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Particle recycling in the TAG hydrothermal plume

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ABSTRACT

Analysis of Th isotope distributions in the TAG hydrothermal plume yields evidence for pronounced $^{234}Th/^{230}Th$ isotope fractionation. This fractionation can be attributed to a combination of four processes: (1) particle ageing; (2) differential scavenging of ^{234}Th and ^{230}Th; (3) differential focusing of ^{234}Th and ^{230}Th and (4) recycling of old particles. We present arguments for the importance of the last of these processes, particle recycling. Particles in the TAG hydrothermal plume exhibit grain sizes which fall in the range 1–10 μm. Applying the range of densities reported for amorphous iron oxyhydroxide and iron oxide mineral phases, Stokes' Law predicts that these particles should achieve terminal settling velocities ranging between 4 and 8 m d^{-1} for coarse-grained (5 μm radius) particles and 0.2–0.3 m d^{-1} for fine-grained particles (1 μm radius). These velocities have been used in a physical model of re-entrainment and recycling in neutrally buoyant plumes. Our results indicate that particle recycling and re-entrainment in hydrothermal plumes may be important over length scales of 1–10 km. The model predicts that the proportion of particles re-entrained is independent of particle size but increases with plume strength. For plumes with volumetric fluxes greater than 10^3 m^3 s^{-1}, the proportion of particles re-entrained exceeds 50%, in agreement with previous calculations based upon ^{230}Th distributions. Sampling strategies in the past have typically concentrated upon processes operating within $\leqslant$ 1 km of active vent fields and will need to be revised accordingly in the future.

1. Introduction

Dispersion of material from hydrothermal sites on the East Pacific Rise and Juan de Fuca Ridge, where plumes rise above the height of the rift valley, involves the eruption of vent fluids [1–3], entrainment of ambient seawater within the buoyant plume [4,5], precipitation of particles [5–7], dispersion of the neutrally buoyant plume by prevailing deep-ocean currents [8,9] and settling of particles to the underlying sediments [e.g., 10–12]. At the TAG hydrothermal site, situated within the mid-Atlantic ridge (MAR) rift valley at 26°08′N, similar dispersion effects prevail, except that the plume height is only ~ 300 m off-bottom [13–15], which is well below the tops of the rift valley walls [16]. As a result, particulate material from the TAG plume tends to be trapped within the rift valley and deposited locally [17–20].

German et al. [21] have argued that the TAG hydrothermal plume is also affected by an additional process to those listed above: recycling of suspended particulate material. From a study of dissolved and particulate ^{230}Th distributions they estimated that more than 50% of particulate material in the TAG plume may have been recycled. Sparks et al. [22] have presented a physical model describing how recycling in sediment-laden plumes may occur. The principal focus of this paper is to investigate the implications of that model for particle recycling in the TAG hydrothermal plume.

2. Evidence from Th isotope distributions

The sampling and analytical procedures employed for radionuclide studies at TAG have been described previously [21]. Particulate $^{234}Th/^{230}Th$ ratios (Fig. 1a) indicate pronounced fractionation between plume-height, below-plume and background samples. By contrast, dissolved and particulate $^{228}Th/^{230}Th$ activity ratios throughout the plume are near-constant and indistinguishable from open North Atlantic Ocean values (Fig. 1b).

