Rejuvenation of the Fish Canyon magma body: A window into the evolution of large-volume silicic magma systems

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ABSTRACT

Voluminous, unzoned, phenocryst-rich pyroclastic deposits, considered as erupted batholiths, provide a unique opportunity to investigate magmatic processes in silicic magmas. The Fish Canyon Tuff, a well-documented example of these monotonous ignimbrites, displays evidence for simultaneous dissolution of feldspars + quartz and crystallization of hydrous phases during gradual near-isobaric reheating from ~720 to 760 °C. These observations, along with a high crystallinity (45%) and near-solidus mineral assemblage, suggest that the Fish Canyon magma cooled to a rigid crystal mush before being partly remelted prior to eruption. Rejuvenation was triggered by intrusion of water-rich mafic magmas at the base of the Fish Canyon mush, but the mechanisms of heat transfer remain poorly understood. The growth of amphibole during reheating requires addition of mafic components, but the absence of any measurable gradients and the paucity of mafic enclaves in the Fish Canyon magma rule out a reheating event dominated by convective mixing with a mafic magma. Closed-system processes, such as heat conduction and convective self-mixing, could not account for the transport of externally derived mafic components. We performed numerical simulations of upward percolation of a hot, low-density H_2O-CO_2 fluid phase (gas sparging) through a crystalline framework saturated with rhyolitic melt to assess the efficiency of such a process in rejuvenating silicic mushes in open systems. Sparging by ~20–40 km^3 of gas extracted from ~3000 km^3 of mafic magma is capable of reheating 7500 km^3 of silicic crystal mush by >40 °C in 150–200 k.y. Moreover, the vertical thermal gradient after 150 k.y. in most of the mush is small (~25 °C in the upper 65%). Gas sparging also produces an increase in the internal pressure of silicic crystal mushes and may lead to the formation of crystal-poor rhyolites by expelling interstitial melt. However, our simulations predict that filter pressing driven by sparging of externally derived gas could not solely account for the generation of the most voluminous rhyolites.

Keywords: Fish Canyon Tuff, San Juan volcanic field, large silicic magma bodies, exsolved vapor phase, multiphase flow, magmatic processes.

INTRODUCTION

The longevity of silicic magmas in the upper crust has been controversial (e.g., Halliday et al., 1989; Sparks et al., 1990). Residence times of several hundreds of thousands of years suggested by different geochronological methods (e.g., Reid et al., 1997; Heumann et al., 2002) seem at odds with the absence of geophysical evidence for kilometer-scale bodies of liquids in the present-day upper crust and would require very slow cooling rates. One scenario that can reconcile this contradiction is to envision that upper-crustal magmas oscillate thermally: episodes of cooling to a near-solidus state are followed by periods of progressive reheating and partial remelting of the mush induced by fresh inputs of hot magmas (referred to as magma defrosting by Mahood, 1990).

Eruptions of remobilized crystal mushes have been documented in several systems of widely different sizes (Keller, 1969; Murphy et al., 2000; Bachmann et al., 2002), but the mechanisms of rejuvenation remain unclear. For example, what are the volumes of magma recharge needed to initiate and sustain a progressive reheating that may lead to an eruption? What are the time scales, and how crystalline can a silicic mush become before it cannot be rejuvenated? Addressing these questions requires the evaluation of the putative mechanics of the heat- and mass-transfer processes. We propose a novel mechanism of rejuvenation and explore the likelihood of the upward percolation of hot gas (hereafter referred to as gas sparging) as a ''defrosting'' agent for mushes that have reached their rheological locking point.

The proposal of gas sparging stems from the recognition that magmas in the upper crust often contain an exsolved gas phase (e.g., Wallace, 2001). This highly buoyant and low-viscosity phase will tend to rise, advecting heat to shallower levels. We employed numerical simulations of multiphase flow in porous media to predict the heat and mass transfer of gas sparging in a mushy magmatic environment (Fig. 1) and assess its impact on the thermal evolution of shallow magma bodies.

