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Bubble growth processes in magma surrounded by an elastic medium

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Abstract

Gas bubble growth in magma plays an important role in volcanic explosivity, and many previous studies have undertaken theoretical and experimental analyses of gas bubble expansion in melt. These previous studies commonly assume constant ambient pressure, but it is more natural to assume that the magma is stressed by the crust or volcanic edifices as the volume of gas bubbles increases. Here we present a bubble growth model that takes into account the elasticity of the surrounding medium; we use this model to examine temporal changes in the bubble growth process. Our model consists of a two-dimensional dike filled with compressible viscous melt and numerous tiny gas bubbles. We use the cell model proposed by Proussevitch et al. [Proussevitch, A., Sahagian, D. L., Anderson, A. T., 1993. Dynamics of diffusive bubble growth in magmas: isothermal case. J. Geophys. Res. 98, 22283–22307] to describe the interaction between the numerous gas bubbles and the melt. The bubble growth process is formulated by the diffusion equation of volatiles in the melt, the mass balance between bubbles and melt, and the momentum equation of the melt. We also introduce pressure balance equations between the melt and the surrounding elastic medium [Nishimura, T., 2004. Pressure recovery in magma due to bubble growth. Geophys. Res. Lett. 31]. Using the finite difference scheme, we numerically calculate temporal changes in bubble radius and melt pressure within magma subjected to sudden depressurization. Simulation results show that the elasticity of the surrounding medium strongly controls the bubble growth process. Under high effective rigidity, the final bubble radius is several times smaller than for zero rigidity, and the time required for bubble growth is an order of magnitude quicker. Temporal changes in the melt pressure are particularly dependent on the elasticity of the surrounding medium. Melt pressure effectively recovers and even exceeds the given pressure drop for conditions of high rigidity and/or small initial bubble radius. Although bubble growth in magma has previously been investigated mainly from geological samples and theoretical perspectives, our model can quantitatively evaluate pressure changes in magma that can also be detected by seismic and geodetic measurements.

Keywords: bubble growth; magma; elastic medium; dike

1. Introduction

Many researchers have investigated bubble growth processes in magma over the past few decades, as bubble growth of volatiles such as H_2O and CO_2 within magma plays an important role in the explosivity of volcanic eruptions and the migration of magma. Sparks (1978) conducted a fundamental

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study on the relationship between bubble growth processes and controlling variables such as magma ascent rate, viscosity of melt, and diffusivity coefficient of volatiles. He numerically examined the bubble growth process in an ascending magma on the basis of a simple physical model. The model assumes a single gas bubble in an infinite melt, and diffusive bubble growth obeys a parabolic growth law as presented by Scriven (1959). Proussevitch et al. (1993) proposed a cell model that simplifies the interaction between numerous gas bubbles and surrounding melt. The authors used the cell model to examine temporal changes in bubble growth by solving the diffusion equation under the condition of a constant ambient pressure for rhyolitic and basaltic magma. Proussevitch and Sahagian (1996) further applied the cell model to an ascending magma to examine temporal changes in bubble radius and the amount of saturated volatiles in rhyolitic and basaltic melt. They showed that bubble radius increases rapidly as the magma reaches shallow depths; in this study, magma ascent within a vertical conduit was simply expressed by reducing ambient pressure at a constant rate.

To compare these numerical simulation results with experimental data, Lyakhovsky et al. (1996) performed a bubble growth experiment under high-pressure conditions of 150 MPa and high temperature of 780–850 °C. They decompressed rhyolitic melt hydrated from 150 MPa to 15–145 MPa and showed that the measured bubble radius and number density of bubbles are well explained by the bubble growth model of Proussevitch et al. (1993). Lensky et al. (2004) recently obtained analytical solutions for the first, second, and third stages of bubble growth, which are controlled by viscous resistance, diffusion of volatiles, and decompression due to magma ascent, respectively. The solutions are in good agreement with their experimental data and numerical solutions based on the bubble growth model of Proussevitch et al. (1993). These previous studies have mainly involved theoretical investigations of magma dynamics in a volcanic conduit and interpretations of the characteristic features of geological samples.

Geodetic measurements such as tilt and strain meters and GPS networks enable the quantitative evaluation of magma activity beneath volcanoes (e.g., Okada and Yamamoto, 1991; Voight et al., 1998). Since magma density is lower than the density of the crust, the buoyancy force is generally considered the most probable driving force of magma intrusions, however recent advances in geodetic and seismic measurements reveal pressure increases that appear to be related to bubble growth within magma. For example, Yamamoto et al. (2001) and Fujita et al. (2002) observed step-like changes in tilt of the ground surface caused by the intermittent opening of cracks over a 2-minute period at depths of about 6–8 km during the 2000 eruption at Miyakejima Volcano, Japan. The authors interpreted crack development to result from vesiculation processes within the magma. Excitation of volcanic low-frequency earthquakes and explosion earthquakes are also considered to be related to rapid bubble growth in magma. For example, recent seismic observations at Suwanosejima Volcano, Japan, detected a deflation that triggered rapid expansion of the magma in the conduit at the initiation of small Vulcanian eruptions (Tameguri et al., 2004; Iguchi, 2005). It is not easy to explain such rapid expansion following deflation processes by buoyancy alone.

These geophysical studies suggest that bubble growth processes in magma can also be investigated from geophysical observations. However, most of the bubble growth models proposed in previous studies presume a constant ambient pressure of the melt so that interactions between the melt and surrounding medium are neglected; this is necessary to quantitatively relate bubble growth processes to seismic and geodetic observations. Recently, Nishimura (2004) examined how the elasticity of the surrounding medium affects bubble growth processes in magma. He examined the final bubble radius and pressure in melt subjected to a pressure drop which may be caused by dike injection, plug opening of a volcanic pipe, and stress changes induced by nearby earthquakes, and he found that the pressure in magma is recovered when the effective elasticity of surrounding medium is sufficiently large. However, his model did not take into account temporal variations.

In the present study, therefore, we present a new bubble growth model that takes into account the elasticity of the medium surrounding the melt. By combining the cell model of Proussevitch et al. (1993) with the interactions of melt and surrounding elastic medium (Nishimura, 2004), we are able to examine temporal changes in bubble radius and the melt pressure within a dike.

2. Bubble growth model

2.1. Outline of bubble growth model

We consider a magma chamber embedded in a volcanic edifice or crust. Magma is saturated with