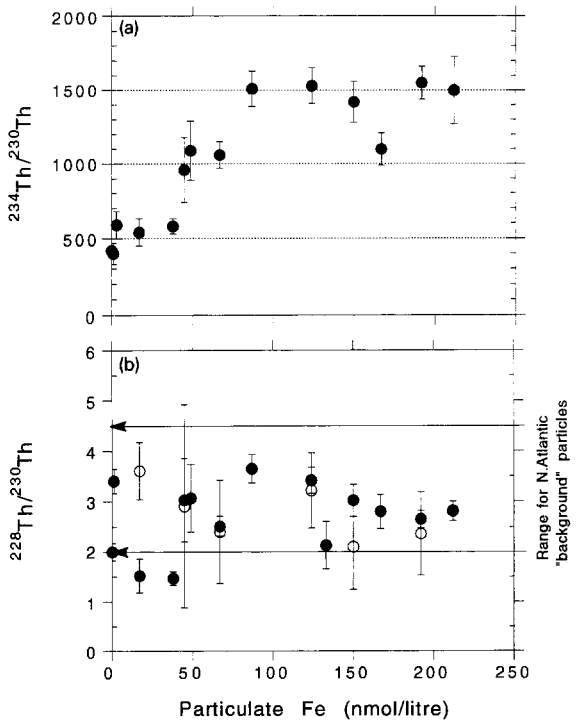

Fig. 1. (a) Plot of particulate $^{234}Th/^{230}Th$ activity ratios against particulate Fe concentrations in the TAG hydrothermal plume. (b) Plot of dissolved (circle) and particulate (dot) $^{228}Th/^{230}Th$ activity ratios against particulate Fe concentrations in the TAG hydrothermal plume. The previously reported range of values for "background" particulate material from the North Atlantic Ocean [29] is also indicated for comparison.

Since ^{234}Th, ^{230}Th and ^{228}Th are all isotopes of the same element, the variations in isotope ratios which are observed must arise due to the differences in half-life between ^{234}Th ($t_{1/2} = 24.1$ d) and ^{230}Th and ^{228}Th ($t_{1/2} = 75{,}200$ yr and $t_{1/2} = 1.91$ yr, respectively).

The simplest interpretation would be that variations in particulate $^{234}Th/^{230}Th$ ratios represent "ageing" of the particles after scavenging of dissolved Th with a characteristic seawater-like ratio ($^{234}Th/^{230}Th \sim 3000$ [23]). Average plume-height $^{234}Th/^{230}Th$ ratios close to 1500 could then be generated by a mixture of $\sim 60\%$ re-suspended background material ($^{234}Th/^{230}Th \sim 400$; Fig. 1a) with $\sim 40\%$ freshly precipitated material, whilst the difference between plume-height and below-plume ratios could be attributed to the ageing of sinking particles.

$^{234}Th/^{230}Th$ fractionation could also arise from other processes, however. First, because of its short half-life, dissolved ^{234}Th can decay substantially in seawater before it is scavenged. Consequently, open-ocean particulate $^{234}Th/^{230}Th$ ratios are typically very low (~ 500–800 [23]). In the TAG plume, scavenging effects are likely to be more pronounced, leading to particulate $^{234}Th/^{230}Th$ ratios higher than open ocean values. In the absence of dissolved ^{234}Th data, however, the full extent to which differential scavenging may affect $^{234}Th/^{230}Th$ fractionation cannot be determined. Secondly, it has been reported previously that excess Th is concentrated or "focused" into the TAG plume [21]. This may be due, in part, to horizontal transport of dissolved Th from distal waters. If we assume that this process would also be slow relative to the decay of ^{234}Th, focusing of ^{234}Th would not be as pronounced as for the longer-lived isotopes. Thus, differential focusing could also contribute to $^{234}Th/^{230}Th$ fractionation in the TAG plume.

In summary, the range in Th isotope distributions observed at TAG can be attributed to a combination of: (1) particle ageing; (2) differential scavenging of ^{234}Th and ^{230}Th; (3) differential focusing of ^{234}Th and ^{230}Th; and (4) recycling of old particles. The model presented in the following section argues that the last of these processes should certainly be important in the TAG plume. To determine the relative importance of all four processes, however, will require more detailed radionuclide studies.

3. Application of the theoretical model

Turbulent, buoyant plumes generated above hydrothermal vents rise to a level of neutral buoyancy. "Momentum overshoot" occurs, however, and a maximum height greater than the level of neutral buoyancy is initially attained [24]. Consequently, a flow of particles and fluid is generated which moves radially *outwards* between this maximum height and the level of neutral buoyancy. At the same time, the turbulent buoyant plume also entrains substantial amounts of ambient seawater during its ascent, thereby creating a surrounding flow field directed *inwards* towards the plume axis, beneath the height of the neutrally buoyant plume.