The voluminous (>5000 km^3) Fish Canyon magmatic system appears particularly well suited to test this model. This sequence of three compositionally identical units erupted in rapid succession ca. 28 Ma in the San Juan volcanic field (Bachmann et al., 2000) and tapped into a near-solidus magma body undergoing a progressive reheating from 720 to 760 °C, possibly initiated by the upward percolation of a hot gas phase released from underplating mafic magmas (Bachmann and Dungan, 2002; Bachmann et al., 2002). The growth of amphibole and biotite in a progressively hotter environment concurrently with the resorption of quartz and feldspars and the absence of thermal or compositional gradients in the voluminous deposits suggest the following:

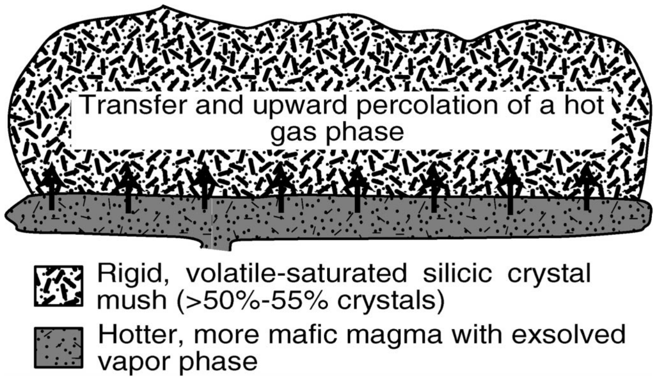

Figure 1. Schematic diagram of gas sparging in magmatic systems. Shallow intrusion of volatile-rich mafic magma stalls against base of cooler, more silicic crystal mush in upper crust and exsolves vapor phase. Hot, low-density gas can then cross mafic-felsic interface (Phillips and Woods, 2002) and percolate upward through silicic mush, potentially rejuvenating it faster than pure conduction.

(1) The magma retained a high volatile content even though new melt was generated via partial remelting of anhydrous phases. (2) Heat and mafic components were rapidly dispersed throughout >5000 km^3 of mush. (3) The mafic melt could not have been the main heat carrier: mafic additions must have been volumetrically small, because mafic enclaves are scarce, and convective stirring in this high-viscosity magma (low Reynolds number convection) would preserve a gradient due to low mixing efficiency (Jellinek et al., 1999).

TESTING THE HYPOTHESES OF GAS-DRIVEN REJUVENATION

Description of a Numerical Model of Multiphase Flow

One means of assessing the efficiency of gas sparging is to numerically simulate the nonsteady percolation of a low-density exsolved vapor through a porous medium, by using the physical properties and geologic constraints of a well-known natural system (the Fish Canyon magma body) as input parameters. We have generalized the conditions in the Fish Canyon mush as an explicitly multiphase mixture: (1) a wetting phase (a high-viscosity silicate melt), (2) a nonwetting phase (an H_2O-CO_2 ideal mixture), and (3) a rigid, porous framework (crystals). Over the ranges of chosen pressure and temperature conditions for shallow silicic systems (100–400 MPa and 600–1000 °C), the three phases are considered to have constant thermal expansion, thermal conductivity, and heat capacity, both fluids are assumed to have constant (but different) viscosities, the silicate melt is assumed to be incompressible, and the crystal framework is assumed to be rigid and to have a constant density (Dobran, 2001).

At the onset of a simulation, a hot H_2O-CO_2 fluid is allowed to enter at the base of the crystal mush (Fig. 1). Our modeling specifically addressed the multiphase flow and heat advection resulting from the buoyant fluid percolating upward through the mush coupled with heat conduction from the hot lower boundary. One-dimensional (vertical) simulations are a reasonable approximation for sill-like bodies such as the Fish Canyon mush, with horizontal dimensions on the order of several tens of kilometers and thicknesses of ~2–3 km. The effects of sidewalls can therefore be neglected.

We assumed the magmas to be gas saturated, and no mass exchange was allowed between the silicate melt and the H_2O-CO_2 mixture. There is abundant evidence—shallow storage of a volatile-rich magma and highly explosive eruptive style—that the Fish Canyon magma was saturated with a vapor phase. A volatile-rich andesite will rapidly become saturated in an upper-crustal environment (<5 kbar). By using VolatileCalc (Newman and Lowenstern, 2002), the saturation pressure for an aphyric, mafic magma at 900 °C containing 5 wt% H_2O and 800 ppm CO_2 is 4.6 kbar.

