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

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[1] 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

[2] 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.

[3] 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

[4] 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 $2\pi b_g \alpha V_G(0)$ where b_g is a length scale (plume radius at 1/e of axial value for Gaussian profile) and $V_G(0)$ 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

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