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Catastrophic caldera-forming eruptions: Thermomechanics and implications for eruption triggering and maximum caldera dimensions on Earth

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ABSTRACT

Approximately every 100,000 years the Earth experiences catastrophic caldera-forming "supereruptions" that are considered to be one of the most hazardous natural events on Earth. Utilizing new temperature-dependent, viscoelastic numerical models that incorporate a Mohr-Coulomb failure criterion, we find that eruptive failure of the largest magma chambers is a function of the geometry of the overlying roof and the location of the brittle-ductile transition. In particular, the ductile halo created around the hot magma chamber buffers increasing overpressures and prevents pressure relief via magmatic injection from the magma chamber. The numerical results indicate that as chamber volume increases, the higher temperatures in the host rock and the decrease in the roof aspect ratio cause a shift from reservoir-triggered eruption to an external roof-triggered mechanism. Specifically, as overpressure increases within the largest magma chambers, extensive uplift in the overlying roof promotes the development of through-going faults that may trigger eruption and caldera collapse from above. We find that for magma chamber volumes $>10^3$ km^3, and roof aspect ratios (depth/width) <0.3, moderate magma chamber overpressures (<30 MPa) will cause extensive through-going fault development in the overlying roof. This result indicates an external mechanism, caused by fault propagation in the roof, is a likely trigger for the largest caldera forming eruptions. The thermomechanical models also provide an estimate of the maximum size of magma chamber growth in a pristine host material and, thus, an estimate of the maximum size of the resultant caldera. We find a maximum reservoir volume range of 10^4–10^5 km^3 for shallow crustal magma chambers emplaced at depths to the top of the magma chamber of 3–7 km. These volumes produce maximum caldera areas of 10^3–10^4 km^2, comparable to the largest calderas observed on Earth (e.g., Toba). These thermomechanical models offer critical new insight into the mechanics of catastrophic caldera collapse and provide a numerical construct for predicting how eruption is triggered in the largest crustal magma chambers.

1. Introduction

Catastrophic caldera-forming eruptions that emplace 1000s of cubic kilometers of ignimbrites are amongst the most devastating of geologic phenomena. The calderas left in the wake of these explosive events are 10s of kilometers in diameter (e.g., Smith and Bailey, 1968; Lipman, 1984) and the magma bodies that supply these events are thought to be as much as an order of magnitude larger in volume (Smith and Shaw, 1979). Growing an eruptible magma reservoir of this size requires tens of thousands to hundreds of thousands of years of material and thermal fluxes well in excess of average mantle to crust flows (de Silva and Gosnold, 2007; Annen, 2009). Over that time period, repeated intrusions from below heat the host rock in the vicinity of the magma reservoir and enhance its ductility (Annen and Sparks, 2002; Jellinek and DePaolo, 2003; de Silva et al., 2006; de Silva and Gosnold, 2007; Annen et al., 2008; Karlstrom et al., 2010), allowing the reservoir to grow without triggering magma evacuation through intrusion and/or eruption (Jellinek and DePaolo, 2003; Annen et al., 2006). Nevertheless, since a preliminary plinian eruption is a common feature of many catastrophic caldera-forming eruptions (e.g., Druitt and Sparks, 1984), a common mechanism invoked for the onset of caldera collapse is the relief of overpressure through an initial eruption from the magma chamber (Roche et al., 2000; Roche and Druitt, 2001). The resultant underpressurization will rapidly deflate the magma chamber and promote reverse ring faulting through the roof, leading to caldera collapse (Roche et al., 2000; Kennedy et al., 2004; Acocella, 2006; Geyer et al., 2006; Scandone and Acocella, 2007; Simakin and Ghassemi, 2010). However, if the ductile region around a magma chamber inhibits dike and sill formation (Jellinek and DePaolo, 2003), it is difficult to cite a pre-cursor dike injection as the optimal trigger for caldera-forming eruptions in large systems. Furthermore, analog models indicate that precursor eruptions must drain a significant portion of the magma reservoir (10–60%; Geyer et al., 2006) for caldera onset. Finally, many of the largest calderas do not record evidence of an initial plinian eruption

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that would underpressurize the magma chamber and catalyze caldera collapse (Druitt and Sparks, 1984; Sparks et al., 1985; de Silva et al., 2006; Chesner, 2012). Thus, critical gaps in our knowledge of the mechanics of triggering the largest silicic eruptions remain.

Numerical models have been utilized extensively to investigate the formation of collapse calderas at a variety of size scales (Gudmundsson, 1988; Gudmundsson, 1998; Burov and Guillou-Frottier, 1999; Guillou-Frottier et al., 2000; Folch and Marti, 2004; Hardy, 2008; Kinvig et al., 2009; Simakin and Ghassemi, 2010; Karlstrom et al., 2012). Some of these efforts have focused on the elastic problem (e.g., Gudmundsson, 1998), and almost all have focused on rapidly underpressurizing the magma chamber via a precursor eruption to trigger caldera formation (e.g., Kinvig et al., 2009). The thermomechanical models of Burov and Guillou-Frottier (1999) provide an examination of fault development due to uplift in the crust above a pressurized magma chamber prior to rapid underpressurization triggered by a central vent eruption, and are some of the first to illustrate fault formation. However, these numerical experiments did not explore the implications of developing weaknesses in the roof overlying a magma chamber in triggering eruption (Burov and Guillou-Frottier, 1999; Guillou-Frottier et al., 2000). Subsequent investigations by Simakin and Ghassemi (2010) impose pre-existing zones of weakness in the roof and explore the role of pre-existing faults in the eruption behavior of a volcanic system. While these numerical modeling studies greatly advanced our understanding of catastrophic caldera formation, none have focused on the mechanism(s) triggering caldera eruptions or the mechanical size limitations of building large magmatic systems.

