Cah. Biol. Mar. (2006) 47 : 379-384

A particle sedimentation model of buoyant jets: observations of hydrothermal plumes

Karen BEMIS[1], Deborah SILVER[2], Peter RONA[1] and James COWEN[3]

(1) *Institute of Marine and Coastal Sciences and the Department of Geological Sciences, Rutgers University, 71 Dudley Rd, New Brunswick, NJ, 08901 USA; fax 732-445-3374. Email: bemis@rci.rutgers.edu*

(2) *Department of Electrical and Computer Engineering, Rutgers University, Piscataway, NJ, USA*

(3) *Department of Oceanography, University of Hawaii at Manoa, Honolulu, HI, USA*

Abstract: We extend the application of exponential settling to hydrothermal plumes to predict hydrothermal sediment patterns on the seafloor by using acoustic observations of particle velocities and concentrations instead of the predictions of dynamic models used by previous studies. We assume settling occurs only from the margins of the plume, which corresponds to the transition from a net upwards force on the particles in the plume to a net downwards force outside. In each volume element where the net force changes from downwards to upwards, the loss of sediment from the volume element is calculated. The losses for five particle sizes are summed to determine the sediment mass deposited. We applied this sedimentation model to acoustic observations of particle concentration and flow velocity in hydrothermal plumes at Grotto Vent on the Endeavour Segment of the Juan de Fuca Ridge. The overall mass flux decreases if the particle size distribution is shifted towards smaller particles or particle density is decreased (as for biological particles). While improvements in both observations and model algorithms are needed, we demonstrate that quantitative predictions of sedimentation can be made successfully from direct observations of plumes.

Keywords: Particle sedimentation model • Buoyant jets • Hydrothermal plumes • Larval transport

Introduction

Most plume sedimentation models incorporate predictions of flow velocity and particle concentration in the plume based on the initial conditions at the vent. In this study, we adapt the sediment transport theories used in many studies of sedimentation for use with direct observations of flow velocity and particle concentration throughout the plume.

A common assumption of sediment transport theories is that the rate of sediment concentration decrease in a suspended layer can be described as exponential decay (Hazen, 1904; Martin & Nokes, 1988). A number of models have applied an exponential decay relationship for sediment mass concentration to settling of particles from the margins of the buoyant stems of volcanic eruption clouds and hydrothermal plumes (Sparks et al., 1991; Bursik et al., 1992; Ernst et al., 1996). These earlier studies used an integral (time-averaged) model, based on Morton et al. (1956), to describe the plume and to compute the fraction of the initial particle mass that settles and its radial dependence. This model depends on knowledge of the source buoyancy flux (difficult to measure for hydrothermal plumes) and total particle mass available (not meaningful for hydrothermal plumes where sedimentation occurs over decades).

There are also other approaches to sedimentation from plumes in the literature (double diffusion, Hoyal et al., 1999; two phase, Veitch & Woods, 2002; large eddy simulations, e.g. Lavelle, 1997; fully turbulent simulations, P. Bagchi, personal communication, 2005); most of these assume you know the forcing function and predict the plume. These models may be useful for data assimilation but are not directly helpful in predicting the sedimentation and transport by an observed plume.

Therefore, we develop a preliminary technique to apply the basic concepts of sedimentation (settling) to observed plumes. In this study, we extend the application of exponential settling to hydrothermal plumes such that the model uses acoustic observations of hydrothermal plumes, including particle velocities and concentrations, to predict hydrothermal sediment patterns on the seafloor. Our previous work developing acoustic imaging techniques to measure the static and dynamic properties of seafloor hydrothermal plumes (Jackson et al., 2002; Rona et al., 2002) provides the necessary input to the preliminary model.

