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FORUM CONTRIBUTION

Simply pyroclastic currents

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Abstract Gravity-driven, ground-hugging gas-pyroclast mixtures produced during explosive volcanic eruptions define a full spectrum of particle concentration, flow regime and particle support mechanisms. To describe these phenomena, the term "pyroclastic density current" (PDC) has become increasingly popular in the last few tens of years. Here, I question the general application of the term PDC to the whole flow spectrum and, instead, I propose the simpler term "pyroclastic current".

Keywords Pyroclastic density current · Pyroclastic current · Pyroclastic flow · Pyroclastic surge · Explosive eruption

Gravity-driven, ground-hugging mixtures of pyroclasts and gas, one of the most hazardous geological events, are produced during volcanic eruptions by a variety of mechanisms, including column collapse, low fountaining, dome collapse, hydromagmatic explosions, overpressured blasts (e.g. Walker 1983; Fisher and Schmincke 1984; Cas and Wright 1987; Druitt 1998 and reference therein). To describe these phenomena, the term "pyroclastic density current" (PDC) has become increasingly popular among volcanologists in the last few tens of years (e.g. Druitt 1998; Branney and Kokelaar 2002; Burgisser and Bergantz 2002; Dellino et al. 2008; Sulpizio et al. 2014; Bonadonna et al. 2016; Breard et al. 2016; Dufek 2016). Here, I question the general application of this term within the full spectrum of particle concentration, flow regime and particle support mechanisms (i.e. including "pyroclastic flows" and "pyroclastic surges" of the classical nomenclature; e.g. Sparks 1976; Fisher 1979; Wilson and Walker 1982; Fisher and Schmincke 1984; Cas and Wright 1987 and reference therein). Instead, I propose the simpler term "pyroclastic current".

By definition, a *density current* is any current in either liquid or gas that is kept in motion by the force of gravity acting on differences in density between the current and its surroundings. A density difference can exist between two fluids because of a difference in temperature, salinity or concentration of suspended material. For example, a turbidity current is a subaqueous density current that flows along the bottom of a sea or lake because the sediments in suspension make it denser than the surrounding waters. The difference in density slows down the mixing of the current with the surrounding waters, enabling it to maintain itself for relatively long distances.

In light of well-established conceptual models and interpretive criteria for deposits, to reconcile the complex physical nature of multiphase gas-pyroclast flows, two end-member types are recognised depending on particle concentration and dominant flow regime, i.e. (1) dilute, turbulent suspensions, in which particle concentration is no more than a few volume percent (i.e. bulk flow density 1–100 kg/m^3) (broadly corresponding to *pyroclastic surges*) and (2) high-concentration flows, in which particle content is in the order of tens of volume percent (i.e. bulk flow density 100–1000 kg/m^3) (*pyroclastic flows*). Accordingly, fluid turbulence is the main particle support mechanism in the first case, while particle interactions (friction, collisions, dispersive pressure), matrix strength and/or buoyancy forces become dominant with increasing concentration; turbulence is mostly suppressed in the main body of these flows, while it may act at flow boundaries (e.g. Sparks 1976; Sparks et al. 1978; Fisher 1979; Sheridan 1979; Wilson

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1985; Valentine 1987; Branney and Kokelaar 1992; Dade and Huppert 1996; Druitt 1998; Anilkumar et al. 1993; Palladino and Valentine 1995; Branney and Kokelaar 2002; Burgisser and Bergantz 2002; Dufek 2016).

Individual flows may, however, show a transitional or composite behaviour, with significant time-space changes of particle concentration, flow properties and dynamics (and consequent particle support and deposition mechanisms) along the flow path and/or the vertical flow profile. Different portions of the current may even decouple and move independently (e.g. concentrated *underflows*, *co-ignimbrite ash clouds* and *ash cloud surges*; Denlinger 1987; Fisher et al. 1993; Druitt 1998; Breard et al. 2016). For example, high-density dispersions may exist as an independently moving bulk flow, as a thin discrete layer beneath a thick dilute flow, as the basal part of a continuous density distribution or as a transient depositional layer (Valentine 1987; Druitt 1998; Kneller and Buckee 2000; Palladino and Simei 2002; Doyle et al. 2010, 2011).

