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Quantum magmatism: Magmatic compositional gaps generated by melt-crystal dynamics

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ABSTRACT

Compositional gaps are common in volcanic series worldwide. The pervasive generation of compositional gaps influences the mechanical and thermal properties of the crust, and holds clues on how our planet differentiates. We have explored potential mechanisms to generate these gaps using numerical simulations coupling crystallization kinetics and multiphase fluid dynamics of magma reservoirs. We show that gaps are inherent to crystal fractionation for all compositions, as crystal-liquid separation takes place most efficiently within a crystallinity window of ~50–70 vol% crystals. The probability of melt extraction from a crystal residue in a cooling magma chamber is highest in this crystallinity window due to (1) enhanced melt segregation in the absence of chamber-wide convection, (2) buffering by latent heat of crystallization, and (3) diminished chamber-wall thermal gradients. This mechanical control of igneous distillation is likely to have played a dominant role in the formation of the compositionally layered Earth's crust by allowing multiple and overlapping intrusive episodes of relatively discrete or quantized composition that become more silicic upward.

INTRODUCTION

R.A. Daly (1925) pointed out a bimodal distribution of rock composition in alkaline volcanic series. This paucity of intermediate compositions (generally most apparent with reference to the SiO_2 content of the magma), coined the "Daly Gap," was revealed in many other volcanic settings globally, including tholeiitic and calc-alkaline volcanic provinces (Brophy, 1991; Bunsen, 1851; Chayes, 1963; Daly, 1925; Thompson, 1972), and has become particularly striking with the advent of more comprehensive databases of erupted rock composition (Sarbas, 2008). Compositional gaps are obvious in oceanic settings (hotspots and island arc environments; Fig. 1), and in continental hotspots, but are less pronounced in mature continental arcs (e.g., Andes). Figure 1 shows examples of some documented compositional gaps. While by no means an exhaustive list, it does illustrate the diversity of geologic settings and composition space in which compositional gaps occur. While pervasive, compositional gaps can be highly nonuniform from one eruptive center to another. For example, gaps are not always of the same magnitude or position in the SiO_2 scale (Brophy, 1991; Thompson, 1972) due to variations in composition, oxygen fugacity (f_{O_2}), and volatile contents of their initial mantle or crustal source (Fig. 1). Likewise, compositional gaps are not restricted to SiO_2, and in particular, gaps in MgO and Al_2O_3 can be more pronounced than SiO_2 in mafic end members.

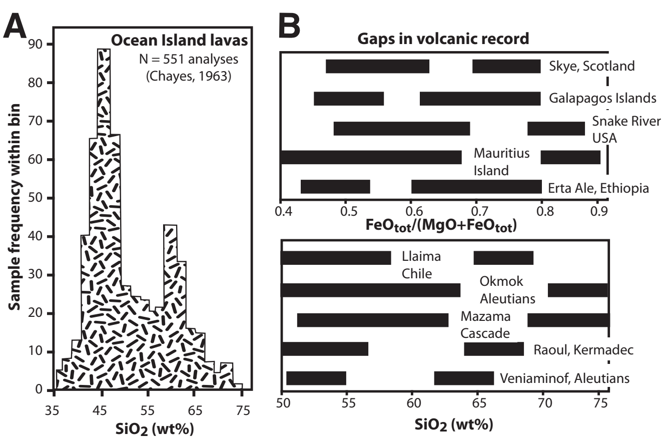

Figure 1. A: Relative abundance of erupted rock compositions, binned by SiO_2, graphically representing "Daly gap" (paucity of intermediate compositions; data are from Chayes, 1963). B: Compositional gaps in FeO_{tot}/MgO + FeO_{tot} and in SiO_2 in volcanic series around the world. Several other examples are listed in Brophy (1991) and Thompson (1972).

Over the past century, several hypotheses for the causes and consequences of the Daly Gap have been proposed. They mostly revolve around either (1) partial melting of preexisting crust (e.g., Chayes, 1963, and many more since) with melt extraction occurring after some critical amount of nonmodal melting (inducing a significant difference in composition between solid residue and extracted melt), or (2) crystal fractionation of more mafic parents, involving some component of gravitational or rheological trapping (Brophy, 1991; Grove et al., 1997; Marsh, 1981; Thompson et al., 2002). Both mechanisms may work in nature, but the crustal melting hypothesis has typically been favored for two reasons: (1) crustal melting was considered more efficient as a mechanism to generate voluminous evolved magma because of mass-balance considerations (i.e., there is not enough mafic residue in the crust to explain its average siliceous composition; Rudnick, 1995), and (2) crystal fractionation is commonly assumed to generate a continuum in chemical composition as crystals settle out (Bonnefoi et al., 1995; Chayes, 1963).