Materials and methods

Particle settling model for a buoyant jet

Our general approach is to assume exponential settling of particles from the margins of the plume following Martin and Nokes (1988) and Bursik et al. (1992). For exponential settling, the rate of mass loss from the plume is given by

$$dm/dt = -\nu C_0 A,$$

where ν is the terminal velocity, C_0 is the concentration of particles of given diameter, and A is the basal area of the region (a voxel which is a small volume unit of side dx) within which the concentration applies. We assume that settling occurs only on the margins of the plume (Fig. 1). This requires a definition of the interface between the plume and its surroundings. Our working definition of the interface is the transition from the upwards force on the particles in the core of the plume which are being transported and the downwards force on the particles outside the plume which are settling. One alternative definition could

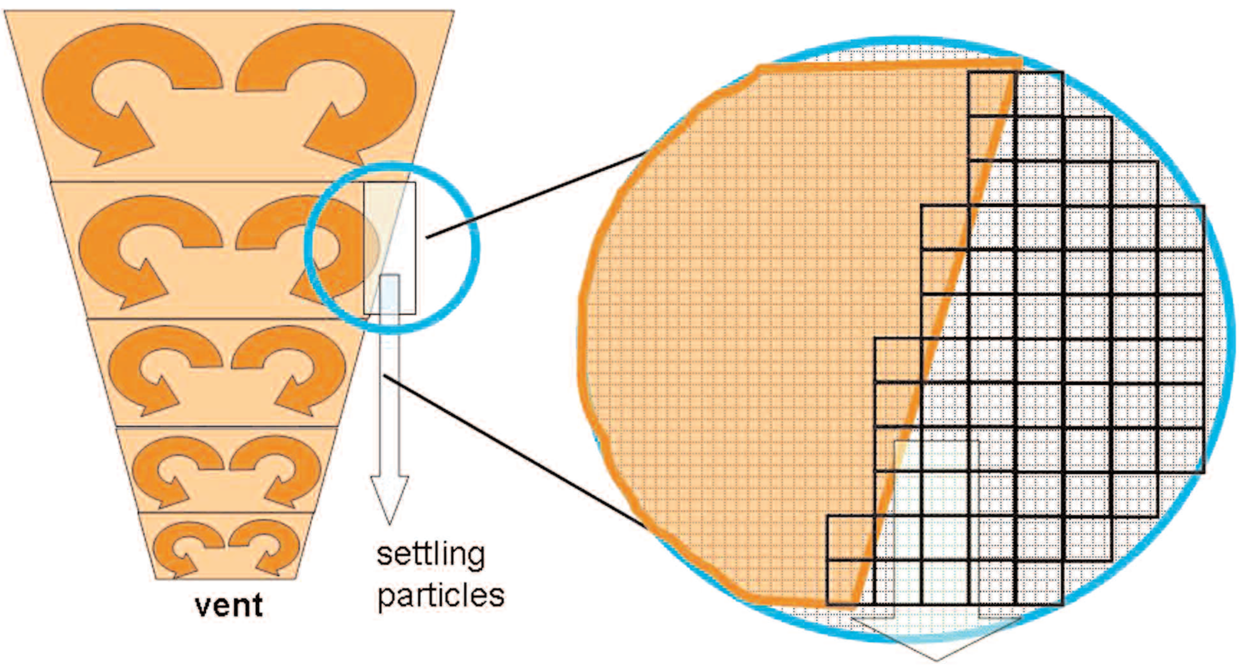

Figure 1. Particles are assumed to settle across an interface at the margins of the plume. The interface is defined by the transition from the upwards force on the particles in the core of the plume which are being transported and the downwards force on the particles outside the plume which are settling. The location of the interface depends on particle size and density as well as the fluid properties and the vertical velocity inside the plume. Settling rates also depend on the terminal velocity and concentration of particles.

Figure 1. Les particules sont supposées sédimenter à travers l'interface sur les bords de la plume. L'interface est défini par la transition entre les forces ascendantes agissant sur les particules qui sont transportées au sein de la plume et les forces descendantes qui sédimentent à l'extérieur de la plume. La localisation de l'interface dépend à la fois de la taille, de la densité des particules et des propriétés du fluide et de la vitesse verticale de déplacement à l'interface de la plume. Les taux de sédimentation dépendent également de la vitesse finale et de la concentration en particules.

be the Gaussian peak width of the concentration distribution around the plume centerline (this was used in Ernst et al. (1996) and Bursik et al. (1992)). Observed concentration is not used here to define the plume edge as it may be affected by settling particles.

