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Transient 3D numerical simulations of column collapse and pyroclastic density current scenarios at Vesuvius

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ABSTRACT

Numerical simulations of column collapse and pyroclastic density current (PDC) scenarios at Vesuvius were carried out using a transient 3D flow model based on multiphase transport laws. The model describes the dynamics of the collapse as well as the effects of the 3D topography of the volcano on PDC propagation. Source conditions refer to a medium-scale sub-Plinian event and consider a pressure-balanced jet. Simulation results provide new insights into the complex dynamics of these phenomena. In particular: 1) column collapse can be characterized by different regimes, from incipient collapse to partial or nearly total collapse, thus confirming the possibility of a transitional field of behaviour of the column characterized by the contemporaneous and/or intermittent occurrence of ash fallout and PDCs; 2) the collapse regime can be characterized by its fraction of eruptive mass reaching the ground and generating PDCs; 3) within the range of the investigated source conditions, the propagation and hazard potential of PDCs appear to be directly correlated with the flow-rate of the mass collapsing to the ground, rather than to the collapse height of the column (this finding is in contrast with predictions based on the energy-line concept, which simply correlates the PDC runout and kinetic energy with the collapse height of the column); 4) first-order values of hazard variables associated with PDCs (i.e., dynamic pressure, temperature, airborne ash concentration) can be derived from simulation results, thereby providing initial estimates for the quantification of damage scenarios; 5) for scenarios assuming a location of the central vent coinciding with that of the present Gran Cono, Mount Somma significantly influences the propagation of PDCs, largely reducing their propagation in the northern sector, and diverting mass toward the west and southeast, accentuating runouts and hazard variables for these sectors; 6) the 2D modelling approximation can force an artificial radial propagation of the PDCs since it ignores azimuthal flows produced by real topographies that therefore need to be simulated in fully 3D conditions.

1. Introduction

Historically, the explosive eruptions of Vesuvius have had a strong impact on the life of the surrounding population. Examples include the 3800 B.P. Avellino eruption, which widely impacted the Campania Plain (Lirer et al., 1973; Santacroce, 1987; Rolandi et al., 1993a; Cioni et al., 2000; Mastrolorenzo et al., 2006), and the famous AD 79 eruption, which caused the destruction of the Roman towns of Pompeii, Herculaneum, and Stabiae (Lirer et al., 1973; Sigurdsson et al., 1982). The most catastrophic explosive eruption of the last millenium occurred in AD 1631. Slightly smaller than AD 79, this eruption claimed more than 1000 victims and caused extensive damage and social consequences in the area of Vesuvius (Rosi et al., 1993; Rolandi et al., 1993b; Guidoboni, 2008-this issue).

Although ash and lapilli fallout, i.e. the airborne dispersal and deposition of volcanic particles (Cioni et al., 2003a; Macedonio et al., 2008-this issue), and lahars, i.e. the remobilization of such deposits under the action of meteoric water (Bisson et al., 2006), are additional significant hazards, the most catastrophic process characterizing the large explosive eruptions at Vesuvius is the collapse of the volcanic column and the generation of devastating pyroclastic density currents (PDCs), or pyroclastic flows s.l. (Cioni et al., 2008-this issue).

This phenomenon, which typically characterizes the later stages of the explosive event, at Vesuvius is usually considered to be produced by two different mechanisms: 1) a gradual or sharp change in the eruptive conditions of the mixture at the vent that causes the destabilization of the volcanic column, and gravitational collapse to the ground of variable portions of the plume, and 2) the abrupt total or partial collapse of the volcanic edifice to generate a caldera, with effective increase of radius, that favours the formation of *boiling-over* type PDCs fed by a relatively short-lived, low-altitude fountain. For

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instance, the first type of column collapse is thought to have occurred during the AD 79 Plinian eruption, and was associated with the change from white magma to grey magma (Lirer et al., 1973; Sigurdsson et al., 1982; Cioni et al., 1992). The second type of column collapse, associated with caldera generation in the summit portion of the volcano, probably occurred in the AD 1631 eruption (Rolandi et al., 1993b; Rosi et al., 1993), and in the late stages of the AD 79 event (Sigurdsson et al., 1982; Cioni et al., 1992).

Understanding the dynamics of column collapse mechanisms is thus vital for properly assessing the hazard associated with PDCs produced by explosive eruptions of Vesuvius. The collapse dynamics in fact determine the mass feeding conditions of the associated PDCs at the air-ground interface, as well as their spatial and temporal variations. The crucial importance of the topic is underscored by an awareness of the present-day situation at Vesuvius, where more than half a million people live in the Red Zone, a high-hazard area with a radius of about 8 km. According to the present Emergency Plan, this area could be affected by PDCs and should therefore be evacuated in advance in the case of renewed volcanic activity (DPC, 1995, 2001).

Modelling column collapse and PDC propagation and runout has always been a very challenging task for volcanological researchers. Although simplified schemes have been developed, any attempt at realism requires the description of an enormously complex 3D transient process, together with appropriate representation of the multiphase nature of the eruptive mixture. Moreover, initial and boundary conditions, such as atmospheric conditions and volcano topography, are also intrinsically 3D and often time-dependent. A further complexity of PDCs is the dual nature of their flow, typically consisting of a basal granular flow underlying a more dilute surge-like ash cloud (Druitt, 1998; Branney and Kokelaar, 2002; Burgisser and Bergantz, 2002).

