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Inside pyroclastic density currents – uncovering the enigmatic flow structure and transport behaviour in large-scale experiments

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ABSTRACT

Pyroclastic density currents (PDCs) are the most lethal threat from volcanoes. While there are two main types of PDCs (fully turbulent, fully dilute pyroclastic surges and more concentrated pyroclastic flows encompassing non-turbulent to turbulent transport) pyroclastic flows, which are the subject of the present study, are far more complex than dilute pyroclastic surges and remain the least understood type despite their far greater hazard, greater runout length and ability to transport vast quantities of material across the Earth's surface.

Here we present large-scale experiments of natural volcanic material and gas in order to provide the missing quantitative view of the internal structure and gas–particle transport mechanisms in pyroclastic flows. We show that the outer flow structure with head, body and wake regions broadly resembles current PDC analogues of dilute gravity currents. However, the internal structure, in which lower levels consist of a concentrated granular fluid and upper levels are more dilute, contrasts significantly with the internal structure of fully dilute gravity currents. This bipartite vertical structure shows strong analogy to current conceptual models of high-density turbidity currents, which are responsible for the distribution of coarse sediment in marine basins and of great interest to the hydrocarbon industry.

The lower concentrated and non-turbulent levels of the PDC (granular–fluid basal flow) act as a fast-flowing carrier for the more dilute and turbulent upper levels of the current (ash-cloud surge). Strong kinematic coupling between these flow parts reduces viscous dissipation and entrainment of ambient air into the lower part of the ash-cloud surge. This leads to a state of forced super-criticality whereby fast and destructive PDCs can endure even at large distances from volcanoes. Importantly, the basal flow/ash-cloud surge coupling yields a characteristically smooth rheological boundary across the non-turbulent/turbulent interface, as well as vertical velocity and density profiles in the ash-cloud surge, which strongly differ from current theoretical predictions. Observed generation of successive pulses of high dynamic pressure within the upper dilute levels of the PDC may be important to understand the destructive potential of PDCs.

The experiments further show that a wide range in the degree of coupling between particle and gas phases is critical to the vertical and longitudinal segregation of the currents into reaches that have starkly contrasting sediment transport capacities. In particular, the formation of mesoscale turbulence clusters under strong particle–gas feedback controls vertical stratification inside the turbulent upper levels of the current (ash-cloud surge) and triggers significant transfers of mass and momentum from the ash-cloud surge onto the granular–fluid basal flow.

These results open up new pathways to advance current computational PDC hazard models and to describe and interpret PDCs as well as other types of high-density gravity currents transported across the surfaces of Earth and other planets and across marine basins.

1. Introduction

Pyroclastic density currents (PDCs) are the most hazardous volcanic phenomena on Earth (Druitt, 1998; Branney and Kokelaar, 2002; Sulpizio et al., 2014). Their high velocity, dynamic pressures and particle cargo generate an extremely high destructive power (Valentine, 1998; Clarke and Voight, 2000). Frequent losses of life and severe damage to infrastructure at volcanoes worldwide (Valentine, 1998; Baxter et al., 2005) make better understanding and forecasting of future events a high priority for research in volcanology.

This task is impeded by several obstacles. The transport of PDCs is amongst the most complex fluid mechanical processes in na-

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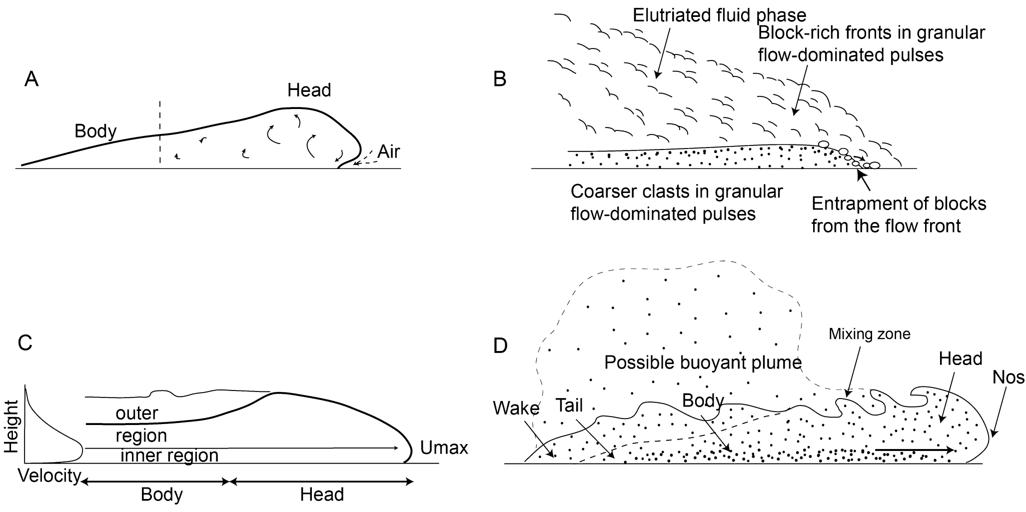