In this study, we calculate the terminal velocity (based on the estimated Reynolds number) and net force on the particles of a given size everywhere within the plume and its surroundings based on local velocity in gridded volume elements. The basic Reynolds number dependence of terminal velocity is taken from Bonadonna et al. (1998) although adjustments were made for the effect of buoyancy in water:

$$\nu = \begin{cases} \left(\frac{8}{3}\frac{gr}{C_D}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)\right)^{1/2}, & for \text{ Re} > 500 \\ 4\frac{gr^2}{18\mu}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)\left(1+\text{Re}^{2/3}\right)^{-1}, & for \ 0.4 < \text{Re} < 500 \\ 4\frac{gr^2}{18\mu}\left(\frac{\rho_p - \rho_f}{\rho_f}\right)\left(1+\frac{3}{16}\text{Re}\right)^{-1}, & for \text{ Re} < 0.4 \end{cases}$$

where ν is the terminal velocity, g is gravity, r the particle radius, ρ is the density of the particle (p) or fluid (f), C_D is the drag force, Re is the Reynolds number and μ is the kinesthetic fluid viscosity.

The gridded volume is searched one column at a time from bottom up to find the plume margin or interface: In each volume element where the net force changes from downwards to upwards, the loss of sediment from the volume element is calculated. Volume elements above this interface are ignored. The calculated losses are summed to determine the sediment mass deposited on the seafloor for an assumed grain size. Table 1 shows the assumed size distribution based on a survey of the available literature (see section below). The results for five particle sizes are then combined using an assumed size distribution to determine the total sediment mass deposited on the seafloor (Fig. 2). This model does not explicitly account for horizontal currents, but should work for bent plumes with minor or no modification.

Particle size distributions

The present size distribution (Table 1) is based on two sources: (1) Feely et al. (1987) report near vent size ranges of 5-500 µm for particulates in the plumes along the Endeavour Segment of the Juan de Fuca Ridge and that chalcopyrite and anhydrite are the dominant minerals present, (2) Walker & Baker (1988) found a distinctive form to the size distributions in samples proximal to the buoyant plumes along the Juan de Fuca Ridge. Although they found much smaller size ranges (mean 6-10 µm), they were also probably sampling much higher in the plume than Feely et al. (1987) did or than is relevant to this study. This study used the function form of Walker & Baker (1988) but the higher mean (50 µm) suggested by the Feely et al. (1987) size ranges. Table 1 gives the actual values used.

Table 1. Particle size distribution for model results in Figure 2
Tableau 1. Distribution de la taille des particules pour les résultats du modèle de la figure 2.

5 µm	10 µm	50 µm	100 µm	500 µm
1%	22%	67%	9%	1%

Results

Results from acoustic observations

We applied the sedimentation model described above to acoustic observations of hydrothermal plumes at Grotto Vent on the Endeavour Segment of the Juan de Fuca Ridge (Rona et al., 2002). Acoustic backscatter data was used to infer particle concentration (as a function of assumed particle size); vertical velocity was inferred from Doppler shifts in the same acoustic backscatter data (Jackson et al., 2003). The acoustic data covers the bottom 30-50 m of the buoyant plume with a spatial resolution of approximately 0.25 m.

As expected, particle size and mass flux generally decease away from the vent (Fig. 2a-b). The exponential decrease in mass flux with distance is consistent with field studies at a different site (13°N East Pacific Rise (German et al., 2002)). The mass flux and average grain size contours are elongated to the northeast because of a slight tilt in the plume centerline towards the northeast; this is likely due to ambient currents flowing from the southwest to the northeast. Although not shown in Figure 2, the overall mass flux increases if the particle size distribution is shifted towards larger particles.

Application to biological transport

We have started to explore the effect of using different particle densities. Field observations suggest that particle composition in the deposited sediments may vary with particle size (Hrischeva & Scott, 2005; C. German, personal communication, 2005). Sediment composition is known to vary with distance from the vent (German et al., 2002). Additionally, biological particles that the plume may transport (e.g., larvae) are much lower in density than the precipitates. Figure 3 shows sizes of particles the plume can transport as the density is decreased from the default assumption of 5000 kg.m^{-3} to nearly the density of water (1000 kg.m^{-3}).

