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Three-dimensional numerical analysis of magma transport through a pre-existing fracture in the crust

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ABSTRACT

Magmas are transported through pre-existing fractures in many repeatedly erupting volcanoes. The study of this special process of magma transport is fundamentally important to understand the mechanisms and conditions of volcanic eruptions. In this paper, we numerically simulate the magma propagation process through a pre-existing vertical fracture in the crust by using the combined finite difference method (FDM), finite element method (FEM) and discontinuous deformation analysis (DDA) approach. FDM is used to analyze magma flow in the pre-existing fracture, FEM is used to calculate the opening of the fracture during magma intrusion, and DDA is used to deal with the contact of the closed fracture surfaces. Both two-dimensional (2D) and three-dimensional (3D) examples are presented. Parametric studies are carried out to investigate the influence of various physical and geometric parameters on the magma transport in the pre-existing fracture. We have considered magma chamber depth ranging from 7 km to 10 km under the crust surface, magma viscosity ranging from 2×10^{-2} to 2×10^{-7} MPa s, and the density difference between the magma and host rock ranging from 300 to 700 kg/m^3. The numerical results indicate that (1) the fluid pressure p varies gradually along the depth, (2) the shape of the magma body during propagation is like a torch bar and its width ranges from 2 m to 4 m approximately in the 3D case and 10 m to 50 m in the 2D case for the same physical parameters used, (3) the crust surface around the pre-existing fracture begins to increase on both sides of the fracture, forms a trough between them, then gradually uplifts during the transport of the magma, and finally takes the shape of a crater when the magma reaches the surface. We have also examined the influence of physical and geometric parameters on the minimum overpressure for magma transport in the 3D case. The numerical results show that our numerical technique presented in this paper is an effective tool for simulating magma transport process through pre-existing fractures in the crust.

1. Introduction

Transport and focusing of magma from the mantle to the Earth's surface is an important, yet poorly understood process. Previously explored mechanisms for magma transport include dyke propagation (e.g., Lister and Kerr, 1991; Rubin, 1995) and porous flow (e.g., Spiegelman and Kelemen, 2003). Dyke propagation has been considered a dominant mechanism for magma transport in the crust. Differential stresses due to the buoyancy and pressure of the magma and local tectonic stresses cause magma-filled cracks to open and propagate from the magma chamber.

Various analytical analyses and numerical simulations for magma-driven crack propagation have been performed in previous works (for example, Petford et al., 1993; Weinberg, 1999; Gudmundsson, 2006; Wei et al., 2006; Xu et al., 2006; Chen et al., 2007, 2011a,b; Currenti et al., 2008; Zhang et al., 2009; Kraus et al., 2010; Bonaccorso et al., 2010; Chen and Jin, 2011). Weertman (1971) demonstrated that a sufficiently large buoyant fluid-filled crack would begin to propagate upwards but did not include the effects of viscous flow in the crack. Spence and Sharp (1985) obtained a similarity solution for a fluid driven crack that propagates symmetrically in an infinite solid from an over-pressured source without consideration of buoyancy. Spence et al. (1987) considered the effect of buoyancy on the propagation of a crack fed by a constant flux of fluid. In geological applications it seems more appropriate to specify the source overpressure instead of the flux. Lister (1990) gave similarity solutions for the horizontal and

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vertical propagation of fluid-filled cracks. Many numerical solutions have been obtained for the opening and propagation speed of a dyke driven by buoyancy and a specified magma source overpressure. Dahm (2000) developed a boundary-element model for fluid-filled buoyancy-driven crack propagating in a homogeneous half-space and studied how stress and density heterogeneities govern the direction of dyke propagation. Roper and Lister (2007) extended the results of Lister (1990) to model the case when the fracture toughness of the hosting rock is large. Maccaferri et al. (2010) developed a mathematical model describing dyke propagation in proximity of an elastic discontinuity of the embedding medium. The mathematical simulations provide a sort of 'refraction phenomenon', that is, a sudden change in the direction of propagation when the crack crosses the boundary separating different rigidities. All the above-reviewed papers modeled dykes as 2D fluid-filled cracks in a homogeneous medium. Attempts to extend the models to 3D or layered media are limited to static cracks. Gudmundsson (2005) analyzed the influence of local stress and layering on dyke propagation in volcanic areas assuming that dykes propagate in the direction of the maximum compressive stress.

Closed or opened fractures exist around repeatedly erupting volcanoes. Magmas may also be transported through these pre-existing fractures. The study of this special process of magma transport is fundamentally important to understand the mechanisms and conditions of volcanic eruptions. Obviously, there are some differences between magma transport through pre-existing fractures and dike propagation (fluid driven fracture propagation). Magma transport through pre-existing fractures does not involve a fracture criterion that governs crack propagation as in the case of dike propagation. Magma transport in a pre-existing fracture is governed by the viscous flow and influenced by the elastic deformation of the host rock as the fracture surfaces are pressured by the magma. Le Corvec et al. (2013) presented an experimental approach to investigate the interaction of a propagating dike through a medium with pre-existing fractures. Their results highlighted the influence of pre-existing fractures on the mechanics and dynamics of dykes.

