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# The remarkable longevity of submarine plumes: Implications for the hydrothermal input of iron to the deep-ocean

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A B S T R A C T

The longevity of submarine plumes generated at sea-floor hydrothermal systems constrains the hydrothermal input of chemical species into the deep-ocean. Decades of observations of episodic "event plumes" suggest that a key process governing the dynamics of an hydrothermal cloud spreading out laterally from a buoyant rising plume is the production of internal layering. Here, we use analog experiments on turbulent, hot particle-laden plumes and clouds to show that this layering occurs where particle diffusive convection driven by the differential diffusion of heat and small mineral precipitates gives rise to a large scale double diffusive instability. Where hydrothermal clouds are enriched in fine minerals, this "particle diffusive convection" can extend the longevity of an event plume to 2 yr after its emplacement. The very long residence time imposed by diffusive convective effects enables complete dissolution of fine sulfide and sulfate minerals. We develop a new theoretical model that includes both sedimentation and dissolution processes to quantify the potential amount of iron produced by the dissolution of iron-sulfide minerals settling through the cloud by diffusive convection. A key prediction is that the concentration of dissolved iron in hydrothermal clouds can reach up to $19 \pm 3$ nM, which represents about 5% of the global hydrothermal discharge. If these results are representative of all hydrothermal vent fields, hydrothermal systems could provide 75% of the global budget of dissolved iron in the deep-ocean. Regionally, this flux is expected to scale in magnitude with mid-ocean ridge heat flow, consistent with observations and global ocean models.



## 1. Introduction

Sea-floor hydrothermal activity at mid-ocean ridges significantly influences the Earth's global energy budget (Elderfield and Schultz, 1996) as well as the trace metal concentration in the oceans (Bruland and Lohan, 2004; German and Von Damm, 2004; Jenkins, 2004; Ramondenc et al., 2006). Among the variety of manifestations of this process, high-temperature turbulent plumes erupting from black smoker chimneys are important conduits for the transport and dispersion of particulate material within the deep-ocean. These complex multiphase flows propel micron-sized metal-rich sulfides, sulfates and oxyhydroxides (Feely et al., 1987) to several tens to hundreds of meters above the sea floor (Speer and Rona, 1989), where they persist and dissolve to varying degrees. The turbulent entrainment and mixing of ocean water into these plumes can enhance precipitation of dissolved chemical species such as iron and manganese (German et al., 1991). Real-time observations suggest that most of these suspended mineral grains are carried upward to the neutral buoyant depth for the particle–fluid mixture where the flow spreads out laterally. This material is, in turn, advected potentially to great distances from the source before either settling to the sea floor or dissolving into the water column (Feely et al., 1992; Elderfield and Schultz, 1996; Langmuir et al., 1997; German and Von Damm, 2004). Because the residence times of entrained minerals can be very long, understanding the dynamics of sedimentation and dissolution is a central issue to constrain the delivery and distribution of chemical species within the deep-oceans.

Hydrothermal plumes are characterized by at least two styles of emission: "chronic" discharges from sustained seawater–oceanic crust interaction (Massoth et al., 1998), and episodic "event" plume (or megaplume) discharges (Baker et al., 1987, 1989), the origin of which is contentious (e.g., Baker et al., 2011). Event plumes are commonly large axisymmetric structures such as EP86 (Baker et al., 1987) and EP87A (Baker et al., 1989). The recent discovery of event plumes associated with a 2008 eruption (EP08A-H) on the Northeast Lau Spreading Center (NELSC) reveals that megaplumes can also be characterized by a thin-layered structure (Baker et al., 2011). Although layering is particularly pronounced in EP08A-H,