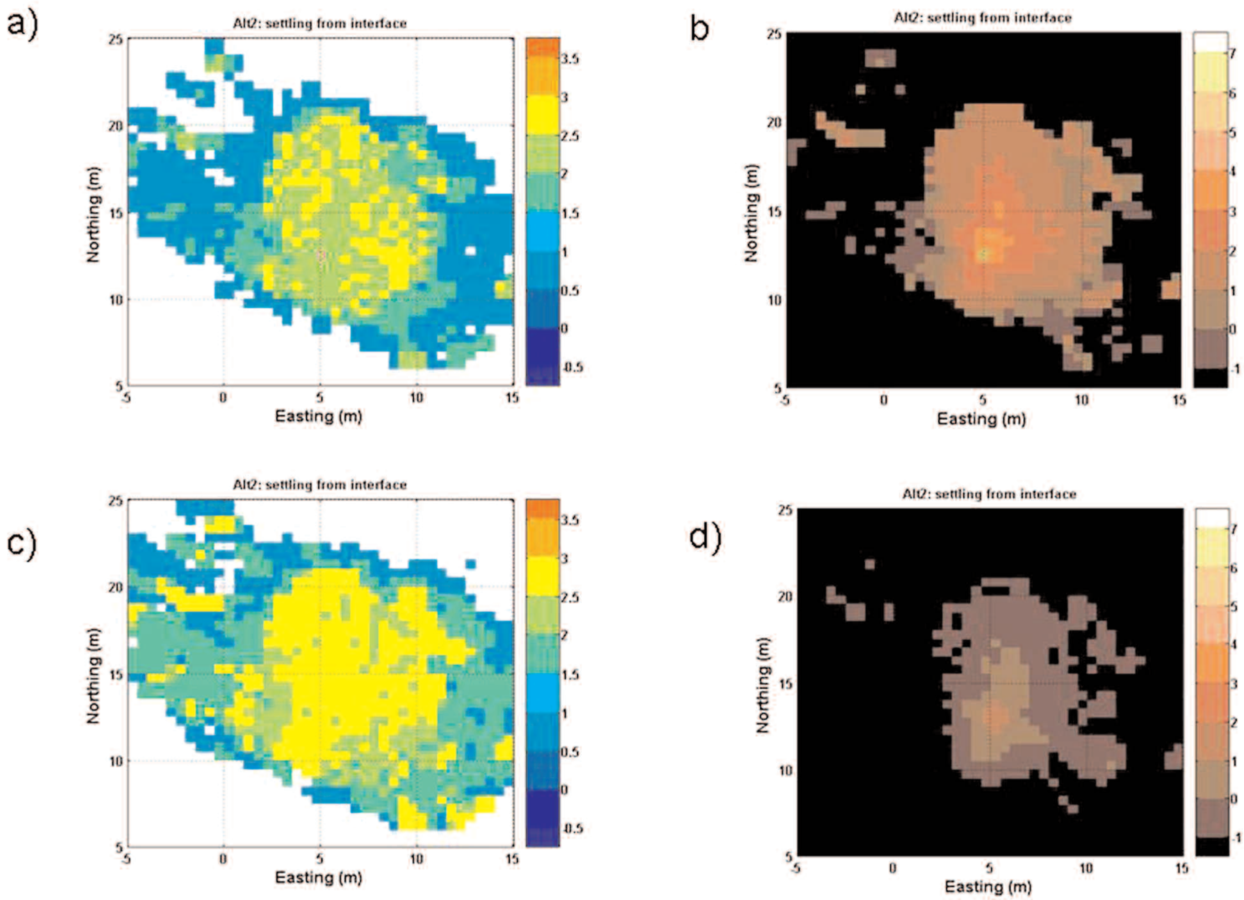

Figure 2. Results of the preliminary model of sediment deposition. Map areas are 20 m by 20 m with north towards the top. (a-b) Application of sedimentation model to mineral paricles (density 5000 kg.m^{-3}): (a) The average grain size settled. White indicates areas with no data coverage. (b) The mass flux settled. Some of the black regions are areas of no data coverage. (c-d) Application of sedimentation model to biological particles (density 1100 kg.m^{-3}): (c) The average grain size settled. White indicates areas with no data coverage. (d) The mass flux settled. Some of the black regions are areas of no data coverage.

