on the sides of the north tower may have contributed to the main plume.

[10] We reconstructed 15 volume images of the Grotto buoyant plume to a height of ~25 m above the source vents during the 23-hour period (Figure 1). The sonar signal was gated (50 m range) to accelerate data collection times and to exclude higher regions of the plume where dilution by entrainment attenuates the backscatter. Projections of the plume volumes show a systematic variation of direction and degree of bending (Figure 1 and Table 1). We extracted cross-sections perpendicular to the plume centerline from each plume volume at 2 m intervals between 6 m and 18 m above the source vents.

[11] We determined expansion rate by measuring the plume radius in each of the successively higher cross-sections (Table 1). These measurements are based on a nonlinear least squares fit of a two dimensional Gaussian curve to the observed backscatter distribution in each cross-section: \[ I = I_c \exp \left(-r^2/b^2\right), \] where \( I \) is the differential scattering area per unit volume (\( I_c \) is centerline value), \( r \) is the distance from the centerline to a point in the cross-section, and \( b \) is the effective radius of the plume (see Table 2 for \( b \) values and fit statistics for key plume volumes). A linear regression fit to the variation in radius with height for each plume volume over the selected height range yielded an expansion rate \( \alpha \) for each volume (time), as the slope of the equation \( b = az + b_0 \), where \( z \) is height above the vent and the subscript 0 denotes the initial radius (which may reflect a virtual source above or below the actual vent; regression fit statistics in Table 2). We then calculated entrainment coefficient \( \alpha \) at each time as \( \alpha = (5/6)\alpha/1.2 \), where the divisor 1.2 reflects the assumption that the particle distribution (and hence backscatter intensity distribution) follows the pattern for concentration instead of velocity and the divisor value was empirically determined in laboratory measurements [Papanicolaou and List, 1988]. The factor (5/6) is a geometrical factor relating expansion to

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**Table 1. Time Series (23 hours) of Observed Bending, Measured Expansion Rates, and Calculated Entrainment Coefficients for the Lower Portion of the Grotto Buoyant Plume**

<table>
<thead>
<tr>
<th>Plume Volume</th>
<th>Time</th>
<th>Plume Cycle</th>
<th>Expansion Rate, ( m/m )</th>
<th>( R^2 )</th>
<th>Inclination, deg</th>
<th>Direction (Azimuth)</th>
<th>Entrainment Coefficient ( \alpha )</th>
</tr>
</thead>
<tbody>
<tr>
<td>137</td>
<td>19.4</td>
<td>1</td>
<td>0.25</td>
<td>0.97</td>
<td>37.4</td>
<td>219</td>
<td>0.18</td>
</tr>
<tr>
<td>145</td>
<td>21.4</td>
<td>1</td>
<td>0.16</td>
<td>0.96</td>
<td>17.9</td>
<td>164</td>
<td>0.11</td>
</tr>
<tr>
<td>149</td>
<td>22.4</td>
<td>1</td>
<td>0.10</td>
<td>0.96</td>
<td>5.0</td>
<td>128</td>
<td>0.07</td>
</tr>
<tr>
<td>153</td>
<td>23.4</td>
<td>1</td>
<td>0.14</td>
<td>0.96</td>
<td>12.0</td>
<td>145</td>
<td>0.10</td>
</tr>
<tr>
<td>163</td>
<td>01.4</td>
<td>1</td>
<td>0.19</td>
<td>0.93</td>
<td>2.7</td>
<td>58</td>
<td>0.13</td>
</tr>
<tr>
<td>167</td>
<td>02.4</td>
<td>1</td>
<td>0.11</td>
<td>0.97</td>
<td>2.8</td>
<td>82</td>
<td>0.08</td>
</tr>
<tr>
<td>175</td>
<td>04.4</td>
<td>2</td>
<td>0.12</td>
<td>0.99</td>
<td>10.7</td>
<td>20</td>
<td>0.08</td>
</tr>
<tr>
<td>179</td>
<td>05.4</td>
<td>1</td>
<td>0.11</td>
<td>0.99</td>
<td>9.1</td>
<td>67</td>
<td>0.08</td>
</tr>
<tr>
<td>183</td>
<td>06.4</td>
<td>1</td>
<td>0.19</td>
<td>0.92</td>
<td>31.8</td>
<td>216</td>
<td>0.13</td>
</tr>
<tr>
<td>200</td>
<td>10.4</td>
<td>1</td>
<td>0.11</td>
<td>0.97</td>
<td>0.7</td>
<td>39</td>
<td>0.07</td>
</tr>
<tr>
<td>208</td>
<td>12.4</td>
<td>2</td>
<td>0.15</td>
<td>0.96</td>
<td>10.7</td>
<td>48</td>
<td>0.10</td>
</tr>
<tr>
<td>216</td>
<td>14.4</td>
<td>2</td>
<td>0.18</td>
<td>0.96</td>
<td>16.6</td>
<td>163</td>
<td>0.13</td>
</tr>
<tr>
<td>222</td>
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<td>0.84</td>
<td>16.9</td>
<td>165</td>
<td>0.14</td>
</tr>
<tr>
<td>226</td>
<td>16.4</td>
<td>1</td>
<td>0.22</td>
<td>0.96</td>
<td>36.8</td>
<td>210</td>
<td>0.15</td>
</tr>
<tr>
<td>234</td>
<td>18.4</td>
<td>1</td>
<td>0.15</td>
<td>0.92</td>
<td>27.5</td>
<td>192</td>
<td>0.10</td>
</tr>
</tbody>
</table>

