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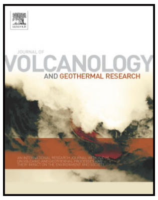

Pyroclastic density currents and local topography as seen with the conveyer model

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ABSTRACT

Pyroclastic density currents (PDCs) are multiphase flows generated during explosive volcanic eruptions, and they move down the volcano, and over the surrounding topography. The flow–topography interaction can play a fundamental role in the sedimentary processes, and in the resulting deposit facies architecture, as well as can play a dramatic role in the flow behavior, and in the associated volcanic hazard. This paper aims at discussing the PDC–topography interaction theme from the viewpoint of both deposits and flow structure, by accounting for appropriate literature, and revising the concepts in light of the theoretical conveyer model of Doronzo and Dellino (2013) on sedimentation and deposition in particulate density currents. First the effects, then the causes of the flow–topography interaction are discussed, in order to follow the historical development of theme concepts. The discussion is relative in terms of inertial and forced currents, which are defined on the basis of a dimensionless quantity (*SD*) representing the conservation of mass. Momentum equation relating depositional unit thickness, flow shear velocity, and density contrast shows that the flow is the cause of PDC motion, whereas the density contrast sustains the momentum, and the deposits are the process effect. In particular, the flow structure is described into three parts, flow–substrate boundary zone, boundary layer (lower part), and wake region (upper part) of the current. The facies architecture of PDC deposits, and the volcanic hazard depend on fluid dynamic and hydraulic behavior represented, in light of the conveyer model, by the balance of sedimentation and deposition rates through transport and erosion ("sedimentation–deposition" ratio, *SD*). This balance acts between flow–substrate boundary zone and boundary layer. The paper discussion mainly applies to small-to-intermediate volume eruptions. Field and modeling examples of Vulcano tuff cone and Colli Albani maar (Italy) constrain the conveyer model, whereas the literature of very large, ignimbrite-forming eruptions, and stratovolcanism is accounted for theme completeness. The main findings are some relative guidelines on PDC–topography interaction that can be used when modeling the flow, and interpreting the pyroclastic deposits: low *SD* is typical of inertial currents, whereas high *SD* is typical of forced currents, which can vary depending on topography.

1. Introduction

Pyroclastic density currents (PDCs) are ground hugging gas-particle flows generated during explosive volcanic eruptions, and they hazardously move down the volcano, and over the surrounding topography (Cas and Wright, 1987). PDCs are known to involve a spectrum of particle loading between two general end members of current, concentrated and dilute (e.g. Cas and Wright, 1987; Burgisser and Bergantz, 2002), which are roughly analogous to the dense and disperse flows of multiphase physics, respectively (Crowe, 2006). They are also described in a spectrum of energy between two end members of flow, forced and inertial, these latter not excluding the classic two end members of PDCs, and vice versa (Doronzo, 2012; see also Giordano and Dobran, 1994; Pittari et al., 2006; Pedrazzi et al., 2013). All of these end members are not conceptual, but are relative to each other around a scalar quantity, in analogy with temperature in mechanics. Proximal PDCs are generally forced by the eruption dynamics, whereas distal PDCs are dominated by inertia, with a sharp or continuous transition in between depending on, among other factors, topography (Esposti Ongaro et al., 2011; Brown and Branney, 2013; Douillet et al., 2013).

PDCs can be generated because of gravitational collapse of a pressure-balanced eruptive column (Sparks et al., 1978; Woods, 1988; Valentine and Wohletz, 1989), explosion of a lava dome, or overpressure jet/blast (Kieffer and Sturtevant, 1988; Esposti Ongaro et al., 2008a, 2011), and they flow downstream as radial currents in the first case, and approximately unidirectional currents in the other two cases. Radial currents can be also generated because of collapse of an overpressurized eruptive column (Ogden et al., 2008; Dellino et al., 2010a), pyroclastic

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fountaining (Woods and Wohletz, 1991; Neri and Dobran, 1994; Sulpizio et al., 2005), or ignimbrite-forming eruptions (Sparks and Wilson, 1976; Fisher et al., 1980; Walker et al., 1980; Cas and Wright, 1987; Branney and Kokelaar, 2002).