Figure 2. Résultats du modèle préliminaire de dépôt de sédiment. Les surfaces de la carte représentent 20 m par 20 m avec le Nord en haut. (a-b) Application du modèle de sédimentation aux particules minérales (densité 5000 kg.m^{-3}): (a) Moyenne de la taille des grains sédimentés. Les surfaces non couvertes par le modèle sont représentées en blanc. (b) Le flux des masses sédimentées. Certaines parties noires sont des surfaces non couvertes par le modèle. (c-d). Application du modèle de sédimentation aux particules biologiques (densité 1100 kg.m^{-3}): (c) Moyenne de la taille des grains sédimentés. Les surfaces non couvertes par le modèle sont représentées en blanc. (d) Le flux des masses sédimentées. Certaines parties noires sont des surfaces non couvertes par le modèle.

Application of the particle settling model to biological particles is implemented simply by decreasing the density of the particles to 1100 kg.m^{-3} (Fig. 2c-d). Overall, less mass is settled consistent with the expectation that small particles of near neutral buoyancy are easily transported vertically out of the volume under consideration. A comparison of Figure 2a-b (mineral particles) and Figure 2c-d (biological particles) suggests that as the particle density decreases, the mass flux will decrease. Also, at a given distance from the vent, the average particle size settled increases with decreasing particle density.

Discussion

At present, limitations in the processing of the acoustic data constrain the interpretations of the settling mass flux in real units; this should not affect the average grain size settled or the overall map patterns. Future experiments will be designed to better constrain the mass concentration of particles in real units. Future improvements will also include attempts to obtain a more detailed description of the mineral particle size distributions in the relevant plumes and information on the likely size distributions of the

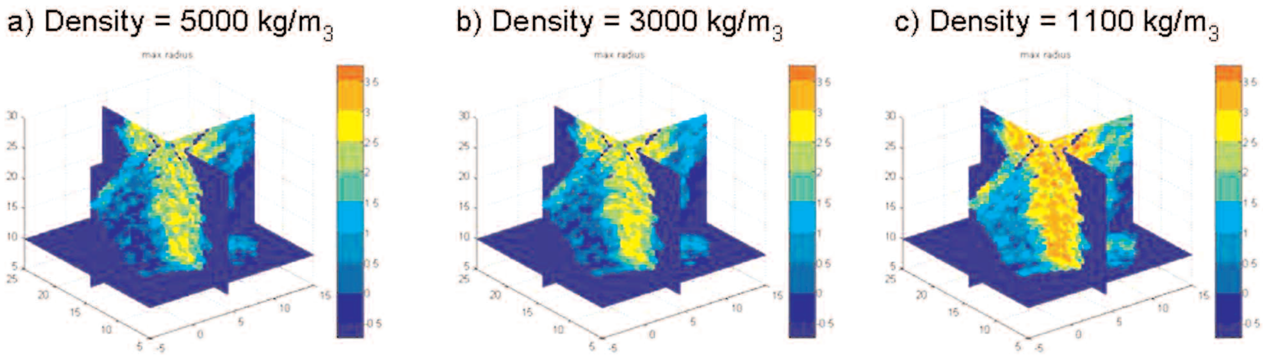

Figure 3. Contours of the maximum size particle that can be supported by the plume at a given location (based on the observed vertical velocity at that location) are shown for three different particle densities. As the density decreases, the particle size that can potentially be transported increases.

Figure 3. Les contours de la taille maximale des particules qui peut être portée par la «plume» à un endroit donné (basé sur la vitesse verticale observée à cet endroit) sont montrés pour trois différentes densités de particules. Quand la densité décline, la taille des particules qui peuvent être potentiellement transportées augmente.

biological particles (which has so far been assumed the same). The sediment map results presented here cover a limited spatial range (~10 m from vent). This is a limitation of the acoustic data not the model; future experiments will be designed to maximize the spatial extent although the acoustic technique has some inherent limitations due to attenuation and the current version of the model is most applicable to the buoyant stem which has a limited spatial extent when vertical.

The sedimentation model implicitly assumes that turbulent plume processes keep the time-averaged particle concentration within the plume and at its edge constant. This is probably reasonable but needs verification with a time series of data. Care is also needed not to settle the particles faster than their supply rate; the current algorithm does not adequately address the constraints of the supply rate. This is tricky to calculate as the supply rate is unknown (our observations give us only velocity and concentration), but will be incorporated into future versions of the model. At present, the sedimentation model is strictly exponential settling. However, other mechanisms have been proposed (Hoyal et al., 1999); further study is needed to determine if these have any significant effect in deep sea plumes.

