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Internal triggering of volcanic eruptions: tracking overpressure regimes for giant magma bodies

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ABSTRACT

Understanding silicic eruption triggers is paramount for deciphering explosive volcanism and its potential societal hazards. Here, we use phase equilibria modeling to determine the potential role of internal triggering – wherein magmas naturally evolve to a state in which eruption is inevitable – in rhyolitic magma bodies. Whole-rock compositions from five large to super-sized rhyolitic deposits are modeled using rhyolite-MELTS. By running simulations with varying water contents, we can track crystallization and bubble exsolution during magma solidification. We use simulations with variable enthalpy and fixed pressure for the five compositions. The interplay between bubble exsolution and crystallization can lead to an increase in the system volume, which can lead to magma overpressurization. We find that internal triggering is possible for high-silica rhyolite magmas crystallizing at pressures below 300 MPa (<11 km depth in the crust), revealing a window of eruptibility within the upper crust from which high-silica eruptions emanate. At higher pressures, the critical overpressure threshold for eruption is only reached once crystallinities are high, >50 wt.%, which makes magma immobile – high-silica rhyolite eruptions from such depths would require external triggering, but examples are scarce or entirely absent. Calculated crystallinities at which the critical overpressure threshold is reached compare favorably with observed crystal contents in natural samples for many systems, suggesting that internal evolution plays a critical role in triggering eruptions. Systems in which fluid saturation happens late relative to crystallization or in which degassing is effective can delay or avoid internal triggering. We argue that priming by crystallization and bubble exsolution is critical for magma eruption, and external triggering serves simply as the final blow – rather than being the driving force – of explosive rhyolitic eruptions.

1. Introduction

Large (>100 km^3) and super-sized (>450 km^3) eruptions pose significant hazards to humanity (Lowenstern et al., 2006; Self, 2006). The mechanisms by which such large volumes of magma assemble, destabilize, and erupt are still greatly debated (Jellinek and DePaolo, 2003; Gregg et al., 2012; Caricchi et al., 2014; Malfait et al., 2014; Gregg et al., 2015). In this context, constraining the pre-eruptive conditions and evolution of these high-silica magma reservoirs is crucial for us to understand their eruptive behavior and potential societal hazards. Interestingly, supereruptions can take place on timescales from a few days (e.g., Bishop Tuff; Wilson and Hildreth, 1997) to over months or even years (e.g., Oruanui Tuff; Wilson et al., 2006), suggesting that different mechanisms or controls may operate in each individual system (Tait et al., 1989). Importantly, many silicic magma bodies seem to be stored and erupt from shallow depths (e.g. Gualda and Ghiorso, 2013), while granites extend a broader pressure range (Anderson, 1996) – to what extent is this pattern related to the ability of magmas stored at various depths to erupt is not well understood.

One critical question is whether these large magma bodies erupt due to external triggers (Jellinek and DePaolo, 2003; Gregg et al., 2012; Caricchi et al., 2014; Malfait et al., 2014; Gregg et al., 2015), or whether they naturally evolve to a state in which eruption is likely or inevitable (Blake, 1984; Tait et al., 1989; Fowler and Spera, 2008). Internal triggering due to buoyancy driven over-pressurization (Caricchi et al., 2014; Malfait et al., 2014) and volatile exsolution (Blake, 1984; Fowler et al., 2007, Fowler and Spera, 2008, 2010) have been invoked to explain eruption. In contrast, external triggering (e.g. earthquakes, roof strength failure) has been used to explain eruption of large magma reser-

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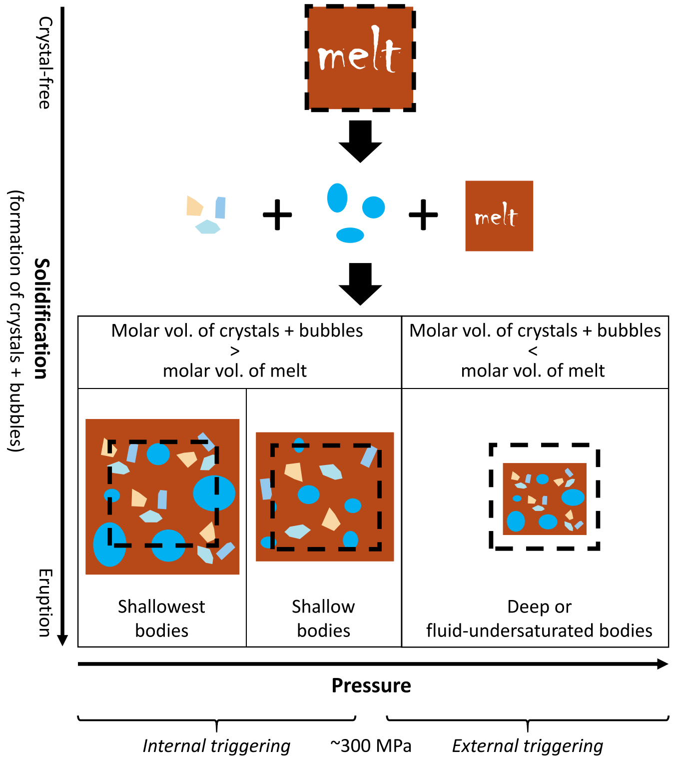

Fig. 1. Effect of crystallization and bubble exsolution on system volume. As a system of a given volume (dashed square) crystallizes and exsolves bubbles, the overall system volume can increase, potentially leading to overpressurization and eruption by internal triggering. If the density of the fluid phase is low, the volume change will be larger than if the fluid phase is dense.

voirs (Jellinek and DePaolo, 2003; Gregg et al., 2012, 2015). In this study, we explore the potential role of internal triggering of large rhyolitic magma reservoirs by modeling the volume changes due to crystallization and bubble exsolution under fluid-saturated and under-saturated conditions (Blake, 1984).