In this paper, we present a 3D numerical model to study the magma transport process through a pre-existing fracture in the crust using the combined finite difference method (FDM), finite element method (FEM) and discontinuous deformation analysis (DDA) approach. We assume that the pre-existing fracture is opened with a defined breadth. FDM is used to analyze magma flow in the fracture, FEM is used to calculate the opening of the fracture during magma intrusion, and DDA is used to deal with the contact of the closed fracture faces. Parametric studies are carried out to investigate the influence of various physical and geometric parameters on the magma transport in the pre-existing fracture. We have also discussed the differences in the simulation results between the 3D and 2D models and the minimum overpressure in the magma chamber for magma to propagate to the surface.

2. Model

Magma generated in partially molten regions in the upper mantle may ascend to crustal magma chambers through porous flow (e.g., Spiegelman and Kelemen, 2003) and dyke propagation (e.g., Johnson and Jin, 2009). The magma chamber pressure increases with the continuous flow of magma into the chamber. Failure occurs in the host rock surrounding the magma chamber when the chamber pressure reaches a critical value, thereby allowing the magma to propagate into the host rock through either newly generated or pre-existing fractures. The conditions of magma propagation direction depend on a number of factors such as rock properties, rock heterogeneities, tectonic stresses, geometry of magma chamber and so on (Currenti and Williams, 2014). Depending on the combined effects of these factors, magma may propagate in either vertical or horizontal directions or along a curved path by opening new cracks in the host rock (Dahm, 2000; Bonaccorso et al., 2010; Maccaferri et al., 2010). Magma may also intrude through pre-existing fractures at the magma chamber. In this paper, we study magma intrusion through a pre-existing fracture at the magma chamber. We further assume that the pre-existing fracture is straight and in the vertical direction. The direction of magma propagation is thus fixed in our model.

Consider a pre-existing vertical fracture in a host rock as shown in Fig. 1. The top of the model is stress-free, and the bottom of the model is fixed along the vertical direction. Tectonic stresses are loaded on the four vertical sides. The bottom of the fracture is at a magma chamber whose depth is denoted by H. Magma flows vertically through the fracture under the magma chamber overpressure as well as the buoyancy force. The propagation distance of the magma from the chamber is denoted by $a(t)$ which is a function of time t. We assume that the breadth of the magma-filled fracture (in the x-direction) is a constant. Both magma solidification and water effect are not considered in the model. Effect of magma solidification may be ignored if the magma does not propagate at a very low speed.

2.1. Lubrication

We model the magma as a viscous fluid. The flow of viscous fluid in the fluid-filled zone ($0<z<a$) is governed by the Reynolds equation, according to lubrication theory (Panton, 1984)

$$\frac{\partial \omega}{\partial t} = \frac{1}{12\eta}\frac{\partial}{\partial z}\left(\omega^3 \frac{\partial}{\partial z}(p+\rho_m g z)\right). \tag{1}$$

where p is the fluid pressure, ω is the fracture opening in the fluid-filled zone, η is the viscosity of the magma, ρ_m is the magma density and g is the gravitational acceleration. Eq. (1) is deduced from the Poiseuille law

$$q = -\frac{\omega^3}{12\eta}\frac{\partial}{\partial z}(p+\rho_m g z), \tag{2}$$

and the local continuity equation

$$\frac{\partial \omega}{\partial t} + \frac{\partial q}{\partial z} = 0, \tag{3}$$

where q denotes the flow rate. The fluid pressure p may be expressed as

$$p = p_s - (\rho_s g z + \Delta\sigma), \tag{4}$$

where $p_s = p_s(z)$ is the fluid excess pressure, ρ_s the density of the host rock and $\Delta\sigma = g\Delta\sigma_0\, z$ is the tectonic stress perpendicular to the fracture surface (Rubin, 1995; Roper and Lister, 2005). Combining Eqs. (2) and (4), we have the following equation

$$q = -\frac{\omega^3}{12\eta}\frac{\partial}{\partial z}[p_s + (\rho_m - \rho_s - \Delta\sigma_0) g z] \tag{5}$$

Eq. (5) may be written as follows using the density difference $\Delta\rho = \rho_s + \Delta\sigma_0 - \rho_m$

$$q = -\frac{\omega^3}{12\eta}\frac{\partial}{\partial z}(p_s - \Delta\rho g z) \tag{6}$$

2.2. Elasticity

The elasticity theory is used to determine the relation between the excess pressure $p_s(z)$ and the opening displacement of the fracture,$\omega(z)$. When $p_s(z)$ is known, $\omega(z)$ may be calculated using finite element method combined with discontinuous deformation analysis, which may also deal with the contact between the fracture