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Experimental study of turbulence, sedimentation, and coignimbrite mass partitioning in dilute pyroclastic density currents

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ABSTRACT

Laboratory density currents comprising warm talc powder turbulently suspended in air simulate many aspects of dilute pyroclastic density currents (PDCs) and demonstrate links between bulk current behavior, sedimentation, and turbulent structures. The densimetric and thermal Richardson, Froude, Stokes, and settling numbers match those of natural PDCs as does the ratio of thermal to kinetic energy density. The experimental currents have lower bulk Reynolds numbers than natural PDCs, but the experiments are fully turbulent. Consequently, the experiments are dynamically similar to the dilute portions of some natural currents. In general, currents traverse the floor of the experimental tank, sedimenting particles and turbulently entraining, heating, and thermally expanding air until all particle sediments or the currents become buoyant and lift off to form coignimbrite plumes. When plumes form, currents often undergo local flow reversals. Current runout distance and liftoff position decrease with increasing densimetric Richardson number and thermal energy density. As those parameters increase, total sedimentation decreases such that >50% of initial current mass commonly fractionates into the plumes, in agreement with some observations of recent volcanic eruptions. Sedimentation profiles are best described by an entraining sedimentation model rather than the exponential fit resulting from non-entraining box models. Time series analysis shows that sedimentation is not a constant rate process in the experiments, but rather occurs as series of sedimentation–erosion couplets that propagate across the tank floor tracking current motion and behavior. During buoyant liftoff, sedimentation beneath the rising plumes often becomes less organized. Auto-correlation analysis of time series of particle concentration is used to characterize the turbulent structures of the currents and indicates that currents quickly partition into a slow-moving upper portion and faster, more concentrated, lower portion. Air entrainment occurs within the upper region. Turbulent structures within the lower region track sedimentation–erosion waves and indicate that eddies control deposition. Importantly, both eddies and sedimentation waves track reversals in flow direction that occur following buoyant liftoff. Further, these results suggest that individual laminations within PDC deposits may record passage of single eddies, thus the duration of individual PDCs may be estimated as the product of the number of laminations and the current's turbulent timescale.

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1. Introduction

Pyroclastic density currents (PDCs) rapidly transport and deposit volcanic material over large areas, and the buoyant coignimbrite plumes generated by currents can inject tephra into the stratosphere, dispersing ash and aerosols over 1000 s of kilometers (Wilson, 2008). Because PDCs are 100 s of meters thick, travel at speeds generally >30 m/s, and are composed of hot (often >500 °C) particles turbulently suspended in air, they present substantial proximal hazards to people and structures (Bursik et al., 1998; Druitt et al., 2002; Macias et al., 2008; Dellino et al., 2010), and coignimbrite plumes formed by the liftoff of PDCs pose distal hazards to aviation (e.g. Woods and Kienle, 1994; Calder et al., 1997). Understanding the behavior of PDCs is thus critical to interpreting ancient eruptions and predicting and mitigating future hazards. Unfortunately, direct observational records do not exist for prehistoric eruptions or are fragmentary for many historic eruptions, and the interiors of PDCs are impossible to directly observe because of their size, velocity and temperature.

Deposits provide insights into PDCs not otherwise available. Analyses of deposit grain size distributions and componentry provide a direct record of at least some portion of the particles transported by currents and changes in the composition of deposits can be used to infer spatial or temporal changes in current behavior and the ability, or lack thereof, of the current to transport particles (Cole, 1991; Branney and Kokelaar, 1997; Sparks et al., 1997; Bryan et al., 1998; Calder et al., 2000; Branney and Kokelaar, 2002; Brown and Branney, 2004; Browne and Gardner, 2005; Vasquez, and Ort, 2006; Dufek and Bergantz, 2007). Structures within the deposits, such as bedding, grading, or cross-stratification, reflect properties of the transporting current, such as its duration or steadiness (Cole, 1991; Branney and Kokelaar,

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1997; Sparks et al., 1997; Bryan et al., 1998; Calder et al., 2000; Branney and Kokelaar, 2002; Brown and Branney, 2004; Houghton et al., 2004; Vasquez and Ort, 2006). Two substantial problems, however, often arise when inferring current behavior from deposits. First, coupling between the transport and depositional systems within a PDC is poorly understood, thus interpretation of sedimentary structures and the relationship between deposits and currents is controversial (Branney and Kokelaar, 2002; Brown and Branney, 2004). Second, not all particles that initially contribute to PDCs are deposited within "PDC deposits." Indeed large fractions of particles are elutriated into buoyant coignimbrite plumes whose deposits are often areally extensive but very thin and easily eroded, resulting in large uncertainties in the initial properties of currents and the volumes and extent of PDC and coignimbrite deposits (Sigurdsson and Carey, 1989; Fierstein and Nathenson, 1992; Calder et al., 1997; Branney and Kokelaar, 2002).

Scaled laboratory experiments provide a means of analyzing both the transport of PDCs as well as some aspects of the resulting deposits. In particular, time-series analysis of the currents and deposits can identify relationships between flow behavior, turbulent structures, and deposition. Coignimbrite mass can be calculated from the difference between the initial current mass and that of the deposit. Because many aspects of PDC behavior depend upon the entrainment and thermal expansion of a compressible fluid (e.g. Woods and Kienle, 1994; Bursik and Woods, 1996; Freundt, 2003; Dufek and Bergantz, 2007; Doronzo, et al., 2010), our experiments are conducted using warm particles turbulently suspended in air. We will show that the bulk, turbulent, and thermal properties of the currents and sediment are properly scaled, thus these laboratory experiments are dynamically similar to dilute natural PDCs.