\[ a = (5/6)\alpha/1.2 \]

Section 6–18 m above source vents; Figure 1.

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Figure 2. (top) Measured inclination (angle from vertical in degrees) and (bottom) azimuth (degrees) of bending of centerline of the lower portion of the Grotto buoyant plume plotted versus time period of measurements (JD 208.6 26 July to JD 209.8 GMT 27 July 2000).
entainment [Morton et al., 1956]. The calculated entrainment rates are presented in Table 1.

An irregular plume bending cycle is present consisting of two sets of two phases over the 23 hours of imaging (Figures 1 and 2 and Table 1). Phase 1 exhibits high values of bending (31.8°–37.4° from vertical), expansion rate (0.19–0.25 m/m), and entrainment coefficient (0.13–0.18); the bending direction is southwest. The bending direction rotates northeast (counterclockwise) at low to nearly vertical inclinations to plume phase 2. Phase 2 exhibits lower values of bending (10.7°), expansion rate (0.12–0.15 m/m), and entrainment coefficients (0.08–0.10); the bending direction is northeast. The bending direction rotates eastward (clockwise) at low to nearly vertical inclinations back to phase 1. The time interval between successive phases is variable (phase 1, 10 to 12 hours; phase 2, 8 hours).

The expansion rate and entrainment coefficient of the plume vary directly with degree of bending throughout the irregular plume cycle (Figures 1 and 3 and Table 1). A least squares fit of expansion rate (m/m) to angle of centerline from vertical over heights from 6 to 18 m above the source vents yields the equation $a = 0.0028 + 0.11$ (line on Figure 3) with a correlation coefficient of $R^2 = 0.57$, where $a$ is the expansion rate for an individual time and $\theta$ is the angle from the centerline for the same time. Inferred initial plume radii, corresponding to our estimates of expansion rate, have absolute values generally less than 0.5 m; these small values (relative to the spatial resolution of the acoustic data) suggest the expansion rate estimates are reasonable.

The overall time period between successive plume phase 1 (~12 hours), and the alternation between plume phases 1 and 2 suggest that the plume bending may be forced by NE-SW reversals of oscillatory near-bottom currents related to the prevalent mixed semi-diurnal tidal cycle. However, the timing and directions of bending are inconsistent with regional analysis of tidal flow [Cannon and Pashinski, 1997], tidal models (H. Mofjeld, personal communication, 2004), and current meter observations (range 0.05 m/s–0.10 m/s [Thomson et al., 1989, 2003; Williams and Tivey, 2001]). The inconsistency may be related to perturbation of the flow field by proximity to the west wall of the axial valley. A comparison of the measured bending angles in the lower portion of the buoyant plume (Table 1) and prevailing current velocities with models of a whole plume [see Middleton and Thomson, 1986] (Table 1 and Figure 4) suggest that the plume observed in this study may become nearly horizontal within the initial 200 m of rise at the times of maximum bending.

5. Discussion and Conclusions

We show that our measurements of expansion rate and calculations of entrainment coefficient (0.07–0.18; Table 1) in the buoyant plume discharging from the Grotto Vent north tower (6–18 m height above source vents) increase directly with degree of bending. Estimated values for the entrainment coefficient $a$ for maintained plumes in a uniform or stably stratified environment based on laboratory measurements include 0.093 [Morton et al., 1956], 0.0875 [Papamicalou and List, 1988], and 0.083 as an average from several experiments [Fischer et al., 1979]. Our prior estimates of entrainment coefficients are based on measurements from our acoustic images of nearly vertical buoyant plumes at the Clam Acres vent field at 21°N on the East Pacific Rise (0.07 and 0.058 [Rona et al., 2002, Table 3; Bemis et al., 2002, Table 4]), and Monolith Vent on the Juan de Fuca Ridge, which changed with time (0.042 to 0.090 [Bemis et al., 2002, Table 4]). The minimum values (for a vertical plume) determined in this study are comparable to these prior values. The increase in entrainment rate with degree of plume bending suggests the higher observed values are due to the interaction of the plume and prevailing currents.