Initial and Boundary Conditions of the Fish Canyon System

As initial conditions, we fixed the temperature and pressure at 720 °C and 200 MPa (Bachmann and Dungan, 2002), the CO_2/H_2O ratio at 0.2, and the porosity at 0.4 (permeability = 4.44×10^{-11} m^2, calculated in this paper by using the Blake-Kozeny-Carman equation; McKenzie, 1984). We have set the thickness of the porous medium at 3 km, following the estimate that the drawdown depth during the Fish Canyon Tuff eruption was at least 2 km (Bachmann et al., 2002) and assuming that some fraction (most likely the deepest) of the mush was not erupted. We specified the lower and upper boundary conditions as follows: (1) At the lower boundary, we assumed a fixed and identical pressure for the gas and molten silicate (270 MPa = top pressure + 3 km of magma-static load + 5 MPa overpressure), no downflow of the molten silicate, a maximum for the Darcy velocity of the gas of 10^{-4} m/yr (constrained by rates of magma input in the crust at convergent plate margins divided by typical width of volcanic arcs; e.g., Dimalanta et al., 2002), and a fixed gas temperature of 800 °C (temperature estimates for San Juan andesites are ~850–900 °C [Parat et al., 2002], and we assumed some cooling; also at $X_{H_2O} > 0.3$, hornblende and biotite become unstable in the Fish Canyon magma at temperatures above 900 °C [Johnson and Rutherford, 1989]). (2) At the upper boundary, we assumed a fixed and identical pressure for both the gas and the molten silicate (200 MPa), but set no restriction on temperature.

The CO_2/H_2O ratio and the porosity are poorly constrained by geologic observations, and the effects of independently varying these two parameters were assessed by running simulations with one parameter increasing incrementally while the other was held constant. (1) Porosity was increased from 0.2 to 0.45 to yield a range of permeabilities from 3.125×10^{-12} to 7.53×10^{-11} m^2 (grain size = 0.5 mm). The assumption that the media is porous requires that the system has reached its rheological locking point (porosity $\leq$ 0.45; Vigneresse et al., 1996), and below 0.2, the permeability of the porous medium rapidly drops to 0. (2) The molar ratio CO_2/H_2O in the gas phase was varied from 0.1 to 0.4. Volatile-rich mafic magmas have 500–1050 ppm of CO_2 and 4–6 wt% H_2O (Roggensack et al., 1997), which results in a CO_2/H_2O molar ratio in the gas phase of 0.1–0.4 (calculated by using VolatileCalc; Newman and Lowenstern, 2002).

In the case of the Fish Canyon system, the maximum time available for the rejuvenation to occur is ~600 k.y. This estimate is based on the difference in eruption age between the Fish Canyon Tuff, dated as 28.03 ± 0.18 Ma (Bachmann et al., 2000), and the preceding major ignimbrite in the central San Juan cluster, the Masonic Park Tuff, dated as 28.60 ± 0.23 Ma (Lipman et al., 1996). Because emplacement of large volumes of silicic magma in the upper crust is not instantaneous, and the Fish Canyon magma cannot be simple ''leftovers'' from the drier and slightly more mafic Masonic Park Tuff (Lipman, 2000), the actual duration of rejuvenation was probably shorter than 600 k.y.

GAS SPARGING AS A ''DEFROSTING'' AGENT

The results of the simulation show that gas sparging can reproduce (1) the reheating from 720 to 760 ± 10 °C of >5000 km^3 of Fish Canyon mush in ~150–200 k.y. (Fig. 2) and (2) the absence of a significant thermal gradient, as the temperature range in the upper 65% of the mush height (assuming that the deepest part of the mush is less likely to erupt) is ~25 °C after 150 k.y. (Fig. 3). In contrast to closed-system processes, such as conduction and self-mixing, gas sparging can also account for some addition of mafic components (e.g., Phillips and Woods, 2002) that is required by the crystallization of hornblende and biotite during reheating.