2. Background

PDCs are mixtures of hot particles transported through a combination of turbulent, tractional, and granular processes. As these mixtures are more dense than the atmosphere, they flow as density currents. The generally accepted model of PDCs is that these currents are often stratified into two regions: a lower, denser region, and an upper, more dilute region (Branney and Kokelaar, 2002; Gardner et al., 2007). The terms *pyroclastic flow* and *pyroclastic surge* are often used for dense and dilute end-members of current behavior. It should be noted, however, that a continuum should exist in PDC density and stratification (Burgisser et al., 2005), thus in this paper we will refer to dense and dilute PDCs. Although a dense undercurrent often underlies the dilute region, dilute lobes have been observed to propagate ahead of the denser undercurrent; such lobes are then overridden by the main current (Fujii and Nakada, 1999). In general, the dense portions of PDCs are often confined to valleys and topographic lows whereas the dilute overcurrents can overtop substantial topographic barriers (Fisher et al., 1993; Gardner et al., 2007; Andrews and Manga, 2011). Although this difference in flow behavior can separate the dense and dilute portions of a PDC, flows can evolve surges and surges can generate flows, thus deposits from "dense" currents can be found on the lee side of topographic barriers that blocked the PDC undercurrent but were surmounted by the dilute overcurrent (Bursik et al., 1998; Bursik and Woods, 2000; Druitt et al., 2002; Gardner et al., 2007).

There is now general acceptance that deposits form aggradationally, rather than en masse (Dade and Huppert, 1996; Branney and Kokelaar, 1997; Calder et al., 2000; Branney and Kokelaar, 2002), even in dense flows (e.g., Lube et al., 2004; Girolami et al., 2010). Consequently, both massive "flow" deposits and stratified "surge" deposits are deposited in a grain-by-grain fashion. Numerous questions and controversies remain, however, regarding the nature and timescales of deposition and their relation to transport. Stratigraphic complexity of proximal PDC deposits suggests a complex variation in transport and depositional behavior over lateral scales of <100 m (Cole, 1991; Bryan et al., 1998; Calder et al., 2000; Houghton et al., 2004; Vasquez and Ort, 2006). Erosional contacts between PDC depositional units record erosion of early deposits by later currents, but the extent and duration of erosion and duration of deposition remain poorly constrained (Sparks et al., 1997; Calder et al., 2000). Cross-stratified deposits are thought to reflect turbulent deposition (Branney and Kokelaar, 2002), but it is not known which turbulent structures control deposition (e.g. the largest eddies that may span the thickness of the current or smaller structures nearer the substrate).

Coignimbrite plumes are generated by PDCs when at least some portion of the current becomes less dense than the ambient atmosphere (Woods and Kienle, 1994; Bursik and Woods, 1996; Calder et al., 1997). The density of PDCs evolves during transport through sedimentation and entrainment of particles, and the turbulent entrainment and thermal expansion of air (e.g. Bursik and Woods, 1996; Dufek and Bergantz, 2007). Because dilute overcurrents have lower densities and entrain more air than dense undercurrents, dilute regions of currents are more likely to undergo buoyancy reversal and generate coignimbrite plumes.

The fraction of tephra that enters coignimbrite plumes, and is therefore not in PDC deposits, can be quite large, complicating interpretation of PDC transport processes from analysis of PDC deposits. Mass partitioning into coignimbrite plumes of >50% is estimated for eruptions ranging in size from the 1991 Redoubt eruption (Woods and Kienle, 1994), to the B3 phase of the May 18th 1980 Mount St. Helens eruption (Carey et al., 1990), to century-scale caldera-forming eruption (e.g. Ksudach KS1; Andrews et al., 2007). In very large eruptions, partitioning is expected to be as large, but the extent and preservation of the flow deposits make accurate volume estimates difficult (Sigurdsson and Carey, 1989; Fierstein and Nathenson, 1992).

3. Methods

Experiments were conducted in a $6.5 \times 1.8 \times 0.6$ m acrylic tank (Fig. 1), using heated 22 ± 6 μm talc powder to generate dilute particle laden gravity currents in air. Talc particles were chosen for the experiments as they were available in a narrow size range, have a known density and heat capacity ($2400\ \mathrm{kg\ m^{-1}}$ and $15.56\ \mathrm{J\ °C^{-1}}$, respectively), and do not damage the acrylic tank. Measured masses of powder, m_o, were heated up to 80 °C above ambient temperature within an oven controlled by a proportional–integral-derivative controller (PID) and PT-100 thermistor probe. Once the powder thermally equilibrated, it was evenly loaded over a specified belt length, L, of a conveyor and the temperature of the powder, T_o, was measured with a second PT-100 probe. The conveyor was then run at a known speed, v_b, to introduce the powder into the tank at a controlled rate, M_o:

$$M_o = \frac{m_o v_b}{L}. \quad (1)$$

Following each experiment, the mass of the powder that remained within the chute, m_d, was measured and the mass of powder within the current, m_c, was calculated as the difference between m_o and m_d. Ranges in experimental parameters are compiled in Table 1; parameters for all experiments are listed in Supplementary material 1.

Temperatures within the tank and the chute were measured before and after each experiment with PT-100 probes mounted ~30 cm from the inlet at heights of 5, 20.5, 35.5, 80, 124.5, and 169 cm above the tank floor and within the chute. Humidity within the tank was measured before and after each run with Extech hygrometer probes mounted at heights of 20.5 and 124.5 cm.

Experiments were illuminated from below using an array of eight 250-W halogen lamps evenly spaced at 60 cm intervals 48 cm below the centerline of the tank; the light from the array was directed through a 1.5 cm wide slit to generate a light sheet illuminating a vertical plane imaged by the cameras. The lighting array was turned on immediately before each experiment, and thus heating of the tank by the lights is considered insignificant.