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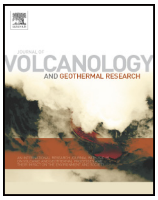

Numerical investigation of temporal changes in volcanic deformation caused by a gas slug ascent in the conduit

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ABSTRACT

Strombolian type eruptions are considered to be generated by a sudden release of a large gas slug that migrates upward in the conduit filled with a low viscous basaltic magma. We examine volcano deformations caused by such a gas slug to understand the Strombolian eruption mechanism from geodetic observation data. We model spatio-temporal pressure changes in the conduit by using a gas slug ascent model presented by James et al. (2008). As a gas slug ascends in the conduit, its volume expands because of depressurization. Hence, the magma head lifts up in the conduit and the upper part of the conduit wall is stressed. In the conduit, magma pressure increases with depth according to the bulk density of magma: the gas slug part with a low density is characterized by a small pressure gradient, while the other parts, consisting of melt, are characterized by a large pressure gradient. We numerically calculate volcano deformations caused by the spatio-temporal changes of magma pressure predicted from the basic equations representing gas slug locations in the conduit. Simulation results show that the radial and vertical displacements and tilt changes indicate volcano deformations that represent the inflation originating from the stress increase at the upper part of conduit. As the gas slug reaches the shallow part of conduit, the rate of inflation observed in the radial displacement decreases, the vertical displacement starts to move downward, and the tilt turns to show down toward the crater. These deflation signals are caused by a moving deflation source in the conduit that is formed beneath the gas slug. Since these predicted features are not observed in the tilt records associated with explosions at Stromboli volcano (Genco and Ripepe, 2010), it is necessary to modify the gas slug ascent model or to introduce other mechanisms to better understand the magma dynamics of Strombolian eruption.

1. Introduction

At volcanoes characterized by a low-viscosity basaltic magma, large gas bubbles with a diameter up to several meters are visible on the ground surface at eruptions (Chouet et al., 1974; Blackburn et al., 1976). These types of eruptions have been considered to be generated by a periodic release of large gas slugs coming up in the conduit from a deep portion. To quantitatively understand the gas slug motions and Strombolian eruptions, many studies have been conducted for the last several decades. Numerical models of gas slug flow based on the two-phase flow equations are presented to understand the gas slug dynamics in the volcanic conditions (e.g., Vergniolle, 1998; James et al., 2008). Vergniolle (1998) numerically investigates the gas slug ascent process in the conduit using the equations of motion of liquid magma and state of gas in the slug, and explains the amplitude of acoustic pressure at Stromboli. James et al. (2008) modified the model of Vergniolle (1998) by including the motion of magma surrounding the gas slug. Laboratory experiments have also been conducted to examine the gas slug generation and ascent processes (e.g., Vergniolle and Jaupart, 1990; Seyfried and Freundt, 2000; James et al., 2006; Llewellin et al., 2011). These experiments demonstrate gas slug flows ascending in water or oil in a vertical narrow tube with a length of a few meters and a diameter of a few centimeters. Gas slug ascent velocity and associated pressure changes measured in these laboratory experiments are well matched with the gas slug ascent models presented by James et al. (2008). Over pressure in the gas slug predicted from their gas slug ascent models is used to discuss observed data such as explosion strength and amount of ejecta (James et al., 2009; Del Bello et al., 2012).

Continuous geophysical monitorings using seismic, geodetic, acoustic sensors and visual and/or thermal videos have been carried out at Stromboli volcano, Italy. These data have improved our understanding of degassing processes and near surface magma dynamics on the basis of gas slug flow processes in the conduit (e.g., Ripepe et al., 2001; Ripepe and Marchetti, 2002; Chouet et al., 2003; Ripepe et al., 2007; Ripepe and Harris, 2008; Chouet et al., 2008; Marchetti et al., 2009). Chouet et al. (2003) analyze very-long-period seismic signals associated with explosions at Stromboli. They estimate the locations of seismic sources at depths of 220 m and 260 m, 160 m northwest from the craters at Stromboli by applying a waveform inversion. Chouet et al. (2008) further analyze these seismic records and estimate two more seismic sources

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located at depths of about 800 m and 1000 m below the craters. These seismic source locations and volumetric mechanisms are interpreted to reflect a sequence of pressure changes associated with piston-like action of melt associated with the disruption of a gas slug transiting through discontinuities in the conduit. Ripepe et al. (2001) investigate the explosive source mechanism by seismic and infrasonic signals at Stromboli volcano by analogy to laboratory experiments using a cylindrical tank with a narrow conduit, and estimate the explosion level at 600 m above sea level. The explosion depth and ejecta velocities are estimated to be about 20–100 m below the crater and 100 m s^{-1}, respectively, from analyses of thermal camera and infrasound data (Ripepe and Marchetti, 2002; Delle Donne and Ripepe, 2012).

Recently, geodetic observations at active volcanoes have succeeded in detecting volcano inflation prior to small explosions from an open conduit such as Strombolian and Vulcanian eruptions. Tilt observations conducted at 0.5 km distance from the active craters captured uplift toward the active crater with amplitudes of about 10–100 nrad before repetitive Vulcanian explosions at Semeru volcano, Indonesia (Nishi et al., 2007; Nishimura et al., 2013). A tiny subsidence (about 10–200 nrad) of the active crater at distance of 0.5–2 km is observed at the last stages of volcano inflation at Sakurajima, Semeru and Suwanosejima volcanoes (Iguchi et al., 2008). These inflations and tiny deflations are interpreted as gas accumulations beneath a cap of the conduit and leakage of the gas just before the explosions, respectively.