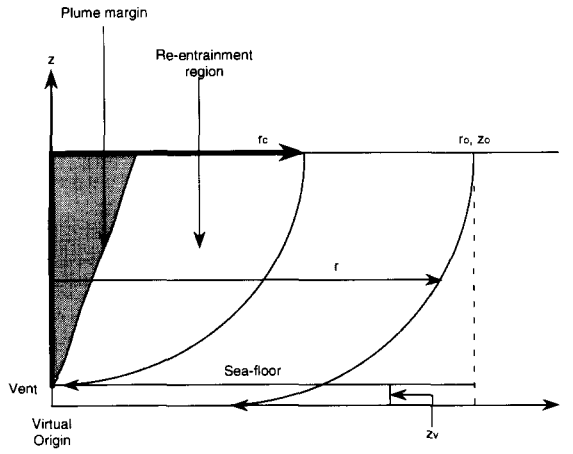

Fig. 2. Schematic diagram showing the trajectories of particles released from a gravity current at height z_0 above the virtual origin of the plume. The inward velocity field is caused by entrainment in the buoyant, turbulent plume. A particle will be re-entrained into the plume if the release distance is less than a critical value, r_c, away from the source [after 22].

As particulate material settles below the radially expanding current, it is drawn back towards the buoyant plume by the net inflow caused by entrainment (Fig. 2). An important case arises when a particle is released at a critical distance, r_c, from the plume axis and has a trajectory which just brings it back to the base of the buoyant plume, so that it is re-entrained. Particles released from the gravity current at all distances less than r_c will be re-incorporated into the plume; whilst those released at all distances greater than r_c will be sedimented to the seafloor. The critical distance, r_c, for any plume can be calculated from the equations [22]:

$$r_c^2 = 6A/5v\left(z_0^{5/3} - z_v^{5/3}\right) \quad (1)$$

$$A = 3.06\alpha^2 F_0^{1/3} \quad (2)$$

where F_0 = the buoyancy flux; α = the entrainment constant (~ 0.1 [24]); v = the terminal settling velocity of the particulate material; z_0 = the height at which neutral buoyancy is attained; and z_v = the height of the vent above the virtual source.

CTD profiles near the TAG hydrothermal mound have revealed the plume to be a broad feature comprising five main layers, centred between 3370 m and 3220 m. This layering has been attributed to the discharge from several different black-smoker chimneys at the TAG hydrothermal field [25]. Particulate samples were collected from the layer at 3340 m, 300 m off the seabed [21]. Thus, $z_0 = 300$ m and the discharging chimney represents the source of the plume: $z_v \approx 0$ m. F_0 has been calculated to have the value $1.6\text{–}2.9 \times 10^{-2}$ m^4 s^{-3} for the 3340 m layer of the TAG plume and $1.5 - 2.8 \times 10^{-1}$ m^4 s^{-3} for its entire thickness (3370–3220 m) [25].

From Stoke's Law, the terminal settling velocity, v, of a small spherical particle, radius, r, is given by:

$$v = 2gr^2\Delta\rho/9\eta \quad (3)$$

where g = gravitational acceleration (9.81 m/s^2); $\Delta\rho$ = the density difference between the particle and the fluid; and η = the dynamic viscosity.