A substantial knowledge on the dynamics of PDC generation and propagation comes from field and sedimentological studies of pyroclastic deposits of past eruptions, and computer simulations that may reasonably approximate those events (e.g. Sulpizio and Dellino, 2008; Cashman and Sparks, 2013). Less attempts, based on field and experimental data, have been done to specifically link the generation of PDCs through vent conditions to flow propagation, particularly when these currents interact with topography, or more generally obstacles (Cas et al., 2011; Doronzo and Dellino, 2011). Finally, some inputs come from a few eruptions generating PDCs that have been directly observed in the recent past. The goals of this paper are those of revising the PDC–topography interaction theme in light of the conveyer model of Doronzo and Dellino (2013), showing how the balance between sedimentation and deposition rates, which can be affected by topography, in turns does affect the emplacement of PDC deposits. This is the effect of such interaction, whereas the cause, i.e. flow structure, is responsible for balancing the sedimentation and deposition, and is directly affected by topography. It will be shown that inertial currents are characterized by low sedimentation relative to deposition, whereas forced currents are characterized by high sedimentation relative to deposition, which is a new perspective on PDCs usable when modeling the flow, and interpreting their deposits.

Concentrated PDCs or pyroclastic flows, and dilute PDCs or pyroclastic surges are generally associated to deposits with massive and laminated facies, respectively (Freundt et al., 2000; Valentine and Fisher, 2000). In particular, when vertical and lateral facies variations are observed in the deposits, they can suggest the flow evolution that occurred during deposition or the depositional styles (massive versus tractive), as time- and space-dependent, respectively (Cas and Wright, 1987; Branney and Kokelaar, 2002; Sulpizio and Dellino, 2008). The deposit facies variability is generally related to the PDC particle loading, which prevents (if high) or favors (if low) individual particle settling (Choux and Druitt, 2002), by affecting current stratification in terms of particle loading through a sedimentation rate (Branney and Kokelaar, 2002; Cantero et al., 2013). For this reason, PDCs are recognized to be density-stratified (Druitt, 1998). The flow structure in the density-stratified currents directly affects sedimentation, implying that the deposit facies variability is also related to the PDC velocity profile (Giordano and Dobran, 1994; Doronzo et al., 2012). This profile prevents (if uniform) or favors (if pronounced) individual particle settling, and affects flow stratification in terms of velocity through a boundary layer (Lajoie et al., 1989; Dellino et al., 2004; Doronzo et al., 2011). For this reason, PDCs are also recognized to be velocity-stratified (Valentine, 1987). A numerical discussion of PDC boundary layer in relation with particle loading is found in Doronzo et al. (2012).

PDCs can undergo time- and space-dependent transformations in the flow, which may result in a change in the currents from concentrated to dilute (Fisher, 1983; Dellino et al., 2004; Vazquez and Ort, 2006), or vice versa from dilute to concentrated (Druitt et al., 2002; Doyle et al., 2011; Gernon et al., 2013), depending on, among other factors, topography (Pedrazzi et al., 2013; Sumita and Schmincke, 2013). The interaction between PDCs and topography is particularly intense in the flow–substrate boundary zone, where deposition occurs (Branney and Kokelaar, 2002; Sulpizio and Dellino, 2008). In particular, the depositional processes in PDCs can be significantly affected by the shape of volcanoes (Valentine et al., 2011), and the nearby topographic changes (Doronzo et al., 2010).