Fig. 1. Schematic representation of gravity and pyroclastic density currents. A: Schematic diagram of the anatomy of a concentrated PDC, modified from Wilson and Walker (1982). B: Schematic illustration of a concentrated PDC, modified from Sulpizio and Dellino (2008). C: Typical schematic diagram of a gravity current with inner and outer regions defined by the velocity profile. D: Generalized structure of a dilute PDC with a head intergradational into a body with an overriding mixing zone and trailing wake, modified from Branney and Kokelaar (2002).

ture, involving highly variable gas–particle and particle–particle interactions with length-, time- and energy-scales encompassing several orders of magnitude (Esposti Ongaro et al., 2012; Dufek et al., 2015). This results in a broad spectrum of possible transport regimes from dense granular flow to dilute fully turbulent behaviour (Druitt, 1992; Sulpizio and Dellino, 2008). There are no direct observations of the PDC interior. This leaves large uncertainties in the selection of appropriate physical models to simulate PDC transport and destruction behaviour computationally (Neri et al., 2003; Esposti Ongaro et al., 2008, 2012; Dufek et al., 2015). To try to understand PDCs better, and to test computational models, researchers have traditionally relied upon deposits to infer PDC behaviour (Sparks and Walker, 1973; Sparks, 1976; Wilson, 1985; Sulpizio et al., 2007; Belousov et al., 2007; Brown and Branney, 2013; Lube et al., 2014). Resulting qualitative transport and deposition models have evolved strongly over the past decades (e.g. Williams et al., 2013), heavily guided by insights gained from field studies in addition to experimental studies of the dense and dilute transport regimes expected to occur in PDCs (Druitt, 1992; Branney and Kokelaar, 2002).

Field studies on PDC deposits provided the earliest evidence that there are two types of PDC: (1) fully dilute, fully turbulent PDCs (also pyroclastic surges), and (2) granular–fluid-based PDCs (sometimes called pyroclastic flows) encompassing concentrated non-turbulent through to fully dilute, fully turbulent transport (e.g. Branney and Kokelaar, 2002). PDC modelling of dilute PDCs has already advanced significantly, because physical models of dilute turbulent suspensions are relatively simple and undisputed (e.g. Valentine, 1987; Bursik and Woods, 1996; Dade and Huppert, 1996). More concentrated (granular–fluid) PDCs, which are the subject of the present study, are far more complex. These are volumetrically more important, travel farther distances, and constitute the greatest hazard. In addition to hazard they are important in being the principle means that pyroclastic material is transported across the Earth's surface, are thought to occur on other planets, and are analogous to high-density turbidity currents (Kuenen, 1951; Postma et al., 1988; Kneller and Branney, 1995), which also have concentrated, much less turbulent lower levels, and dilute fully turbulent upper levels (e.g. Cantero et al., 2011). In fact, the unresolved debate on the emplacement of massive turbidites, as metre-thick beds extending for tens to hundreds of kilometres along the lower continental margins and into deep abyssal plains (e.g. Sylvester and Lowe, 2004), is analogous to the enigma of the formation of massive ignimbrite units at tens to hundreds of kilometres from source (e.g. Wilson et al., 1995).

Understanding of PDCs advanced through major shifts in paradigms that sought to explain their internal structure, transport and deposition (Wilson, 1985; Fisher, 1990; Bursik and Woods, 1996; Freundt and Bursik, 1998; Sulpizio et al., 2014). Early models envisaged a simple longitudinally-variable flow structure dominated by one type of transport behaviour (Fig. 1A). Several lines of argument point towards vertical segregations of the PDC into two co-existing regions (e.g. Lube et al., 2011): a dense granular–fluid base of highest mass flux and an overriding dilute ash-cloud surge of higher volume (Fig. 1B). In PDC and turbidity current research, uncertainties remain as to whether dense and dilute (end-member) transport regimes are bounded by sharp rheological interfaces, or whether these two extremes are connected through a gradual continuum of regimes of intermediate concentration and turbulence (Branney and Kokelaar, 2002).

To date, the lack of quantitative data from within real-world flows has resulted in somewhat diverging pathways of PDC research through fieldwork on deposits, theoretical and computational models, and experimental work. Studies on deposits lack a general theory to quantitatively link sediment characteristics to transport behaviour and experimental and computational models have thus far failed to generate deposit facies variations analogous to those left by real-world PDCs. Advances in numerical multiphase models result in detailed simulations of the PDC structure and transport (Dufek and Bergantz, 2007a, 2007b; Esposti Ongaro et al., 2011, 2012; Dufek, 2016), but validation datasets to test, improve and generalize them are absent. Furthermore, laboratory analogues are increasingly recognised as suffering from issues of scale in replicating the inertia of particles (Burgisser et al., 2005; Dellino et al., 2010; Andrews, 2014).

Here we report the results of large-scale PDC experiments conducted at the eruption simulator PELE (Lube et al., 2015). We describe the internal flow structure and its evolution during runout through observations with high-speed video and measurements of velocity and concentration fields. The data analysis aims to test current qualitative PDC models and to provide insights to several major gaps in current understanding: in what ways do PDCs differ from the current analogue of aqueous (particle-laden) gravity currents (Fig. 1C), how does the presence of a dense, granular–fluid component in lower levels affect overall PDC transport and sedi-