Nelsen et al. [14] have carried out SEM/EDA analyses of particulate material from the TAG hydrothermal plume, collected on 0.4 μm Nuclepore filters. They have reported that, although individual particulate Fe oxyhydroxide phases are finely divided and colloidal (i.e. sub-micron in size), aggregation of these colloids appears to occur within the hydrothermal plume, resulting in the formation of Fe oxyhydroxide aggregates with a coarser *effective* grain size. Samples from our more recent study [21] were retained on 1 μm pore size Nuclepore filters. SEM analyses have revealed that, although fine-grained particles are again common, coarse particles up to 10 μm on the longest axis also occur [R. Mills, pers. commun., 1993]. For illustration, therefore, we have assumed effective particle grain sizes of $r = 1$ μm (for fine-grained particles) and $r = 5$ μm (for coarse-grained particles) in the calculations which follow. To calculate $\Delta\rho$, both the density of the seawater and the density of the settling particles is required. For seawater, $\rho \sim 1{,}035$ kg/m^3. Previously reported density values for goethite (FeO · OH) and for amorphous Fe oxyhydroxides ($Fe_2O_3 \cdot nH_2O$) fall in the range $\rho = 2{,}400\text{–}3{,}600$ kg/m^3 [26]. This yields a range of values between $\Delta\rho_{max} = 2565$ kg/m^3 and $\Delta\rho_{min} = 1405$ kg/m^3. Given the viscosity coefficient for water at 4°C (the approximate temperature of seawater in the TAG hydrothermal plume) is $\eta = 1.567 \times 10^{-3}$ kg/m s^{-1} [26] then particle settling velocities can be estimated.

For fine-grained (1 μm radius) particles, $\Delta\rho_{max}$ yields $v = 0.3$ m d^{-1} and $\Delta\rho_{min}$ yields $v = 0.2$ m

TABLE 1

Calculated values of the critical distance, r_c, for particle re-entrainment in the TAG hydrothermal plume

Particle radius (μm)	v (settling velocity) (m day^{-1})	r_c 3340 m layer (km)	r_c whole plume (km)
1	0.2	7.3–8.1	10.6–11.8
1	0.3	6.0–6.6	8.7– 9.6
5	4	1.6–1.8	2.4– 2.6
5	8	1.2–1.3	1.7– 1.9

d^{-1}, while for coarser (5 μm radius) particles, $\Delta\rho_{max}$ yields $v = 8$ m d^{-1} and $\Delta\rho_{min}$ yields $v = 4$ m d^{-1}. Values of r_c corresponding to these estimated settling velocities are listed in Table 1. Values of r_c have been calculated using F_0 values for both the 3340 m layer and for the full (3370–3220 m) TAG plume. For fine-grained particles ($r = 1$ μm and $v = 0.2$–0.3 m d^{-1}) these calculations indicate that any particulate material which begins to settle from the base of the neutrally buoyant plume within approximately 6–12 km of its source would be expected to be drawn inward, towards the vent field source, and re-entrained into the rising buoyant plume. Therefore, recycling of particulate material should be an important process across the entire 13 km width of the MAR rift valley. For coarser grained particles ($r = 5$ μm and $v = 4$–8 m d^{-1}), lower values of r_c, in the range 1.2–2.6 km, are obtained.

Assuming a steady state within the TAG plume system, the net export of particulate material away from the vent field (i.e., the particle concentration, C_c, remaining in suspension at plume height at distance r_c away from the source), must be matched by an equivalent production of fresh particles (C_f) at the plume axis ($C_f = C_c$). Therefore, the concentration C_c at r_c serves as a measure of the concentration of young new particles at the plume source ($r \sim 0$), whilst C_0 (at $r = 0$) is the total, steady-state concentration of new (freshly precipitated) and old (re-entrained) particles. Then, the Sparks et al. model [22] predicts that:

$$C_c/C_0 = e^{-Br_c^2} \quad (4)$$

$$B = \pi v/Q \quad (5)$$

where Q = the volumetric flow rate into the base of the radially spreading plume and v = the vertical settling velocity of the particles.

Equation (4) can be combined with eqn. (1) to show that the critical concentration is independent of particle settling velocity and size:

$$C_c/C_0 = exp\left[-\left(6\pi A z_0^{5/3}\right)/5Q\right] \quad (6)$$

The implication of eqn. (6) is that re-entrainment ($C_r/C_0 = 1 - C_c/C_0$) becomes increasingly important as plume strength increases.

