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Thermomechanics of shallow magma chamber pressurization: Implications for the assessment of ground deformation data at active volcanoes

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ABSTRACT

In this study, we utilize thermomechanical models to investigate how magma chambers overpressurize as the result of either magmatic recharge or volatile exsolution. By implementing an adaptive reservoir boundary condition we are able to track how overpressure dissipates as the magma chamber expands to accommodate internal volume changes. We find that the size of the reservoir greatly impacts the resultant magma chamber overpressure. In particular, overpressure estimates for small to moderate-sized reservoirs (1–10 km^3) are up to 70% lower than previous analytical predictions. We apply our models to Santorini volcano in Greece where recent seismic activity and ground deformation observations suggested the potential for eruption. The incorporation of an adaptive boundary condition reproduces Mogi flux estimates and suggests that the magma reservoir present at Santorini may be quite large. Furthermore, model results suggest that if the magma chamber is >100 km^3, overpressures generated due to the high magma flux may not exceed the strength of the host rock, thus requiring an additional triggering mechanism for eruption. Although the adaptive boundary condition approach does not calculate the internal evolution of the magma reservoir, it represents a fundamental step forward from elastic Mogi models and fixed boundary solutions on which future investigations of the evolution of the magma can be built.

1. Introduction

It is commonly accepted that volcanic eruption occurs when the chamber wall stresses imposed by the internal pressure of a magma reservoir exceed the sum of the resisting forces, or strength, of the surrounding rock (Blake, 1984; Gerbault et al., 2012; Grosfils, 2007; Grosfils et al., in press; McLeod and Tait, 1999; Tait et al., 1989). Excess internal pressure above lithostatic pressure, referred to herein as overpressure, can be caused by a number of factors including, but not limited to: the influx of new melt (magmatic recharge) and/or the exsolution of volatiles (Tait et al., 1989). Along with seismicity and gas chemistry, ground deformation data provide an effective early warning signal for volcanic eruption, because surface uplift often precedes eruption (Chadwick et al., 2006; Chaussard and Amelung, 2012; Elsworth et al., 2008; Mogi, 1958). In particular, ground deformation data acquired by GPS, tilt meters, and/or Interferometric Synthetic Aperture Radar (InSAR) at an active volcano provide important information about the magma dynamics and pressurization occurring at depth. While surface inflation can indicate magma recharge and provide an early warning for eruption, there are many cases when surface inflation does not result in an eruption (Battaglia et al., 1999; Chaussard and Amelung, 2012; Long and Grosfils, 2009; Lu et al., 2000; Miura et al., 2000; Newman et al., 2001; Papoutsis et al., 2013; Sato and Hamaguchi, 2006; Wicks et al., 2002). As such, understanding the magmatic processes behind the observed inflation is critical for assessing eruption potential for vulnerable populations.

The elastic Mogi point source model (McTigue, 1987; Mogi, 1958) is most commonly used to evaluate ground deformation data and provide a first-order approximation of parameters such as magma chamber depth and volume flux. Nevertheless, source overpressure, which is critical for assessing eruption hazard, is not well constrained from elastic solutions, and thus a more sophisticated viscoelastic rheology is required. Previous analytical studies have investigated the effect of host rock rheology on overpressurization (Folch and Marti, 1998; Jellinek and DePaolo, 2003; Woods and Huppert, 2003). While these efforts provide insight into how the wall rock responds to reservoir overpressurization, a major limitation is that overpressure is assumed constant and is applied as a fixed boundary condition in the model. The fixed boundary condition does not allow magma chamber expansion to

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dissipate overpressure and these models do not provide details of how reservoir overpressure evolves in time.

Classically, numerical investigations of pressurizing magma chambers have all utilized the assumption of a fixed pressure boundary condition (e.g., Trasatti et al., 2005). While more sophisticated numerical approaches have been developed to evaluate observed surface uplift of active volcanic systems (e.g., Currenti et al., 2010; Del Negro et al., 2009; Long and Grosfils, 2009; Newman et al., 2001, 2006), there have yet to be any systematic investigations that look specifically at how the reservoir boundary condition evolves as the magma chamber expands. The Newman et al. (2006) 4D numerical modeling investigation of uplift at Long Valley has come the closest in this regard by utilizing assumed changes in overpressure at discrete times intervals. However, while the Newman et al. (2006) approach provides important insight into the uplift observed at Long Valley, it does not capture the dynamic between reservoir expansion and overpressure dissipation.

These numerical and analytical investigations provide an important foundation upon which the current study builds. A critical gap in our understanding of the evolution of magmatic systems is how the feedback between overpressurization and expansion of the magma chamber occurs. Clearly, this is not a simple matter and chamber growth likely requires the melting and incorporation of wall rock in addition to its deformation to accommodate the increasing chamber volume. Furthermore, it is unlikely that pressure change within the magma chamber will be uniform and there may be an additional feedback between volatile exsolution and overpressure as pressure dissipates during reservoir expansion. That said, an important first step in approaching this problem is to constrain the material response of the surrounding rock to changes in internal chamber pressure. One way to approach this problem is to update previous numerical models to incorporate an evolving reservoir boundary condition that calculates the change in chamber volume in response to the deformation of the wall rock. This addition provides essential new insight into the mechanics of overpressurizing a magma chamber.