The amount of mafic magma required to thermally drive rejuve-

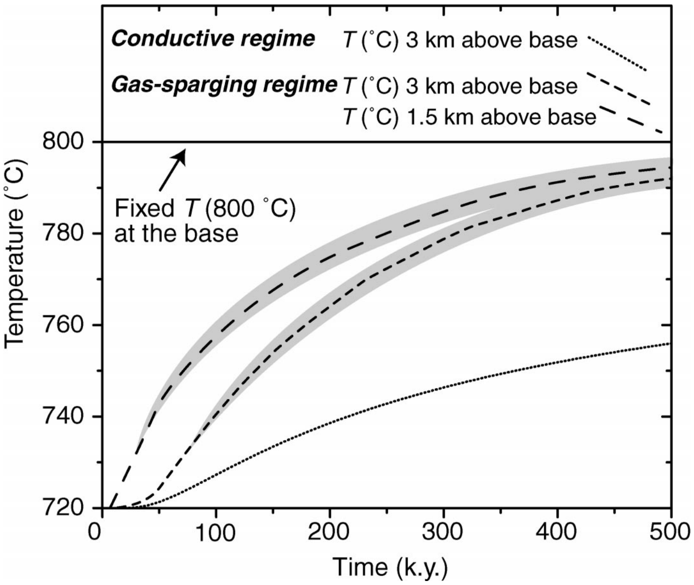

Figure 2. Temporal change of temperature (*T*) at middle and at top of 3-km-thick silicic mush during gas sparging (see text for description of input parameters) and at top of mush for purely conductive regime.

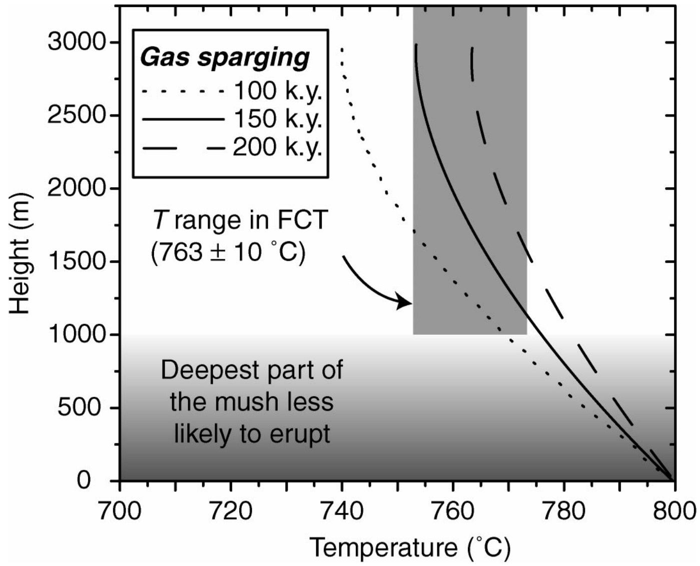

Figure 3. Temperature variation with depth in Fish Canyon mush during gas sparging after 100, 150, and 200 k.y. Initial temperature of mush was set at 720 °C and temperature of gas was set at 800 °C (see text for details). Deepest part of mush is less likely to erupt, and highest-temperature part may thus be largely unerupted. Range in temperature in Fish Canyon Tuff (FCT; 763 ± 10 °C), shown as gray rectangle, is based on quartz-magnetite oxygen isotope thermometry (Bindeman and Valley, 2002).

nation can be estimated by equating the amount of sensible and latent heat released by the mafic magma $\{m_{\mathrm{mafic}}[C_{p,\mathrm{mafic}}(T_{\mathrm{initial}} - T_{\mathrm{final}}) + X_{\mathrm{c}}L_{\mathrm{mafic}}]\}$ with the energy needed to heat a mush with Fish Canyon dimensions (surface of 2500 km^2 and thickness of 3 km) by 40 °C $\{m_{\mathrm{mush}}[C_{p,\mathrm{mush}}(T_{\mathrm{initial}} - T_{\mathrm{final}}) + X_{\mathrm{m}}L_{\mathrm{mush}}]\}$, where m is mass, C_p is specific heat, L is latent heat, and X_{c} and X_{m} are weight fractions crystallized and melted in the mafic and silicic magma, respectively. Accounting for 90% crystallization of the mafic magma, 20% dissolution of the silicic mush, $\Delta T_{\mathrm{mafic}}$ of 150 °C, ρ_{mush} of 2450 kg/m^3 (Whitney and Stormer, 1985), ρ_{mafic} of 2900 kg/m^3, L_{mush} of 2.7×10^5 J/kg, L_{mafic} of 4×10^5 J/kg, $C_{p,\mathrm{mush}}$ of 1370 J·kg^{-1}·K^{-1}, and $C_{p,\mathrm{mafic}}$ of 1484 J·kg^{-1}·K^{-1} (Bohrson and Spera, 2001), ~3000 km^3 of mafic magma is necessary (accounting for cooling over 150 k.y.). The volume of gas predicted by the numerical simulations to reach a 40 °C increase at the top of the Fish Canyon mush with a porosity of 0.4 is ~30 km^3. As typical mafic magmas erupted after the Fish Canyon Tuff have 4–6 wt% volatiles (20–30 vol%; Parat et al., 2002), extracting 3–4% of the volatiles present in the 3000 km^3 of mafic magma is sufficient to drive sparging.

