Earth and Planetary Science Letters 404 (2014) 98–110

Contents lists available at ScienceDirect

Earth and Planetary Science Letters

www.elsevier.com/locate/epsl

An integrated model of magma chamber, conduit and column for the analysis of sustained explosive eruptions

S. Colucci [a,b,*], M. de' Michieli Vitturi [b], A. Neri [b], D.M. Palladino [a]

[a] Dipartimento di Scienze della Terra, Sapienza-Università di Roma, Rome, Italy
[b] Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy

ARTICLE INFO

Article history:
Received 11 October 2013
Received in revised form 11 July 2014
Accepted 29 July 2014
Available online 14 August 2014
Editor: T. Elliott

Keywords:
explosive eruptions
magma chamber
conduit
eruption column
sensitivity analysis
Vulsini

ABSTRACT

Explosive volcanic eruptions comprise a complex series of processes involving withdrawal from the magma chamber, magma ascent along the conduit and eruption column dynamics. Numerous studies have modeled the different sub-domains of a volcanic system, but their interplay has seldom been analyzed. To this end, we developed C^3 (C-cubed, that stands for Chamber, Conduit and Column), a new integrated model that describes the dynamics of an explosive eruption as a series of steady state regimes and as a function of geometry and initial conditions of the magma reservoir. We used Global Sensitivity Analysis to quantify the role of the relevant model parameters and describe the interplay between the different volcanic sub-domains. In particular, we analyzed the evolution of a sustained explosive eruption in order to identify the conditions for buoyant, super-buoyant and collapsing columns. Input data were based on field reconstructions of Quaternary explosive eruptions in the Vulsini Volcanic District (Roman Province, central Italy). Model results show that: 1) the column regime, although affected by complex interactions among several factors, mostly depends on the conduit radius, the volatile content (i.e. supersaturation concentration at the top of the chamber) and length of the conduit, in decreasing level of importance; 2) the amount of mass erupted is independent of the conduit radius and depends mostly on volatile supersaturation, the radius of the magma chamber, the length of the conduit and the overpressure at the conduit inlet; 3) the mass flow-rate, column height and duration of the eruption are largely controlled by the conduit radius; 4) the flow pressure and density at the conduit exit are mostly controlled by the conduit inlet overpressure at the onset of the eruption, and by the length of the conduit at the end of the eruption; 5) the exit velocity from the conduit is mostly controlled by the volatile content, the length of the conduit and the inlet overpressure. In this model framework, and with specific reference to selected Plinian events of the Vulsini Volcanic District, simulation results show that column collapse is not achieved for reasonable eruption durations (order of hours) and conduit widths (tens of meters). This is consistent with field reconstructions suggesting that column collapse did not likely occur and that pyroclastic flows were therefore generated by independent mechanisms from ring fissures and/or multiple vents concomitant to caldera collapse.

1. Introduction

Column behavior in explosive eruptions commonly varies, ranging from fire fountaining to sustained, buoyant and superbuoyant plumes, and collapsing columns (Di Muro et al., 2004; Papale and Dobran, 1994; Sparks, 1978; Valentine and Wohletz, 1989; Woods, 1988). These transitions in eruptive style typically reflect the changing dynamics of the subsurface feeder system. The onset of a sustained, buoyant or superbuoyant plume is typically related to a temporal increase in the energy parameters. Buoyant plumes are characterized by high volatile contents and velocities at the plume base that favor effective atmospheric air entrainment. The shift from a sustained plume, producing a fall-out deposit, to a collapsing column, generating a pyroclastic flow, has been ascribed to a number of causes, including: modification of conduit-crater size/geometry, properties of the feeder magma system (e.g. magma composition and volatile content), properties of the erupting gas–particle mixture (particle concentration and grain size/density distribution) and style of magma fragmentation (Bursik and Woods, 1991; Carey et al., 1990; Papale, 1999; Valentine and Wohletz, 1989; Wilson et al., 1980; Woods, 1995).

* Corresponding author at: Istituto Nazionale di Geofisica e Vulcanologia, Sezione di Pisa, Italy.
E-mail address: simone.colucci@pi.ingv.it (S. Colucci).