In this study, we employ thermomechanical models to investigate how overpressure evolves in response to deformation of the host rock. We utilize the general viscoelastic formulation of Gregg et al. (2012) and have developed a pseudo 3D (2D axisymmetric) dynamic reservoir model that utilizes an adaptive boundary condition along the reservoir boundary. The adaptive boundary condition allows overpressure to evolve through time in response to chamber expansion. This modeling advancement is key for determining how overpressure is accommodated in magmatic systems, and improves our ability to assess the potential for chamber rupture. Finally, we apply the adaptive boundary condition model to investigate the recent inflation event at Santorini volcano, Greece.

2. Numerical approach

We follow the numerical formulation of Gregg et al. (2012) utilizing COMSOL Multiphysics 3.5a to develop an axisymmetric finite element model (FEM). The magma reservoir is treated as a pressurized ellipsoid within a gravitationally loaded temperature-dependent viscoelastic medium (Fig. 1). Overpressure is defined relative to lithostatic pressure at the depth coincident with the top of the chamber. The model geometry is varied to examine parameters such as source size and aspect ratio. The pressurized void model does not take into consideration the evolution of the material properties within the magma reservoir and rather focuses solely on the effect of the host material rheology on deformation and overpressure.

Of particular interest in this investigation is the response of the host material to overpressure within the magma chamber due to a volume increase caused by magmatic intrusion or volatile exsolution, ΔV_m. In the numerical formulation the initial response of the system is governed by the elastic response of the material. In other words, the time = 0 calculation is the elastic solution and the viscoelastic response is calculated as time progresses. The applied increase in ΔV_m may be due to a number of processes, but we focus on magmatic recharge and crystallization-induced volatile exsolution. It is assumed that volatile exsolution is due to oversaturation of volatile phases after crystallization. As such, to investigate ΔV_m due to volatile exsolution, the initial overpressure at time = 0 (OP_0) is calculated from the Tait et al. (1989) elastic formulation for pressurization due to crystallization-induced volatile exsolution:

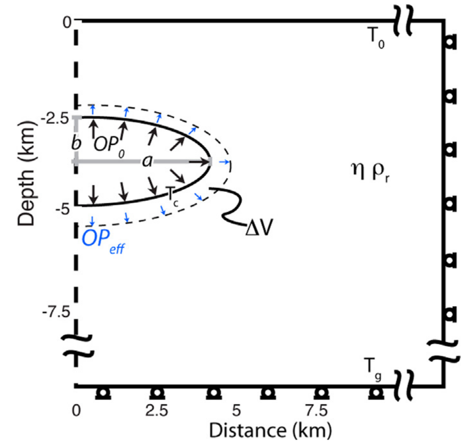

Fig. 1. The axisymmetric numerical model setup. The left boundary condition is axial symmetry and zero displacement, roller conditions are implemented along the right and bottom boundaries. The top of the model is free to deform, as is the magma chamber boundary. The magma chamber is approximated by a pressurized void. The magma overpressure, *OP*, is defined as the magma overpressure at the top of the magma chamber relative to lithostatic pressure. An initial overpressure, OP_0, is applied at $t = 0$ and the magma chamber responds by expanding to a new volume, ΔV. At some time, $t =$ end, the magma chamber reaches a steady-state geometry and *OP* reaches a steady-state, decreased value of OP_{eff}. The magma chamber geometry is varied using major and minor ellipse axes, *a* and *b* respectively. The third dimensional radius, *c* (not shown here), is equal to *a*. For geometrical variations, *b* is kept constant at 0.5, 1, and 2 km, and *a* is varied to achieve the desired 3D chamber volume. For the thermal model used in the temperature-dependent viscoelastic runs, the temperature of the magma chamber ($T_c = 800\,°C$, 900 °C, and 1000 °C) is defined along the magma chamber boundary and an initial background thermal model is calculated using a constant geotherm (30 °C/km), where $T_0 = 0\,°C$ and $T_g =$ geotherm. The magma chamber is assumed to have a constant magma flux and, thus, a steady-state thermal structure is used.

$$P = \left(\frac{P_L^n}{1 - m_c/M}\right)^{1/n}, \tag{1}$$

where P is total pressure ($P_L + OP_0$), m_c/M is the percent crystallization, n is the Henry's law exponent, and the lithostatic pressure $P_L = \rho_r \cdot g \cdot z$. The elastic solution at $t = 0$ is calculated utilizing a P boundary condition along the boundary of the magma chamber. For parameter values used in the numerical model see Tables 1 and 2.

When $OP_0 > 0$, the magma reservoir responds by expanding. The volume change associated with magma chamber expansion dissipates the overpressure. To calculate the pressure decrease due to chamber expansion, we utilize the material definition of the bulk modulus, K:

$$K = -V_R \frac{dP}{dV_R}, \tag{2}$$

where V_R is the volume of the reservoir, dP is the change in pressure, and dV_R is the change in volume of the reservoir. Rearranged to solve for change in pressure:

$$dP = -K \frac{dV_r}{V_r}. \tag{3}$$