The following argumentation is organized first by describing the effects of PDC–topography interaction, i.e. PDC deposits, then by analyzing the causes that generate those effects, i.e. PDC flow structure. This argumentation applies to volcanic islands, and calderas, with focus on the topographic influence on deposits and flow. In Fig. 1, the example of Vulcano tuff cone (Italy), which is located in a geological setting of both volcanic island and caldera, is shown; see Section 2.3 for a detailed discussion on Vulcano. However, the details of very large, ignimbrite-forming eruptions, which generate PDCs and pyroclastic sequences that may strongly also depend on vent conditions (e.g. Bacon, 1983; Cas et al., 2011), are mentioned, but not discussed in this paper. Instead, the details of stratovolcanism are accounted for (e.g. Doronzo et al., 2012). Both effects and causes are discussed in light of the conveyer model of Doronzo and Dellino (2013), which gives a new perspective on sedimentation and deposition in particulate density currents. This paper does not represent a review on PDC–topography interaction, and the presented argumentation goes through effect and cause, rather than a subdivision of field-to-numerical approaches, for which there are dedicated works (e.g. Roche et al., 2013).

2. Effects of PDC–topography interaction

In this section, the effects that can be ascribed to PDC–topography interaction, and hence the deposit facies architecture and associated sedimentology are discussed in light of the conveyer model, without directly taking into account the causes that may lead to those effects, i.e. the flow structure. PDC deposits and their features are universally recognized as an effect of the processes leading to the emplacement (Cas and Wright, 1987; Branney and Kokelaar, 2002; Sulpizio and Dellino, 2008). Then, the causes of PDC–topography interaction are discussed in the next section, in order to follow the historical development of concepts.

2.1. Literature background and the conveyer model

Before introducing the conveyer model, it is worthy to mention all main works that have been done on PDC–topography interaction, which may be useful as a guide to the literature through the different approaches, field, theoretical, geophysical, experimental, and numerical, however they are not discussed in detail as this paper is not a review, and also has not the presumption to account for all of them in a single model. Instead, they are properly mentioned throughout the text, as PDCs and their deposits are revised in light of the conveyer model. There is a wide literature of field investigations on the effects of PDC–topography, or more generally PDC–obstacle, interaction (Walker et al., 1981; Druitt and Sparks, 1982; Wilson, 1985; Wilson and Walker, 1985; Kieffer and Sturtevant, 1988; Lajoie et al., 1989; Fisher, 1990; Branney and Kokelaar, 1992, 1997, 2002; Druitt, 1992; Sohn and Chough, 1993; Bryan et al., 1998; Bursik et al., 1998; Giordano, 1998; Calder et al., 2000; Dellino and La Volpe, 2000; Freundt et al., 2000; Valentine and Fisher, 2000; Druitt et al., 2002; Giordano et al., 2002; Dellino et al., 2004, 2011; Brown and Branney, 2004a,b, 2013; Burgisser, 2005; Pittari et al., 2005, 2006, 2008; Belousov et al., 2007; Lube et al., 2007; Sulpizio et al., 2007, 2008, 2010a; Martí et al., 2008; Sulpizio and Dellino, 2008; Cas et al., 2011; Garcia et al., 2011; Pedrazzi et al., 2013). Several workers have also modeled or scaled this interaction through theoretical, geophysical, experimental, and numerical approaches, or have combined different approaches to each other, with an eye to the counterpart of dynamics (Sparks et al., 1978; Malin and Sheridan, 1982; Sheridan and Malin, 1983; Valentine, 1987; Valentine et al., 1992, 2011; Fisher et al., 1993; Dobran et al., 1994; Giordano and Dobran, 1994; Neri and Dobran, 1994; Woods and Bursik, 1994; Coniglio and Dobran, 1995; Fisher, 1995; Bursik and Woods, 1996, 2000; Dade and Huppert, 1996; Freundt and Bursik, 1998; Wohletz, 1998; Woods et al., 1998; Freundt, 1999; Legros and Kelfoun, 2000; Esposti Ongaro et al., 2002, 2008a, 2008b, 2011, 2012; Todesco et al., 2002, 2006; Ort et al., 2003; Porreca et al., 2003; Neri et al., 2007; Doronzo et al., 2010, 2011, 2012; Dellino et al., 2010b; Sulpizio et al., 2010b; Doronzo and Dellino, 2011; Andrews and Manga, 2012; Oramas-Dorta et al., 2012; Doronzo, 2013). This literature background includes the works done on PDC–topography