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An improved quantitative measure of the tendency for volcanic ash plumes to form in water: implications for the deposition of marine ash beds

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ABSTRACT

Laboratory experiments and numerical simulations have shown that volcanic ash particles immersed in water can either settle slowly and individually, or rapidly and collectively as particle-laden plumes. The ratio of timescales for individual and collective settling, in the form of analytical expressions, provides a dimensionless quantitative measure of the tendency for such plumes to grow and persist which has important implications for determining particle residence times and deposition rates. However, existing measures in the literature assume that collective settling obeys Stokes' law and is therefore controlled by the balance between gravitational forces and viscous drag, despite plume development actually being controlled by the balance between gravitational forces and inertial drag even in the absence of turbulence during early times. This paper presents a new measure for plume onset which takes into account the inertial drag-controlled (rather than viscous drag-controlled) nature of plume growth and descent. A parameter study comprising a set of numerical simulations of small-scale volcanic ash particle settling experiments highlights the effectiveness of the new measure and, by comparison with an existing measure in the literature, also demonstrates that the timescale of collective settling is grossly under-estimated when assuming that plume development is slowed by viscous drag. Furthermore, the formulation of the new measure means that the tendency for plumes to form can be estimated from the thickness and concentration of the final deposit; the magnitude and duration of particle flux across the water's surface do not need to be known. The measure therefore permits the residence times of particles in a large body of water to be more accurately and practically determined, and allows the improved interpretation of layers of volcaniclastic material deposited at the seabed.

1. Introduction

Explosive volcanism generates vast quantities of small ash particles which can be transported over great distances, eventually depositing both on land and on the seabed to form particle layers (Carey and Schneider, 2011). These layers are a textbook example of isochroneity and have been used for stratigraphic correlation of past eruption events (e.g. Ver Straeten (2004, 2008)), allowing a wealth of information regarding their duration and frequency to be determined. Furthermore, ash deposits can potentially preserve information about the environmental conditions at the time of an event (Manville and Wilson, 2004). However, the process behind the settling of ash and the resulting formation of the particle layers is far from simple.

It was once assumed that the settling of ash in the deep sea occurred passively such that particles always descend slowly and individually under Stokes' law (Ledbetter and Sparks, 1979; Carey and Schneider, 2011), but several field-based observations have provided contradictory evidence. For example, following the 1991 eruption of Mount Pinatubo, ash fallout in the South China Sea settled at speeds of over 2 cms^{-1} which is two to three orders of magnitude greater than the calculated Stokes' law velocities of individual particles (Wiesner et al., 1995). Through analogous laboratory experiments, Carey (1997) set out to explore this apparent contradiction in timescales and revealed the important role of vertical density currents in the rapid, collective transportation of material to the seabed.

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The generation of vertical density currents is a complex multiphase process. Particles entering a body of water, either as fallout from ash clouds in the atmosphere or from a pyroclastic density current, undergo abrupt deceleration as they cross the air–water interface. Initially, slow and individual settling under Stokes' law ensues, allowing the particle concentration near the surface to rapidly increase and form a layer of particle-rich water over time. However, if the particle concentration in the layer is large enough for the particles to affect each other's settling through drag reduction and drifting such that the layer becomes gravitationally unstable, then finger-like Rayleigh–Taylor instabilities eventually form along the interface between the layer and the particle-free water below it. These instabilities grow exponentially to form plumes — clouds of particles that settle rapidly and collectively as vertical density currents.

Knowing whether plumes are likely to form, if at all, is important if one wishes to better determine the timescale of settling from the surface to the seabed. This can reveal information about the residence time of particles in the water and therefore the extent to which ambient ocean currents redistribute volcaniclastic material as it settles (Carey and Schneider, 2011). Similarly, knowing the rate of deposition can help determine the degree of bioturbation of the growing particle layer by marine organisms (Bramlette and Bradley, 1941). Plume formation also has implications for fossil preservation and stratigraphy. Rapid sedimentation has long been recognised as a means of increasing the likelihood that an organism could be preserved as a fossil (Seilacher et al., 1985) and so ash plume formation can impact upon the completeness of the fossil record. Perhaps one of the most celebrated and geologically significant examples of exceptional preservation beneath a marine ash deposit is that of the Neoproterozoic Ediacaran biota in Newfoundland which preserves some of the earliest metazoan fossils on Earth (Narbonne, 2005).