In spite of recent theoretical advances, also supported by numerical simulations (e.g. Doronzo et al. 2011; Dioguardi and Dellino 2014) and laboratory experiments (e.g. Dellino et al. 2007; Andrews and Manga 2011; Rowley et al. 2014; Sulpizio et al. 2014; Lube et al. 2015; Breard et al. 2016; Roche et al. 2016) and of alternative views (i.e. a new subdivision based on forced convection-dominated and inertia-dominated end members; Doronzo 2012), the term PDC spans indiscriminately currents ranging from highly dilute and turbulent blasts to dense block-and-ash flows from gravitational dome collapse (Charbonnier et al. 2013), often with a specification that echoes the dual nature of these currents in terms of density: e.g. cf. *dilute* PDCs (Palladino and Taddeucci 1998; Dellino et al. 2008; Dioguardi and Dellino 2014) vs. *dense* or *concentrated* PDCs (Dufek et al. 2009; Rowley et al. 2014; Sulpizio et al. 2016).

The dynamics of dilute, turbulent flows are described in the volcanological literature by analogy with other suspension currents (e.g. turbidity currents) (Valentine 1987; Sohn and Chough 1989; Fisher 1990; Druitt 1992; Cole and Scarpati 1993; Palladino and Taddeucci 1998; Dellino and La Volpe 2000; Kneller and Buckee 2000; *type 1 current* of Palladino and Simei 2002). As the flow power declines with distance from source, the settling of particles according to their Rouse number determines a vertical concentration profile (density-stratified flow; Valentine 1987). Due to air entrainment, elutriation of fines and bedload deposition, the bulk flow density decreases downcurrent, until the density contrast with the surrounding atmosphere will drop to zero and the lateral flow motion ceases (eventually giving birth to a buoyant “phoenix” cloud; Bursik and Woods 1996). Flow density and runout may be enhanced by splash-driven particle entrainment from the substrate (Fauria et al. 2016). Thus, the runout distance of a dilute current is primarily controlled by the positive density contrast with the surrounding medium (i.e. true *density current*).

High-concentration flows have been described in volcanology by three main types of physical models: (1) *viscoplastic*, (2) *sliding block* and (3) *rapid granular flow* models (Druitt 1998). The first model type, which mostly includes *plug* flow models (Sparks 1976; Wilson and Head 1981; Valentine and Fisher 1986; Battaglia 1993) and *laminar* flow models (coupled to a granular flow model; Palladino and Valentine 1995; *type 3 currents*, Palladino and Simei 2002), assumes that the particle-gas mixture is a continuum fluid, characterized by viscosity and yield strength, in which flow turbulence is damped by high particle concentration and coarse-clast support is controlled by the density contrast of large clasts with the matrix. These viscoplastic models have close analogies with models for *cohesive debris flows* (Postma 1986). Among viscoplastic models, very fast examples, even though dense, have been viewed as turbulent flows (McEwan and Malin 1989; Levine and Kieffer 1991).

The *sliding block* and the *rapid granular flow* models treat dense gas-pyroclast dispersions respectively as slow- or fast-moving granular mass flows (*cohesionless debris flows*; Postma 1986), in which the stress tensor is dominated respectively by intergranular friction or by short-lived intergranular collisions, and the role of the interstitial fluid (if present) is negligible (Bagnold 1956; Savage 1984; Palladino and Valentine 1995; Straub 1996; Iverson 1997; Iverson and Vallance 2001; *type 2 currents*, Palladino and Simei 2002; Dartevelle et al. 2004; Schwarzkopf et al. 2005; Lube et al. 2007; Rowley et al. 2014; Sulpizio et al. 2016).

