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Temporal evolution of flow conditions in sustained magmatic explosive eruptions

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Abstract

The temporal evolution of fundamental flow conditions in the magma chamber plus conduit system–such as pressure, velocity, mass flow-rate, erupted mass, etc.–during sustained magmatic explosive eruptions was investigated. To this aim, simplified one-dimensional and isothermal models of magma chamber emptying and conduit flow were developed and coupled together. The chamber model assumed an homogeneous composition of magma and a vertical profile of water content. The chamber could have a cylindrical, elliptical or spherical rigid geometry. Inside the chamber, magma was assumed to be in hydrostatic equilibrium both before and during the eruption. Since the time-scale of pressure variations at the conduit inlet–of the order of hours–is much longer than the travel time of magma in the conduit–of the order of a few minutes–the flow in the conduit was assumed as at steady-state. The one-dimensional mass and momentum balance equations were solved along a circular conduit with constant diameter assuming choked-flow conditions at the exit. Bubble nucleation was considered when the homogeneous flow pressure dropped below the nucleation pressure given the total water content and the solubility law. Above the nucleation level, bubbles and liquid magma were considered in mechanical equilibrium. The same equilibrium assumption was made above the fragmentation level between gas and pyroclasts. Due to the hydrostatic hypothesis, the integration of the density distribution in the chamber allowed to obtain the total mass in the chamber as a function of pressure at the chamber top and, through the conduit model, as a function of time. Simulation results pertaining to rhyolitic and basaltic magmas defined at the Volcanic Eruption Mechanism Modeling Workshops (Durham, NH, 2002; Nice, France, 2003) are presented. Important flow variables, such as pressure, density, velocity, shear stress in the chamber and conduit, are discussed as a function of time and magma chamber and conduit properties. Results indicate that vent variables react in different ways to the pressure variation of the chamber. Pressure, density and mass flow-rate show relative variations of the same order of magnitude as the conduit inlet pressure, whereas velocity is more constant in time. Sill-like chambers produce also significantly longer and more voluminous eruptions than dike-like chambers. Water content stratification in the chamber and the increase of chamber depth significantly reduce the eruption

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duration and volume. Maximum erupted mass fractions of about 0.2 are computed for small water-saturated and shallow chambers.

Keywords: explosive eruptions; magma chamber discharge; conduit flow; temporal evolution; pressure evolution

1. Introduction

Sustained explosive eruptions are large-scale catastrophic phenomena during which mass and energy are transferred from a magmatic reservoir located in the Earth's crust to the atmospheric environment (Sparks et al., 1997; Sigurdsson et al., 1999). Typical values of erupted mass range between 0.1 and 100 km^3 of magma (i.e. VEI between 4 and 6) corresponding approximately to energies between 10 million and 10 billion of tons of TNT (TriNitroToluene) (Woo, 1999). Although such a transfer can be affected by a large number of factors including, among the most important, the magmatic and structural properties of the system, the geodynamic context, the volume of the magmatic reservoir, etc., it always occurs during a significant period of time, typically from a few hours up to a few days, during which the initial energy of the system is gradually transformed and dissipated (Sparks et al., 1997). As a consequence, an explosive eruption is never, strictly speaking, at steady-state but slowly evolves from an initial state up to its end. It is therefore important to analyze the evolution in time of the volcanic system behavior in order to better interpret and understand its dynamics. Such evolution indeed dictates the main characteristics of the eruptive event, such as its style, scale, duration and, ultimately, its hazard.

The reference picture of our modeling analysis is here the existence of a purely magmatic volatile-rich reservoir, or magma chamber, located several kilometers below the ground surface, that suddenly, due to some trigger, becomes able to decompress into the atmosphere through a volcanic conduit to produce a central-vent explosive eruption (Sparks et al., 1997). Although the influence of volcanic structure and atmospheric dispersal processes on eruption evolution is, under certain circumstances, quite important, it is definitely the dynamics of magma chamber and conduit flow that mostly control the temporal scale of the eruption as well as its magnitude and intensity. It is therefore particularly instructive to analyze together these two sub-domains of the volcanic system in order to determine their mutual effects and to provide input data for the analysis of the associated atmospheric dispersal and stress evolution in the volcanic edifice.

Magma chamber decompression and discharge have already been investigated by a number of studies. Druitt and Sparks (1984) analyzed the pressure variation in a magma chamber during a caldera-forming eruption by using a simple lumped-parameter model. Woods and Koyaguchi (1994) studied the dependency of the eruptive style (effusive vs. explosive) as a function of magma chamber overpressure, mass eruption rate, and gas loss through a permeable conduit. More recently, Bower and Woods (1997) investigated the influence of magma chamber depth and magma water content on the amount of mass erupted in explosive eruptions by assuming a lithostatic distribution of pressure in the reservoir. More complete thermo-fluid-dynamic numerical models of magma chamber able to elucidate on some important aspects of magma flow circulation and thermodynamics were also developed by Spera (1984), Tait et al. (1989) and Folch et al. (1998). Finally, Martì et al. (2000) revised the Bower and Woods' (1997) model of magma chamber decompression by assuming an hydrostatic distribution of pressure in the chamber and applying it to the analysis of pressure evolution in caldera-forming eruptions. Similarly to magma chamber, the dynamics of magma ascent in a volcanic conduit during sustained magmatic eruptions have been described by several modeling works (see, for instance, Wilson et al., 1980; Dobran, 1992; Melnik, 2000; Papale, 2001). A complete and updated inventory of conduit flow models can actually be found in this special volume where the main results of two Volcanic Eruption Mechanism Modeling workshops held in Durham, New Hampshire, in November 2002 and Nice, France,