The reheating rate is fairly insensitive to variations of (1) the Darcy velocity at the base from 10^{-5} to 10^{-3} m/yr, (2) the porosity from 0.2 to 0.45, and (3) the molar ratio CO_2/H_2O in the gas phase from 0.1 to 0.4. The Darcy velocities are low enough that these different parameters do not have a significant impact on behavior of sparging (see error envelopes in Fig. 2). The results of the simulations become sensitive to these parameters for Darcy velocities above 0.1 m/yr, which is unrealistically high.

SPARGING-DRIVEN FILTER PRESSING OF SILICIC MELT

The buoyancy-driven injection of gas inside a rigid porous medium saturated with incompressible melt has to be balanced by the expulsion of a fraction of interstitial liquid (assuming no counterflow). Therefore, in silicic mushes, gas sparging will induce some mass flow of molten silicate out of the mush. As the interstitial liquid in silicic mushes is generally rhyolitic, this process, similar to in situ gas-driven filter pressing described by Sisson and Bacon (1999), may provide a potential mechanism to form crystal-poor rhyolites.

In order to assess the efficiency of gas sparging in forming a rhyolite cap, the upper boundary was left open to flow of interstitial liquid during the simulation, and the flux (+ cumulative volume) across was recorded. Maximum thicknesses of molten silicate (over any surface area) predicted by the simulations are 4–5 m. So, for a surface of 2500 km^2 (as estimated for the Fish Canyon mush on the basis of the surface area of its caldera), the volume of crystal-poor, high-SiO_2 rhyolite that will be expelled out of the mush after 150–200 k.y. is ~9–10 km^3. Decreasing porosity does not significantly increase the volume of melt expulsion. This observation is in accord with the absence of compositional zoning and significant crystal-poor fallout in the Fish Canyon deposits and suggests that filter pressing by an externally derived gas phase is not very efficient in separating large volumes of silicate melt from a mush, although filter pressing could play a role in forming aplitic dikes and small cupolas of crystal-poor melt.

CONCLUSION

Our numerical simulations demonstrate that an exsolved gas phase at the base of a silicic crystal mush stored in the upper crust may reactivate large volumes of near-solidus mushes by reheating and partially remelting them over periods of ~100 k.y. If the temperature increase is limited to a few tens of degrees and the crystallinity of the mush is lower than ~70%, the volume of volatile-rich mafic recharge required to sustain rejuvenation is ~40% of the mush volume, and the fraction of gas predicted by the numerical simulations to produce sparging is ~3–4% of the available volume in the mafic magma.

Results of the simulations using data gathered on the Fish Canyon system as input parameters accurately reproduce the geologic observations described in Bachmann and Dungan (2002) and Bachmann et al. (2002). However, the fact that the Fish Canyon magma body erupted a chemically homogeneous crystal suspension (even though crystals are large and complexly zoned) suggests that the crystal framework became unlocked. We propose that a combination of gas sparging (acting as the defrosting agent) and self-mixing (Couch et al., 2001; acting as a late stirrer) accounts for the petrologic characteristics of the Fish Canyon magma. This model may be tested by looking for compositional effects of gas fluxing (i.e., content of volatile species such as S, Cl, F, and B in hydrous minerals, interstitial glass, and melt and fluid inclusions).

Gas sparging may play a role in separating interstitial melt from crystals in silicic mushes, but in order to produce the most voluminous crystal-poor rhyolites (several hundreds of cubic kilometers), other mechanisms must be invoked.

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