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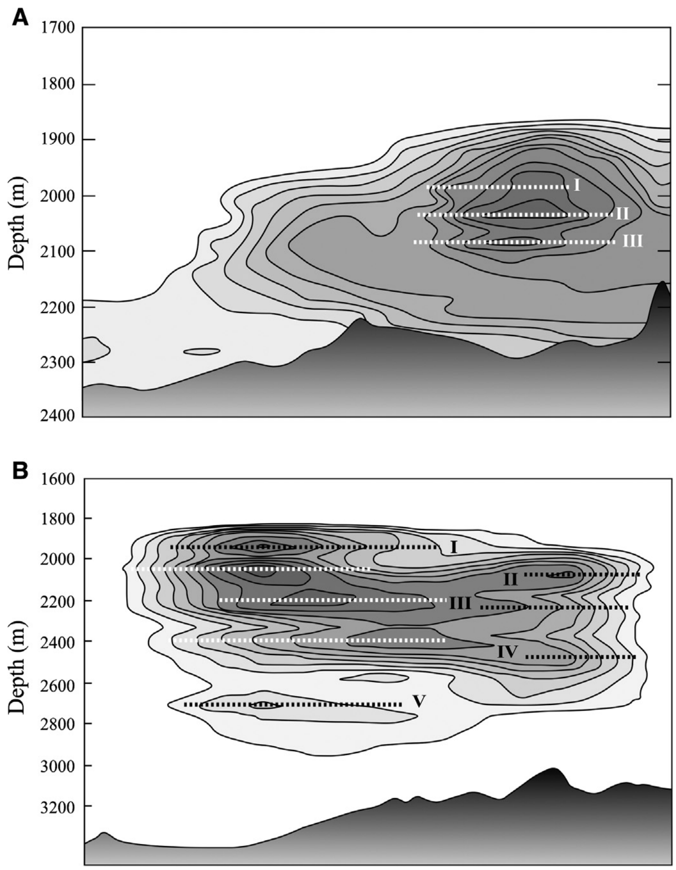


**Fig. 1.** Layering observed in event plumes as defined by temperature anomalies: (A) EP89 (modified from Coale et al., 1991); (B) EP96A (modified from Kelley et al., 1998). Contour interval is 0.01 °C for both events. Dotted lines highlight the different layers detected (I to V).

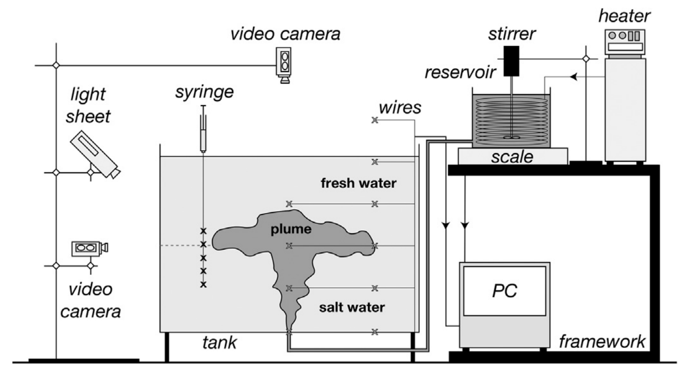


**Fig. 2.** Experimental setup showing arrangements in the tank of temperature wires (crosses) and sampling syringes for salinity measurements. Thermocouples are located at 0 cm, 10 cm, 20 cm and 30 cm above the source, and at 0 cm, 10 cm, 20 cm, 30 cm and 40 cm above the tank floor (20 cm away from the source). An additional thermocouple records the room temperature. Sampling syringes are located at 11 cm, 13 cm, 15 cm, 17 cm, and 19 cm above the tank floor (20 cm away from the source). The nozzle is a straight pipe with a 6.35 mm diameter.

this enigmatic structure has been observed in a number of past event plumes. Striking examples include EP89 at South Juan de Fuca Ridge (Fig. 1A), EP93A and EP93B at North Juan de Fuca Ridge (Baker et al., 1995), EP96A at Gorda Ridge (Fig. 1B), EP01 at Gakkel Ridge (Edmonds et al., 2003), EP03 at Carlsberg Ridge (Murton et al., 2006), and EP08A-H at NELSC (Baker et al., 2011).