To quantitatively understand these geodetic data, several models on magma ascent in a shallow conduit are presented. Nishimura (2009) studies volcano deformations caused by three simple magma ascent models of Poiseuille flow, diffusive gas bubble growth and rising bubbles models, and pointed out that differences of these models appear in temporal changes of ground deformation. Kawaguchi et al. (2013) further examine volcano deformations by numerically calculating magma flow with diffusive gas bubble growth, and showed that volcano inflation prior to an eruption increases with an accelerated rate, when the magma ascent is effectively driven by the gas bubble growth in magma. These studies are used to interpret the tilt motions observed at Semeru and Suwanosejima volcanoes (Nishimura et al., 2012, 2013).

At Stromboli volcano, Genco and Ripepe (2010) conducted tilt observations at five stations that were deployed at 300–1000 m distances from the crater (Fig. 1). They report that about 5–80 nrad tilt motions are observed before each explosion. These tilt motions indicated accelerated inflation of the direction of active crater. Such motions may be interpreted with the gas slug ascent model that are used to theoretically examine VLP seismic signals associated with Strombolian eruptions or gas bursts at Hawaii (O'Brien and Bean, 2008; Chouet et al., 2010). However, there are few studies quantitatively examining relations of theoretical gas slug ascent model in the conduit with the geodetic signals observed by volcanic monitoring that could capture macroscopic views in magma motion in a shallow conduit. In the present study, therefore, we examine volcano deformation caused by gas slug ascent in the conduit. First, we briefly explain the gas slug ascent process in an open conduit based on the model by James et al. (2008) that well explains laboratory experimental data. Subsequently, we calculate spatio-temporal changes of magma pressure in the conduit and volcano deformation caused by the gas slug ascent in the conduit. Then, we examine the characteristics of volcano deformations. Finally, we compare simulation results with the tilt data observed at Stromboli volcano by Genco and Ripepe (2010) to test whether or not the gas slug ascent model can be applied to explain the recorded signals.

2. Model

2.1. Slug ascent model

Fig. 2 shows a schematic illustration of the gas slug ascent process in an open cylindrical conduit. A cylindrical conduit with a constant radius a vertically elongates beneath a vent. We suppose no magma flux from the bottom of the conduit. We set one large gas slug with a constant radius r_s and an initial length L_0 at a deep portion in the conduit. The initial gas pressure of the slug p_{g0} is assumed to be equal to the overburden pressure that is expressed by the sum of atmospheric P_a and static magma pressures:

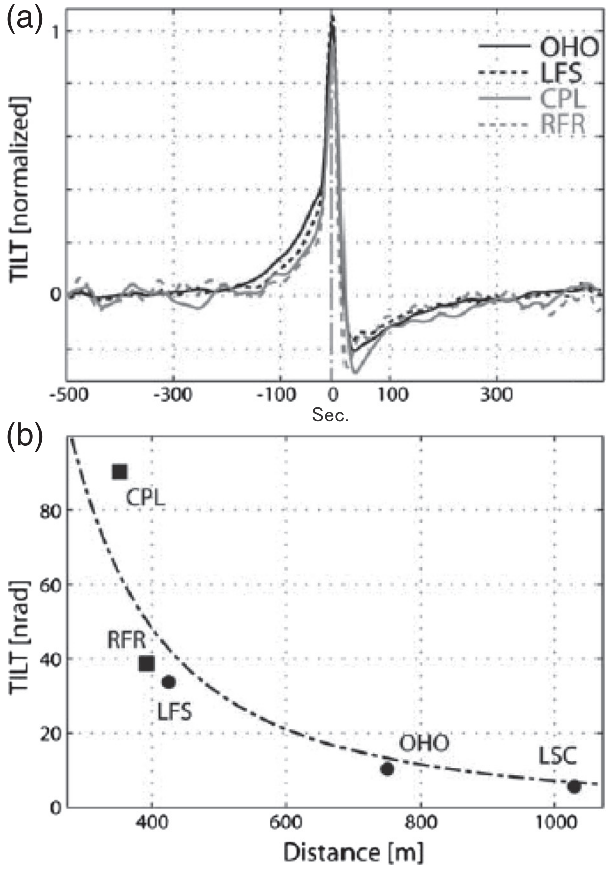

Fig. 1. Tilt records at five stations with distances of 300 to 700 m from the active crater at Stromboli volcano (modified from Fig. 4 in Genco and Ripepe, 2010). Tilt records are observed by tilt meters at "LFS", "OHO" and "LSC" stations (circle) and are retrieved from broadband seismometers at "CPL" and "RFR" stations (square). (a) Temporal changes of tilts at four stations. Stacked tilt records using about 2000 events are normalized by the maximum amplitudes of each station. Tilts at all stations show uplift toward the active crater about 200 s before explosive onset (dashed gray line at $t = 0$ s). (b) Tilt amplitudes versus horizontal distance from the active crater. Dashed line shows the theoretical tilt amplitude calculated from an infinite extending open conduit (see detail in Genco and Ripepe, 2010).

$$p_{g0} = \rho_m g l_0 + P_a, \tag{1}$$

where ρ_m is the melt density, g is the gravitational acceleration and l_0 is the initial length of melt above the top of the slug.

The gas in the slug is assumed to be ideal gas under isothermal conditions. Hence, the gas pressure p_g is expressed by

$$p_g = p_{g0}\left(\frac{L_0}{L}\right), \tag{2}$$

where L is the slug length. As the gas slug ascends in the conduit, the pressure at the top of the slug decreases and the volume of gas slug increases. Incompressible melt is assumed so that the equation of mass conservation is written as:

$$l_0 \pi a^2 + L_0 \pi (a^2 - r_s^2) = (l + l_b) \pi a^2 + L \pi (a^2 - r_s^2), \tag{3}$$

where l_b is the length of melt below the bottom of the slug.