Although large caldera forming eruptions have a potentially devastating impact on the local and global environment, little is known about the maximum size and frequency of these events (Mason et al., 2004). Of particular interest is whether there is an absolute limit to the potential size of eruptions on Earth and how the magma body accumulating in the crust may govern this size limit. The accretion of large bodies of magma in the crust has been the topic of several previous investigations (Annen and Sparks, 2002; Jellinek and DePaolo, 2003; de Silva et al., 2006; de Silva and Gosnold, 2007; Annen et al., 2008; Karlstrom et al., 2010). Of particular note are the models of magma chamber growth developed by Jellinek and DePaolo (2003), which reveal that the ductile shell generated around a very large magma reservoir will prevent dike initiation and allow the reservoir to grow indefinitely without eruption. This finding led Jellinek and DePaolo (2003) to pose two critical questions: (1) what mechanics limit the maximum size of magma chamber growth; and (2) what ultimately triggers eruption of the largest magma chambers? The primary field constraints available to provide limits on the largest eruptions are the resultant collapse caldera areas and the extrusive lava volumes. While these surface expressions provide crucial information about the magmatic plumbing systems that feed these eruptions, there are no detailed mechanical models which link caldera size and erupted volume to the size of the reservoir beneath. In this paper, we investigate both the eruption trigger in the largest systems and the mechanics limiting their size.

To investigate the pre-collapse evolution of large silicic magma chambers and the maximum size of magma chamber growth, we develop a new viscoelastic model that incorporates a temperature-dependent formulation for viscosity and a Mohr–Coulomb failure criterion. This paper is organized as follows: first, elastic and viscoelastic numerical modeling advancements are benchmarked against analytical solutions for a pressurized spherical magma chamber. Second, the effects of incorporating a temperature-dependent viscosity and temperature-dependent material parameters into the viscoelastic rheology are investigated. Third, the numerical models are applied to a spectrum of magma chamber geometries. The incorporation of a Mohr–Coulomb failure criterion in the numerical model allows for critical investigation of fault formation in the overlying roof and its role in triggering eruption as the system evolves. Finally, we compare our numerical results to the global database of collapse calderas.

2. Analytical solution

The analytical solution for the surface deformation in response to a pressurized point source at depth in an elastic half space (Mogi, 1958) is widely utilized to describe the pressurization of a spherical magma chamber at depth within the crust. In this solution, the Earth's crust is considered to be an ideal semi-infinite elastic body and the radius of the source, a, is assumed to be much less than the depth to the center of the source, d. It follows that the horizontal and vertical displacements at the surface, U_x and U_z respectively, are functions of source location and the elastic properties of the crust:

$$U_x = \frac{\Delta P a^3 x}{r^3}\frac{3K+4G}{2G(3K+G)}, \tag{1}$$

$$U_z = \frac{\Delta P a^3 d}{r^3}\frac{3K+4G}{2G(3K+G)}, \tag{2}$$

where ΔP is the change in pressure of the sphere, r is the radial distance to the mid-point of the source, K is the bulk modulus, and G is the shear modulus.

While the elastic model has proven to be effective for describing surface displacement in small reservoir systems (McTigue, 1987; Grosfils, 2007), when $a/d \ll 1$ or the material properties are not purely elastic, the Mogi model may not be effective (Newman et al., 2001; Newman et al., 2006). As such, to calculate the predicted deformation in large magmatic systems with long thermal histories it is necessary to also consider the viscous and temperature-dependent responses of the crust to changes in magma chamber pressurization. To this end, we first consider the analytical solution for a linear viscoelastic material, which will be used to benchmark our numerical solutions.

A simple description of a viscoelastic material is a linear Maxwell model in which the instantaneous elastic response of the material is given by a spring with a stiffness, given by G, while the time-dependent viscous response is defined by a dashpot with viscosity, η. The deformation response of a viscoelastic material is further defined in the generalized Maxwell model (Fig. 1), which utilizes j linear Maxwell series in parallel with each other. The viscoelastic response is dependent on the characteristic relaxation times given by:

$$\tau_0 = \frac{\eta}{G_0 \mu_1} \tag{3}$$

$$\tau_1 = \frac{3K+G_0}{3K+G_0\mu_0}\tau_0 \tag{4}$$

$$\tau_2 = \frac{\tau_0}{\mu_0} \tag{5}$$

where μ_0 and μ_1 are the fractional moduli.

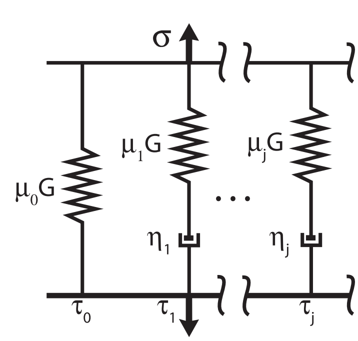

Fig. 1. Generalized Maxwell model.