The origin of layering and its influence on the dynamics of particle suspension and sedimentation are poorly understood. Previous explanations for layering invoke pulsed eruption activity (Baker et al., 2011). However, this picture is merely intuitive and the regularity of the layer thicknesses in Figs. 1A and 1B would require unrealistically periodic time-dependent variations in the discharge rate at the vent. An alternative mechanism is the process known as “particle diffusive convection”, which leads to periodic layering by definition (Green, 1987; Huppert et al., 1991; Hoyal et al., 1999; Carazzo and Jellinek, 2013). Particle diffusive convection is a class of multicomponent convection (Turner, 1985) driven as a result of the differential diffusion of heat and very fine particles in particle-laden suspensions (Burns and Meiburg, 2012; Yu et al., 2013). This phenomenon is recognized to be important in hydrothermal clouds where concentrations of dissolved salts and precipitates are high and initial temperature gradients are strong (Hoyal et al., 1999) but a detailed analysis of the effects of this process on the dynamics of submarine clouds is currently missing in the literature. Here, we extend Hoyal et al. (1999) and Carazzo and Jellinek (2013) to the context of hydrothermal clouds in order to understand the enigmatic layered structure observed in event plumes.

We present a series of new laboratory experiments simulating hot particle-laden plumes capable of forming stable neutrally buoyant clouds. Dynamic scaling laws are used to test the reliability of our experiments in simulating hydrothermal plumes. Our laboratory experiments show that the neutrally buoyant clouds resulting from the rise and spread of turbulent plumes may break-up in a series of relatively thin layers due to diffusive convective effects. We show that particle diffusive convection can arise in any hydrothermal cloud and is favored where the mixture is enriched in fine minerals. A sedimentation model validated by our laboratory experiments is used to calculate the residence time of particles in event plumes and to understand how particle sedimentation driven by diffusive convective effects preserve or alter the delivery of iron-particulates in the deep-ocean. Lastly, we discuss the implications of these results on the global mass balance of iron the deep-ocean.

## 2. Laboratory experiments

### 2.1. Experimental device

The laboratory experiments consist in injecting upwards a mixture of hot particle-laden water into a salt water-filled tank that is 0.8 m high and 1 m × 1 m cross-section (Fig. 2). Prior to an experiment, a well-stirred mixture of either fresh or salt water and well-sorted Custer feldspar particles ($d_p = 300$ μm, $\rho_p = 2600$ kg m$^{-3}$) is heated in a reservoir disconnected from the tank. In the meantime, the tank is filled with an aqueous NaCl solution with either a stepwise or linear density stratification. In all experiments (except #6) the tank is filled with a 0.2 m-thick basal layer of salt water and an overlying 0.4 m-thick layer of fresh water that is carefully introduced using a float with an open foam base and polystyrene perimeter in order to minimize mixing across the density interface as the stratification develops.

At the start of an experiment, we connect the reservoir containing the heated particles and water to the bottom of the tank, which results in the turbulent expulsion of the hot mixture in the tank. The mass loss in the reservoir is recorded using a scales connected to a computer in order to determine the mass discharge rate feeding the turbulent plume. Thermocouples located at different depths above the nozzle and above the tank floor record temperatures in the tank, while five syringes are used for salinity measurements (Fig. 2). An array of video cameras is used to record the experiment while a long time exposure camera records the complete evolution of the suspended particle-laden mixture.

In our experiments, the mass flow rate ($Q_0 = 2.6$–$4.1 \times 10^{-5}$ m$^3$ s$^{-1}$), the particle concentration ($C_0 = 0.01$–$0.1$ g g$^{-1}$), the mixture temperature ($T_0 = 15$–$90$ °C) and salinity ($S_0 = 0$–$20$ p.s.u.)