Calculated values of C_c/C_0, using the buoyancy and volume fluxes reported by Rudnicki and Elderfield [25] are 69% and 23% for values of Q of 175 and 1463 m^3 s^{-1}, respectively, indicating that, at steady state, the proportion of material which is recycled (C_r/C_0) is 31–77%. Were the larger buoyancy and volume fluxes derived from the study of Speer and Rona [27] to be employed, values of C_c/C_0 would be reduced, indicating that only 57–11% of the particulate material at plume height was freshly precipitated and, thus, that 43–89% was re-entrained. Evidently, the TAG hydrothermal plume system is sufficiently powerful to support re-entrainment of more than 50% of the suspended particulate matter, in agreement with values calculated previously from Th isotope distributions [21].

Of course, the calculations presented above are only directly applicable to an enclosed environment and a steady-state plume in which radial symmetry is obtained, that is, in which there are no residual currents flushing the plume material away from its source region. In the case of the TAG plume, this need not necessarily be the case. The rift valley is bounded by steep block-faulted walls on two sides and the effect of this partly enclosed morphology should enhance re-entrainment because filling of an enclosed area by a plume leads to additional recirculation [24]. However, the rift valley is not completely enclosed but is open along-axis, allowing for flushing of the ridge segment by residual currents. Nevertheless, short-term current-meter moorings (15–17 d), deployed in the TAG hydrothermal plume during our 1988 sampling expedition, failed to resolve any strong residual currents. Instead, the data indicated the presence of weak mean currents, typically with velocities of less than 0.5 cm s^{-1}, which exhibited semi-diurnal variations [28]. In the future, long-term deployments of current moorings will be required for the TAG hydrothermal plume to address this issue satisfacto-

rily; no such deployments have been completed successfully to date. A further future requirement will be to expand the models of Sparks et al. [22] to investigate the behaviour of buoyant plumes as they rise through a fluid which *does* exhibit some residual current flow. Relevant present-day examples would be hydrothermal plumes rising above the East Pacific Rise and Juan de Fuca Ridge.

4. Conclusions

From the above, the following conclusions can be drawn:

(1) Analysis of Th isotope distributions in the TAG hydrothermal plume yields evidence for pronounced $^{234}Th/^{230}Th$ isotope fractionation, which can be attributed to a combination of four processes: (a) particle ageing; (b) differential scavenging of ^{234}Th and ^{230}Th; (c) differential focusing of ^{234}Th and ^{230}Th and (d) recycling of old particles.

(2) Particle sizes in the TAG plume typically fall in the range 1–10 μm. Stokes' Law indicates that, during settling, these Fe oxyhydroxide particles should achieve terminal settling velocities ranging between 4 and 8 m d^{-1} for the coarser (5 μm radius) particles and 0.2–0.3 m d^{-1} for the more fine-grained particles (1 μm radius).

(3) A model of sedimentation of particles from the TAG plume predicts that re-entrainment and recycling into the neutrally buoyant plume will occur for all coarse (5 μm) particles settling out of the base of the TAG plume within 1.2–2.6 km of the active vent field and for all fine-grained (1 μm) particles settling out within 6–12 km (approximately the entire width of the MAR rift valley).

(4) Re-entrainment proportions are not dependent upon particle size and increase with volume flow rate of the plume:

$$C_r/C_0 = 1 - exp\left[-\left(6\pi A z_0^{5/3}\right)/5Q\right]$$

Re-entrainment becomes comparable to values estimated from ^{230}Th distributions for plumes with flow rates greater than 10^3 m^3 s^{-1}.

(5) These results indicate that particle recycling and re-entrainment in the TAG plume occurs over a length scale of 1–10 km. By contrast, sampling strategies have typically concentrated upon processes operating within $\leqslant 1$ km of the active vent field in the past. Those strategies will need to be revised accordingly in the future.

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