Sparks et al. (1978) first attempted to quantify the dynamics of column collapse and associated PDCs: by adopting a 1D steady-state homogeneous flow formulation and simple geometrical constraints, they quantified the main influence of vent parameters on collapse and PDC features. A simplified approach for the definition of a region inundated by PDCs generated by column collapse was later developed by Malin and Sheridan (1982); based on an energy-line concept originally developed for landslides. This simplified approach and its extensions have been widely applied to the assessment of PDC hazard in many areas, including Vesuvius (Sheridan and Malin, 1983; Rossano et al., 1998; Mastrolorenzo et al., 2006).

A significant advance was made a few years later by a research group at Los Alamos National Laboratory (US) through the adoption of 2D transient two-phase flow codes able to provide insight into several aspects of these complex phenomena as well as the influence of vent conditions on the eruptive style of the column (Wohletz et al., 1984; Valentine and Wohletz, 1989). This approach was extended by Dobran et al. (1993), Neri and Macedonio (1996), and Neri et al. (2003), who further developed the 2D multiphase flow formulation by adopting the kinetic theory and multiparticle descriptions of the solid phase. These models were also applied to the assessment of PDC hazard at Vesuvius by coupling the magma ascent dynamics with the modelled dispersal process (Dobran et al., 1994; Todesco et al., 2002; Esposti Ongaro et al., 2002). Due to the limited resolution of the computational grid, and limitations on the particle sizes, such models are more suited to describe the surge-like component of the PDC rather than its dense basal flow. Despite the useful insights provided by these models on the first-order features of the collapse process and PDC propagation, they are all limited by the 2D description, which allows neither an appropriate representation of the 3D dynamics of the process nor a realistic description of the influence on the flow dynamics of the volcano's topography.

With the aim of overcoming the limitations of 2D modelling and in order to better describe the dynamics of such complex processes, a fully 3D transient multiphase flow model was recently developed (Esposti Ongaro et al., 2007). The new model, named PDAC (Pyroclastic Dispersal Analysis Code), extends the Neri et al. (2003) formulation to a 3D Cartesian domain and further advances several numerical features of the previous 2D model (De'Michieli Vitturi et al., 2007). The first applications of this model to Vesuvius were briefly described by Neri et al. (2007). A similar 3D homogeneous flow model able to describe the collapse of the volcanic column and PDC propagation has been recently developed by Suzuki et al. (2005).

This paper presents a selected number of numerical simulations of the collapse of the volcanic column at Vesuvius, and associated generation and propagation of PDCs, for a variety of eruptive mixtures at the vent. The conditions for the simulated scenarios correspond to a Sub-Plinian I explosive event at Vesuvius (Cioni et al., 2008-this issue), i.e. the reference scenario on which the National Emergency Plan is based (DPC 1995, 2001), and assume a location of the vent corresponding to the present Gran Cono. The study investigates in 3D the complex dynamics of the collapse with the aim of better describing the column collapse process as well as the initial conditions and dynamics of PDCs, with specific reference to surge-like flows. The assumed conditions at the vent appear to strongly affect the collapse style, which varies from incipient collapse to nearly total collapse of the column. The fraction of the eruptive mass flow that collapses to the ground appears to be a key parameter for characterizing collapse regimes and PDC hazards. Simulations also quantify the effect of volcano topography on PDC propagation, particularly the influence of Mount Somma on the diversion of flows.

2. The physical and numerical model

The adopted physical model for simulating column collapse and PDC propagation along the volcano flanks is based on the transport theory of multiphase flows (Gidaspow, 1994; Dartevelle, 2004). According to this theory, each phase of the eruptive mixture (gas and pyroclasts of different size and density) is described separately from the others by solving the corresponding mass, momentum and energy balance equations. The multiphase flow model can thus

Table 1

Reference vent conditions (Todesco et al., 2002) and pressure-balanced source conditions of the jet for the five simulations presented. Conditions of SIM1 were calculated by a 1D pseudogas decompression model (Woods and Bower, 1995), whereas those of SIM3 through a 2D axisymmetric multiphase flow simulation (see text for explanation). Conditions of SIM2 and SIM4 represent modifications of those of SIM3 whereas SIM5 is an upper bound simulation in terms of intensity (Sub-Plinian I category). $\dot{m}$ is the mass flow-rate, Y_{H_2O} the water content, T the temperature, R the radius of the inlet, w_{av} and w_{max} represent the averaged and the maximum values of the vertical velocity over the inlet surface area (see text for details), P is pressure, ε_1 and ε_2 are the volume fraction of the 30 and 500 μm particles, and ρ_m is the mixture density. All values, except the reference vent conditions of Todesco et al. (2002), refer to the source (pressure-balanced jet). Units are reported in the table

Simulation	$\dot{m}$ [kg/s]	Y_{H_2O} [wt.%]	T [K]	R [m]	w_{av}/w_{max} [m/s]	P [bar]	ε_1	ε_2	ρ_m [kg/m^3]
Reference vent conditions (Todesco et al., 2002)	5×10^7	2	1223	28.8	137.1	17.5	0.0245	0.0686	133.9
SIM1	5×10^7	2	1210	94.4	225/225	0.885	0.0014	0.0036	7.6
SIM2	5×10^7	2	1210	117.5	175/220	0.885	0.0011	0.0031	6.3
SIM3	5×10^7	2	1210	125	155/192.5	0.885	0.0011	0.0031	6.3
SIM4	5×10^7	2	1210	175	80/100	0.885	0.0011	0.0031	6.3
SIM5	8×10^7	2	1210	175	143/180	0.885	0.0011	0.0031	6.3