The model presented represents a first and preliminary attempt to use newly available acoustic data on the particle concentration distributions and velocities in seafloor hydrothermal plumes to predict sedimentation on the seafloor and transport of particles to the upper plume. Our model did resolve the major processes such as that the bending of the plume in local currents shifts the locus of sedimentation away from the vent, especially for smaller particle sizes and that larger biological (lower density) particles can be transported so that the average grain size settled is lower and the overall mass flux lower compared to mineral (higher density) particles. Although several areas for improvement have been discussed, we have established that quantitative predictions of sedimentation can be made successfully.

References

Bonadonna C., Ernst G.G.J. & Sparks R.S.J. 1998. Thickness variations and volume estimates of tephra fall deposits: the importance of particle Reynolds number. *Journal of Volcanology and Geothermal Research*, **81**:173-187.

Bursik M.I., Sparks R.S.J., Gilbert J. & Carey S.N. 1992. Sedimentation of tephra by volcanic plumes: I. Theory and its comparison with a study of the Fogo A plinian deposit, Sao Miguel (Azores). *Bulletin of Volcanology*, **54**: 329-344.

Ernst G.G.J., Sparks R.S.J., Carey S.N. & Bursik M.I. 1996. Sedimentation from turbulent plumes. *Journal of Geophysical Research*, **101**: 5575-5589.

Feely R. A., Lewison M., Massoth G.J., Robert-Baldo G., Lavelle J.W., Byrne R.H., Von Damm K.L. & Curl Jr. H.C. 1987. Composition and dissolution of black smoker particulates from active vents on the Juan de Fuca Ridge. *Journal of Geophysical Research*, **92** (B11): 11347-11363.

German C.R., Colley S., Palmer M.R., Khripounoff A. & Klinkhammer G.P. 2002. Hydrothermal plume-particle fluxes at 13°N on the East Pacific Rise. *Deep Sea Research I*, **49**: 1921-1940.

Hazen A. 1904. On sedimentation. *Transactions of the American Society of Civil Engineers*. **53**: 45-88.

Hoyal D.C.J.D., Bursik M.I. & Atkinson J.F. 1999. The influence of diffusive convection on sedimentation from buoyant plumes. *Marine Geology,* **159**: 205-220.

Hrischeva E. & Scott S. 2005. Geochemical and morphological characteristics of metalliferous deposits at the Endeavour Segment, Juan de Fuca Ridge. *Eos Transactions of the American Geophysical Union,* **86**, Fall Meet. Suppl., Abstract T31A-0482.

Jackson D.R., Jones C.D., Rona P.A. & Bemis K.G. 2003. A method for Doppler acoustic measurement of black smoker flow fields. *Geochemistry, Geophysics, Geosystems*, **4**:1095.

Lavelle J. 1997. Buoyancy-driven plumes in rotating, stratified cross-flows: plume dependence on rotation, turbulent mixing, and cross-flow strength. *Journal of Geophysical Research*, **102**: 3405-3420.

Martin D. & Nokes R. 1988. Crystal settling in a vigorously convecting magma chamber. *Nature*, **332**: 534-536.

Morton B.R., Taylor G.I. & Turner J.S. 1956. Turbulent gravitational convection from maintained and instantaneous sources. *Proceedings of the Royal Society of London*, A, **234**: 1-23.

Rona P.A., Jackson D.R., Bemis K.G., Jones C.D., Mitsuzawa K., Palmer D.R. & Silver D. 2002. Acoustics advances study of sea floor hydrothermal flow. *Eos Transactions of the American Geophysical Union*, **83**: 497.

Sparks R.S.J., Carey S.N. & Sigurdsson H. 1991. Sedimentation from gravity currents generated by turbulent plumes. *Sedimentology*, **38**: 839-856.

Veitch G. & Woods A.W. 2002. Particle recycling in volcanic plumes. *Bulletin of Volcanology,* **64**: 31-39.

Walker S. & Baker E. 1988. Particle-size distributions within hydrothermal plumes over the Juan de Fuca Ridge. *Marine Geology*, **78**: 217-226.