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The effect of magma flow on nucleation of gas bubbles in a volcanic conduit

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Abstract

We solve the dynamics of magma ascent and the kinetics of bubble nucleation and growth simultaneously, which allow us to predict bubble sizes and number densities under ascent conditions. As magma rises toward the surface, the pressure decreases and eventually becomes less than the solubility pressure. When the degree of supersaturation becomes great enough, bubbles nucleate. Nucleation will stop as the concentration of volatiles in the melt decreases due to growth of existing bubbles and hence the degree of supersaturation decreases. We show that a second nucleation event may occur just below the fragmentation level. Near that level, the degree of supersaturation continuously increases as the magma is rapidly decompressed. As a result, nucleation will not stop until fragmentation occurs. This second nucleation event should be taken into account when interpreting bubble size distribution measurements made on natural pumices. The bubbles of the second nucleation event have high internal gas pressures up to 2 MPa greater than the liquid pressure, suggesting that the second nucleation event may enhance fragmentation of magma. We apply the model to the calculation protocol defined at the “Volcanic eruption mechanism modeling workshop, Durham, 2002”. We found that as a result of disequilibrium degassing fragmentation occurs higher in the conduit than under equilibrium degassing.

Keywords: nucleation; magma; explosive eruption; viscosity; gas bubbles

1. Introduction

Eruptions involving a viscous magma are the most destructive and unpredictable volcanic events. These eruptions are explosive or effusive, mainly depending on the behavior of the gas phase within the magma. During ascent from the chamber to the surface, pressure decreases and the volatiles dissolved at depth exsolve to form gas bubbles. The flow regime is laminar until the gas volume fraction becomes high, and then the magma fragments and the flow becomes turbulent. This level is called the fragmentation level. The occurrence of fragmentation determines whether

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the eruption is explosive or effusive. Previous numerical models already investigated a wide range of processes occurring within the conduit and involving the gas phase (Toramaru, 1989; Wilson et al., 1980; Jaupart and Allègre, 1991; Massol et al., 2001; Melnik, 2000; Papale, 2001; Mastin, 2002).

In order to better understand important features of volcanic eruptions such as change in eruptive style or the interpretation of geophysical measurements, it is necessary to couple magma flow with more microscopic processes occurring during magma ascent, such as nucleation of bubbles and crystals or the mechanism of fragmentation. The dynamics of bubble growth, such as the evolution of gas volume fraction, bubble size distribution, and gas overpressure before and after fragmentation have been widely studied from this point of view (Sparks, 1978; Navon et al., 1998; Proussevitch and Sahagian, 1996; Thomas et al., 1994; Kaminski and Jaupart, 1997). Sparks first showed in his pioneering work (Sparks, 1978) that gas overpressure can be built inside bubbles during ascent of highly viscous magmas (Wilson et al., 1980), and this idea has been supported by recent experimental and theoretical studies on bubble growth (Navon et al., 1998; Proussevitch and Sahagian, 1996; Gardner et al., 1999; Mourtada-Bonnefoi and Laporte, 2002). Nucleation of bubble is another key process which controls the behavior of the gas phase in conduits (Toramaru, 1989). Whether and how deep in the conduit nucleation occurs control the vesiculation dynamics, and hence influence the explosivity of an eruption (Mangan et al., 2004). Two end-members of nucleation exist at present; those are homogeneous nucleation that requires high volatiles supersaturation in the melt and heterogeneous nucleation on crystals or any solid surface that requires less supersaturation. It has also been suggested that some molecular scale heterogeneities or region in melts with crystal-like structure may aid heterogeneous nucleation. Recent publications (Mourtada-Bonnefoi and Laporte, 2002) pointed out that in the case of homogeneous nucleation in rhyolitic magmas, no nucleation occurs even for melts containing up to 4 wt.% water, suggesting that wide variations in the degree of disequilibrium degassing may contribute to the observed diversity of the eruption dynamics. In this study we focus on the interplay between (1) nucleation and growth of bubbles and (2) decompression due to magma ascent. We model the ascent dynamics of a viscous magma by solving simultaneously bubble nucleation and growth together with magma flow submitted to given boundary conditions at the bottom and top of the conduit. Such an approach allows us to assess whether degassing occurs at equilibrium and the effects on bubble pressures and ascent dynamics in general. Furthermore, because bubble growth is explicitly taken into account, bubble size is calculated as an output of the model.

In the following sections, we first describe the theory and the calculation method. Next, we show results and differences from the chemical equilibrium case. The effects of homogeneous or heterogeneous nucleation are investigated by varying effective surface tension in the calculations. The effects of nucleation and growth of bubbles on the process of fragmentation are studied by applying the different criteria available at present (i.e. critical gas volume fraction, critical strain rate (Papale, 1999), and stress around bubble (Zhang, 1999)) to our model. Finally we briefly discuss some geological implications, particularly from the viewpoint of resultant bubble size distribution.

The aim of this paper is not to reproduce exactly a true eruption but rather to understand: (1) what are the differences introduced by a non-equilibrium degassing in terms of magma ascent dynamics and the implications for eruptive processes, and (2) to predict, to a first order, bubble-size distributions that can be measured on natural eruptive products (i.e. pumices).

2. Governing equations

Magma ascends from the top of the magma chamber to the surface driven by the pressure difference between the chamber and the surface. During ascent, pressure decreases and the volatiles dissolved at depth exsolve to form gas bubbles. We calculate the dynamics of one-dimensional steady flow of the gas–liquid mixture through a cylindrical conduit of constant radius between the magma chamber and the surface and simultaneously the decrease in dissolved water and change of viscosity in the melt with nucleation and bubble growth at each step.