http://dx.doi.org/10.1016/j.epsl.2014.07.034
0012-821X/

In this paper we present a newly developed code, C^3 (*C-cubed*, for Chamber, Conduit and Column) which can be used to generate integrated reconstructions of the entire volcanic system controlling the dynamics of sustained magmatic explosive eruptions. The new model extends the CPIUC model developed by Macedonio et al. (2005) by also taking into consideration flow decompression at the vent and plume dynamics. Previous numerical studies have considered different subdomains of the volcanic system (i.e., magma chamber, conduit and column), but relatively few modeling studies have addressed the complex interplay between these different subdomains. Wilson et al. (1980) first studied eruption column behavior by integrating conduit, vent and plume dynamics producing the first regime diagram for steady volcanic plumes. Similarly, Papale et al. (1998) and Neri et al. (1998) investigated the effects of magma composition and water content on conduit exit conditions and plume style using 1D/2D numerical simulations of conduit plus plume dynamics. Along the same lines, Clarke et al. (2002) simulated the transient dynamics of vulcanian explosions at Soufrière Hills Volcano (Montserrat, 1997) by coupling conduit evacuation and pyroclastic dispersion to better understand the complex mass partitioning of the volcanic fountain. Using an approach similar to that adopted in this work, Folch and Felpeto (2005) presented a model for tephra fallout by coupling the dispersal model with simple 1D models for volcanic plumes, flow along the conduit and withdrawal from the magma chamber. Here, in addition, we also take into consideration flow decompression at the vent, following the simplified approach presented in Woods (1995) where the presence of a crater and gravitational forces are ignored. More recently Koyaguchi et al. (2010), by using a 1D model, coupled the conduit and column flow dynamics by investigating the effect of crater shape and magma chamber conditions on the column regime. The interplay between chamber pressure variations and fluctuations of discharge rate at the vent have also been studied in Barmin et al. (2002) for dome eruptions using a 1D transient model, where the magma chamber is described through a set of lumped variables, thus neglecting vertical variations considered in this work. More recently, a similar simplified model of magma chamber has been used to investigate the effect of wall-rock elasticity on magma flow in dykes with different geometries (Costa et al., 2009). In our work, the magma chamber and conduit walls were considered rigid at all times thus assuming that they may not deform elastically or that the elastic deformation is of the order of few percentages (Macedonio et al., 2005). Finally, magma chamber and conduit have also been coupled, using a set of 1D equations similar to those presented in this work, to analyze the temporal evolution of source conditions during sustained and caldera-forming eruptions (Folch and Martí, 2009; Macedonio et al., 2005). In these papers, as in our work, for the eruptions considered the time scale of magma chamber pressure variations is one order of magnitude higher than the travel time of magma in the conduit, thus justifying the simulation of the transient dynamics of the eruption through a series of steady-state solutions.

Using the new model C^3, we analyzed, by a Global Sensitivity Analysis (GSA), the model's sensitivity to the different system input parameters (such as chamber and conduit geometries, water and crystal content of the magma, initial pressure in the magma chamber) in order to quantify their relative role in column dynamics and regime transitions. Although the model can be applied to any volcanic system producing explosive eruptions, we here report on its first application to specific trachy-phonolitic explosive eruptions of the Quaternary Vulsini Volcanic District (Roman Province, central Italy).

This paper is organized as follows: Section 2 presents the new physical model and its governing equations; Section 3 describes the classification of column behavior; Section 4 introduces the adopted GSA; Section 5 describes the model's application to the Vulsini eruptions and reports the main results; finally the main conclusions of the study are presented in Section 6.

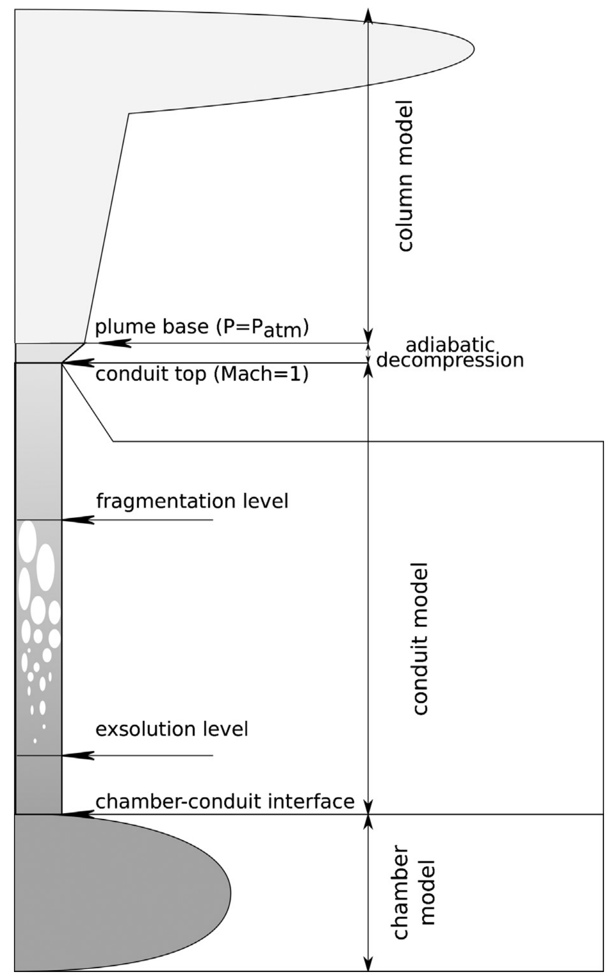

Fig. 1. The four physical domains modeled by the C^3 code: magma chamber, conduit, decompression region and column.

2. The physical model

In this work, we extended the CPIUC model (acronym for Chamber plus Conduit; Macedonio et al., 2005) by adding the description of flow decompression at the vent and the plume dynamics to the description of magma chamber withdrawal and conduit flow. The new model thus attempts to study links among magma chamber, conduit, crater and columns dynamics (Fig. 1). The original CPIUC code coupled a quasi-steady-state magma chamber withdrawal model with a steady-state conduit flow model. This steady-state assumption is justified by the fact that during explosive eruptions the time scale of pressure variations at the conduit base (top of magma chamber) is one order of magnitude higher than the travel time of magma in the conduit ($\tau_{chamber} \approx$ hours, $\tau_{conduit} \approx$ minutes) (Macedonio et al., 2005). According to this model the end of the eruption is controlled by the mechanical threshold of the rocks, which determines the failure of the chamber roof (Macedonio et al., 2005) or the collapse of the conduit walls.

The steady-state assumption adopted for conduit flow was also used in the new description of flow decompression in the underexpanded jet at the crater and in the description of plume dynamics. Although both processes are characterized by significant multidimensional and transient effects (Carcano et al., 2013;