In a closed system, the total volume can increase or decrease depending on which phases form during solidification. The formation of bubbles has the greatest effect on volume change. This is because, at shallow depths, the difference in density between bubble and melt is greater than the difference in density between crystals and melt, such that the volume increase due to volatile exsolution can more than offset the volume decrease due to crystallization (Fig. 1). Contraction (volume decrease) will occur if the combined molar volume of new crystals and bubbles is smaller than the molar volume of the melt from which they formed (Fig. 1). In contrast, if expansion (volume increase) takes place, it can lead to overpressurization of the system, potentially priming the magma body for eruption (Blake, 1984). If the pressure increase occurs over a small time interval, the surrounding rock may not be able to deform quickly enough to accommodate the expanding magma body, which could lead to eruption (Blake, 1984; Tait et al., 1989; Fowler et al., 2007; Fowler and Spera, 2008).

Using the phase equilibria calculation tool rhyolite-MELTS (Gualda et al., 2012a), we model the solidification path of magmas with compositions representative of erupted silicic magma systems, characterized by crystallization at a variety of crustal depths (85 MPa to 350 MPa; see Gualda and Ghiorso, 2013). We explore the effects of varying water content and pressure in the crust on priming and internal triggering of eruptions. Our treatment differs from that of Fowler and Spera (2008, 2010) in that we model the evolution of magma bodies that are initially crystal-free and rhyolitic in composition, rather than from a primary basaltic melt that undergoes in situ differentiation all the way to high-silica rhyolite (see Gualda and Ghiorso, 2011). The low crystallinity of most high-silica rhyolites is consistent with nearly crystal-free high-silica rhyolite magma bodies at their inception, which is also confirmed by more detailed studies of specific systems (e.g. Bishop Tuff: Hildreth, 1979; Hildreth and Wilson, 2007; Taupo Volcanic Zone: Bégué et al., 2014, Wilson, 2001; Wilson et al., 2006; Ammonia Tanks Tuff: Deering et al., 2011; Peach Spring Tuff: Pamukcu et al., 2013, 2015). Our treatment is consistent with the so-called "Mush Model" (Bachmann and Bergantz, 2004), which attributes the formation of high-silica rhyolites from parental magmas of dacitic to rhyolitic composition. The fundamental question we are interested in is whether such magma bodies evolve to a primed state and erupt, or whether their eruptions require external triggering.

2. Methods

2.1. Rhyolite-MELTS calculations

We use whole pumice compositions as a proxy for pre-eruptive magma compositions. We assume closed-system crystallization from an initially crystal-free state. Even if generation of the high-silica magma requires segregation from a crystal-rich residue (Bachmann and Bergantz, 2004; Gualda and Ghiorso, 2013), the low crystallinity of most high-silica rhyolites suggests inefficient to absent crystal or liquid loss after segregation and mobilization (Hildreth, 1979; Hildreth and Wilson, 2007), which supports the assumption of crystallization of the magmas that form crystal-poor rhyolites as closed systems. Even if xenocrysts and antecrysts are present (Jellinek and DePaolo, 2003; Hildreth and Wilson, 2007; Gregg et al., 2012; Caricchi et al., 2014; Malfait et al., 2014; Gregg et al., 2015), their volume and mass contributions are negligible and can be effectively ignored. Although we present a closed-system model, in our discussion we analyze our results considering the possibility of degassing of a system prior to eruption. For simplicity, we do not consider the possibility of magma recharge; importantly, characteristics of erupted material (e.g. absence of mineral zoning) suggest that magma recharge was not an important process for the systems we examine, except perhaps during the final stages of evolution (Wark et al., 2007; see Gualda and Sutton, 2016 for an alternative interpretation).

We use rhyolite-MELTS to simulate the volume change of various systems crystallizing from this crystal-free state. We allow the volume of the system to expand and contract by performing isobaric (constant pressure) calculations. Importantly, we are interested in understanding the effect of pressure on priming of silicic magma bodies, rather than modeling in detail the onset of eruption of any of the selected systems. We use natural compositions to capture the effect of pressure on the composition of silicic melts (Gualda and Ghiorso, 2013). It is important to use natural compositions given that expected rhyolitic melt compositions vary with pressure within the shallow crust, which makes it impractical to use a single composition for this exercise.

We chose compositions of five explosive, high-silica, large to super-sized eruptions that have been estimated to have formed at a variety of pressures – from shallow (85–100 MPa, Oruanui Tuff and Mamaku Tuff) to deep (300–350 MPa, Young Toba Tuff) (Table 1). All crystallization pressures used in this study were determined previously with the rhyolite-MELTS phase-equilibria geobarometer using major-element glass inclusion compositions (Gualda and Ghiorso, 2013; Bégué et al., 2014; Gualda and Ghiorso, 2014; Pamukcu et al., 2015). Crystallization pressures calculated using the rhyolite-MELTS geobarometer (Gualda and Ghiorso, 2014) generally agree well with independent estimates of crystallization