1.1. Theoretical considerations

Quantitatively describing the tendency for plumes of particles to form in an ambient fluid has been achieved in previous works (Marsh, 1988; Goldin, 2008; Carazzo and Jellinek, 2012) through a dimensionless number B. This is defined in such a way that values of B less than or equal to unity imply that plumes do not form, whereas a value greater than unity implies favourable conditions for plume growth and persistence. In particular, existing dimensionless numbers have been defined by the ratio of timescales for individual particle settling under Stokes' law and collective settling as a gravitationally unstable plume, such that

$$B = \frac{\tau_{\text{individual}}}{\tau_{\text{collective}}}. \quad (1)$$

That is, given information about the current state of Rayleigh–Taylor instabilities, the time required for particles to reach that state through individual and collective settling modes can be approximated using analytical expressions. Clearly a value of $B \gg 1$ implies favourable conditions for plume formation and persistence since collective settling happens over a shorter timescale (e.g. days or weeks in the ocean) than individual settling (e.g. months), whereas a value of $B \approx 1$ implies that plumes cannot form since the timescales of individual and collective settling are of the same order of magnitude. Note that a value of $B < 1$ also implies that plumes cannot form, but when B is defined by the ratio of timescales this value has no physical meaning except for the case of hindered settling (Kuenen, 1968) which is not considered here. The parameters needed to compute these expressions include the particle concentration and the thickness of the particle-rich layer which often have to be estimated in practice. Alternatively, the measure can be re-formulated in terms of a critical layer thickness that must be attained in order for pluming to take place (discussed later). This only requires knowledge of the mass influx across the water's surface and particle diameter which is often readily available during or after an eruption event.

One such formulation of B is the one derived by Marsh (1988) for the study of crystal settling in magma, denoted by B_{vv} in this paper. This formulation is based on the assumption that both individual particles and plumes obey Stokes' law and are therefore controlled by the balance between gravitational forces (weight and buoyancy) and the viscous drag force (i.e. the drag arising from the friction between the descending particles/plumes and the ambient fluid), hence the use of the subscript vv to denote 'viscous–viscous'. The time taken for an individual (spherical) particle to settle through a layer of thickness h is therefore given by

$$\tau_{\text{individual}} = \frac{18h\mu_f}{\left(\rho_p - \rho_f\right)gd_p^2}, \quad (2)$$

where d_p is the particle diameter, g is the acceleration due to gravity, μ_f is the viscosity of the fluid phase, and ρ_f and ρ_p are the density of the fluid and particle phase, respectively (Stokes, 1851). The assumption that all particles have a perfect spherical shape is implicitly built-in to the timescale above through the Stokes drag coefficient. Furthermore, it has been shown (see for example Whitehead and Luther (1975); Goldin (2008)) that the timescale of collective settling is given by:

$$\tau_{\text{collective}} = \frac{18\mu_f}{\alpha_p\left(\rho_p - \rho_f\right)gh}, \quad (3)$$

where α_p is the volume fraction of particles in the layer. Taking the ratio of these two timescales yields the dimensionless number B_{vv}:

$$B_{vv} = \frac{\alpha_p h^2}{d_p^2}. \quad (4)$$

Further work by Carazzo and Jellinek (2012) derived similar non-dimensional numbers for the scenario of volcanic ash settling through the atmosphere. Coarse-grained ash and lapilli can settle individually with a particle Reynolds number several orders of magnitude greater than that of fine ash (Bonadonna et al., 1998), so three forms of B were derived using different expressions for $\tau_{\text{individual}}$ to cover a wide range of individual particle settling regimes. However, none of these measures address the fact that plume growth and descent are controlled by the balance between gravitational forces and the inertial drag force (Bergantz and Ni, 1999; Dalziel et al., 2008). This inertial drag force arises from the need for the plumes to accelerate and displace the surrounding fluid, even in the absence of fluid viscosity, and dominates the viscous drag force as shown by plume Reynolds numbers[1] much greater than unity (Jacobs et al., 2013). At this point Stokes' law no longer holds even if no turbulent effects are observed until the plumes are fully developed and begin to mix, which has a significant impact on entrainment and settling rates (Manville and Wilson, 2004). A measure which assumes that collective particle settling is slowed by inertial drag (rather than viscous drag) may therefore be more appropriate.

This paper presents a new measure of the tendency for particles to form plumes and settle collectively which accounts for the fact that collective particle settling is slowed by inertial drag. The new non-dimensional number, denoted by B_{vi}, is derived by applying Stokes' law and a well-founded expression for the growth rate of Rayleigh–Taylor instabilities (Youngs, 1984). The validity of the measure for predicting the formation of plumes as particles settle in water is then evaluated and compared against B_{vv}. This is accomplished by (a) using

[1] The Reynolds number is a dimensionless quantity defined as the ratio of inertial to viscous drag force.