High-density particulate flows thus share the key characteristics of polydisperse granular avalanches (Gray and Ancey 2011) and/or viscoplastic rheologies typical of cohesive debris flows. The physics of granular mass flows and rheological analysis (e.g. plastic vs. Coulomb rheologies; Kelfoun 2011) indicates that the emplacement of high-density flows may occur by en-masse freezing, rapid stacking of flow laminae and/or progressive sedimentation (e.g. Sparks 1976; Palladino and Valentine 1995; Girolami et al. 2010). The simple Mohr-Coulomb model, commonly applied to rock avalanches (e.g. Hsü 1989), considers the motion of a sliding rigid block for slope angles greater than the internal angle of friction of the granular material. At any point downslope, the total energy is given by the sum of potential energy + kinetic energy + frictional loss. Due to its own momentum, such a flow can climb all relief below the energy line (i.e. the straight line connecting the point of flow origin to the most distal flow reach). Flow mobility is expressed by the ratio of the total vertical drop vs. the total horizontal distance travelled (H/L, Heim coefficient). In this regard, pyroclastic flows share the negative dependence of H/L with volume that is observed for cold, dry rock avalanches (Hayashi and Self 1992).

To summarize, ground-hugging gas-pyroclast currents (thus without referring to air-suspended column jets and plumes) are fluid-particle mixtures that move by virtue of the force of gravity and exhibit a positive density difference with the ambient fluid. With the exception of overpressured blasts, which are essentially driven by pressure (rather than density) differences, the other currents can be viewed as part of a continuum from *fluid gravity flows* to *sediment gravity flows* (Hsü 1989). In very dilute gas-particle dispersions (i.e. true suspension currents), the motion of the *fluid* (i.e. the fluid medium of volcanic gases, ingested air and ground water plus suspended particles) is driven by the density contrast with the ambient fluid, and particle interactions are negligible. Conversely, in highly concentrated gas-particle mixtures, it is the gravity acting on the pyroclasts which makes the interstitial fluid move, and particle interactions dominate the transport system.

In the first case, where a thick, dilute suspension current supplies and drives a thin, dense bedload (also cf. Todd 1989), the density contrast is a crucial parameter that actually controls flow motion over the landscape. The term “density current”, when referring specifically to relatively dilute examples of the flow spectrum (e.g. Palladino and Taddeucci 1998; Dellino et al. 2008), may be useful to stress that the gas-pyroclast mixture is kept in motion so long as it remains denser than the surrounding atmosphere. In the second case, where a dense basal avalanche feeds an upper dilute ash cloud, the bulk flow density of the driving avalanche is always well beyond (2–3 orders of magnitude) that of ambient air even when the flow eventually stops. Sustained, very long runout (>170 km from source) examples are reported that show evidence of regional transport as dense granular dispersions (Roche et al. 2016). Because it is not the waning excess density that controls the magnitude of final flow runout, the term “density current” seems at least redundant for a high-density mass of pyroclasts and entrapped gas that travels across the landscape in a way similar to a dry rock avalanche or a mass of billiard balls.

Thus, the term “PDC” suggests a dynamic characterization of the flow (i.e. density- vs. pressure-driven; dilute, turbulent suspension controlled by density contrast vs. granular flow regime), which can be somehow qualitative and ambiguous, also considering space-time changes within individual flow events. A *flow* of electrons is defined “electrical current”; likewise, I propose to call a *flow* of pyroclasts simply a “pyroclastic current” (PC), irrespective of envisaged/inferred/assessed flow properties (including density) and regimes. Since its early appearance (e.g. Fisher 1995; Palladino and Valentine 1995), the term “PC” has been used in a broad sense in relatively few cases (e.g. Palladino and Simei 2002; Taddeucci and Palladino 2002; Doyle et al. 2010 in the article title, yet PDC in the text). Also, “PC” is more apt than “PDC” for further qualification (e.g. *low-density*, *high-density* or *density-stratified PC*). When necessary, to avoid possible ambiguity, it can be specified to “ground-hugging PC” vs. “air-suspended (or unconfined) PC” (i.e. eruptive jets and plumes). Finally, the term “PC” (instead of “PDC”) might be still valid in the future, as the integration of new theoretical studies, computer simulations, analogue experiments and field studies of deposits, will refine what appears a well-established theoretical framework, even though nature will surprise us by showing new as yet unimagined processes.

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