Middleton and Thomson [1986] model an increase in maximum height of rise of a buoyant hydrothermal plume to a level of no momentum as a consequence of increase in source buoyancy flux; they present two end member cases.
for plumes in a stagnant environment and plumes in a strong current. They predict a decrease in maximum rise for the same source buoyancy with bending as a consequence of an increase in cross-flow for a given ocean stratification (equation 3.26):

$$z_{\text{max}} = \left( \frac{6B_o}{(\pi \alpha^2 U N^2)} \right)^{1/3},$$

for $U > 0$ where $z_{\text{max}}$ is the maximum height of rise, $B_o$ is the initial buoyancy flux, $\alpha$ is the entrainment coefficient, $U$ is the current velocity and $N$ is the buoyancy frequency of the stratified water column. Our measurements of expansion rate (Figure 3), calculations of entrainment coefficient (Table 1), and observations of rise height (Figure 4) provide experimental support for the Middleton and Thomson [1986] model and contribute to explaining the mechanism of their modeled reduction in rise height. The increase in entrainment coefficient with bending increases the dilution of the plume by ambient seawater. As the density deficit decreases, the plume attains neutral buoyancy with the surrounding stratified ocean at a deeper level than if a slower rate of entrainment acted through a near vertical rise.

[17] The predicted full vertical rise height of the Grotto vertical (for $U = 0$) plume is about 400 m, when calculated using Middleton and Thomson’s [1986] equation 2.9:

$$z = 2^{-5/8} \alpha^{-1/2} \left( \frac{B_o}{\pi} \right)^{1/4} N^{-3/2} z_1,$$

where $z_1 = 2.1$ at the level of zero buoyancy and $z_1 = 2.8$ at the level of zero momentum and the measured source parameters (fluid temperature 359°C, discharge velocity 1 m s$^{-1}$; diameter of summed area of the 5 vent orifices 20.5 cm), an average density gradient for the deep water column ($4.5 \times 10^{-3}$ kg/m$^3$), and properties of the venting solutions assuming seawater salinity (coefficient of thermal expansion $5.91 \times 10^{-3}$ 1/C [Bischoff and Rosenbauer, 1985]).

[18] The currents observed at Endeavor lie between the stagnant and strong current environments of the two end members above. Although a weak current will not produce as strong an enhancement of entrainment as a strong current, its effect will go in the same direction [Frick et al., 1994; Huang et al., 1998; Bursik, 2001]. This study’s observed increase in entrainment coefficient would decrease the predicted rise height of the plume to as low as 150 m. Figure 4 compares the predicted range in rise height, based on the observed range in entrainment coefficient and current velocity, with profiles from two CTD-transmissometer casts taken one day after the acoustic time series. The CTD-transmissometer casts (one hour apart) detected the Grotto plume at levels above the vents ranging from a few meters to 300–350 m; the lower (0–75 m) detections have fairly high signals which may indicate that the casts intersected a bent buoyant stem of the plume. The top level of detection, about 300–350 m, is well below the ~400 m predicted for a vertical plume, consistent with a reduction in rise height related to bending and increased entrainment. These observations support attribution of a variability of a component of rise height of a major plume in the Atlantic (TAG) to plume bending due to currents [Rudnicki et al., 1994].

[19] The reciprocal directions of bending, and associated decrease in rise height, change the near-field pattern of dispersal of heat and matter from the plume; the impacts on the surrounding seafloor and ocean remain to be determined.

[20] Acknowledgments. The Deep Submergence Group and the ROV Jason team of the Woods Hole Oceanographic Institution, and the Marine Office, officers, and crew of the R/V T.G. Thompson of the University of Washington gave strong support to our VIP 2000 cruise. We thank R.E. Thomson of the Canadian Institute of Ocean Sciences for his deep current meter information and discussion; H. Mojfeld and W. Lavelle of NOAA’s Pacific Marine Environmental Laboratory for their tidal cycle model; N. Zabusky and D. Silver, directors of the Laboratory for Visionetics and Modeling at Rutgers University, for access to their expertise, students, and facilities; and two anonymous reviewers for incisive comments. Graduate student K. Santilli constructed the sequence of plume images (Figure 1).

References


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