In contrast to the commonly held idea that crustal melting may alleviate the mass and thermal balance in generating silicic magmas, recent numerical models of basalt interaction with preexisting crust have shown that the amount of basalt needed to generate a given amount of silicic magma is roughly similar between crustal melting and crystal fractionation in most settings. In the crustal melting case, the voluminous amounts of basalt are required for enthalpy transport, and in the fractionation case they provide the raw material for silicic magma production. New constraints on the thermal response of the crust to reasonable fluxes of mafic magmas (variable thermal gradients, thickness of crust, convergence rate; Barboza and Bergantz, 2000; Dufek and Bergantz, 2005a) suggest that crustal melting efficiency can be relatively limited except in favorable cases (e.g., areas of thick crust, rapid convergence rate, high fertility of crustal rocks). Hence, most oceanic arcs and some continental arcs (e.g., Aegean arc, Cascades, New Zealand) should lead to a limited crustal melting efficiency. Likewise, the paucity of observations of extensive melting in preserved and exposed island arc sections indicates that this mode of evolution is not universal (Jagoutz et al., 2007).

NUMERICAL MODELING OF CRYSTAL-MELT SEPERATION

The ubiquity of compositional gaps, especially in magmatic provinces on thin oceanic crust (Brophy, 1991) (areas not prone to pervasive crustal melting), has led us to quantitatively test the assumption of a narrow crystal-liquid separation window in crystallizing systems. We have adapted a multiphase flow model to magmatic environments, including crystallization kinetics, to test this hypothesis (Dufek and Bergantz,

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2005b; Ruprecht et al., 2008; Syamlal et al., 1993). The multiphase calculation is coupled to a thermal model encompassing a much larger section of the crust to enable thermally evolving boundary conditions. Physical properties of representative magmas (e.g., viscosity and density) were calculated using the MELTS software that incorporates thermodynamic properties from a compilation of experiments (Ghiorso and Sack, 1995). Our initial proxy compositions are given in the GSA Data Repository.[1] Viscosity and density of the melt vary with compositional evolution calculated in the numerical simulations.

Separate equations are solved for the conservation of mass, momentum, and energy for both the magma and crystal phases (see the Data Repository) with coupling due to (1) drag between magma and crystals and (2) phase change. The drag between melt and crystals is dependent on the volume fraction of crystals, and encompasses dilute single particle settling velocities to compaction-driven extraction at crystal fractions higher than lock-up (Fig. 2; McKenzie, 1985). Phase change plays a first-order role in altering the density and rheology of the chamber and ultimately controls the dynamics in these systems. When the magma is undercooled, the rate of crystallization is ultimately governed by the crystallization kinetics. Here we use a rate of 10^{-4} kg/m^{3}s. This is equivalent to a growth rate of ~1.0×10^{-9} mm/s assuming initial crystal sizes of 100 µm and nucleation number density of 10^{12} nucleation sites/m^3. Growth rates for multicomponent compositions have been reported in the range of 10^{-6} to 10^{-11} mm/s (Hammer, 2008; Ruprecht et al., 2008). In addition, we solve a separate equation for the evolution and advection of SiO_2 in the magma based on the local melt fraction. This composition is used to calculate the evolving viscosity and density of the melt phase using the MELTS parameterization.

The calculations examine the coupled cooling and crystallization and resulting convection for a number of compositions, intrusion sizes, and thermal environments. Initially a crystal-free silicate liquid that has a range of initial temperatures (due to its position relative to the crustal geothermal gradient) is assumed to intrude the crust. The magmas then cool and crystallize in sill-like containers, the most common shape for large magma reservoirs (Brown, 2007). We calculate the cumulative probability of extraction to quantify the relative proportions of melt that can escape the magma reservoir and intrude at higher levels in the crust or erupt. The probability of extraction is calculated by examining the relative velocity between melt and crystals over all times and all spatial locations and integrating the volume of separation in specific melt fraction bins (0.02 melt fraction) relative to the total volume of separation over the lifetime of the chamber. This gives a measure of the spatially and temporally averaged melt extracted at specific melt fractions (and hence compositions) from the magmatic system. The probability of extraction is analogous to the measurement of the relative volume of erupted composition given exceptional exposure and if measured at fine resolution.

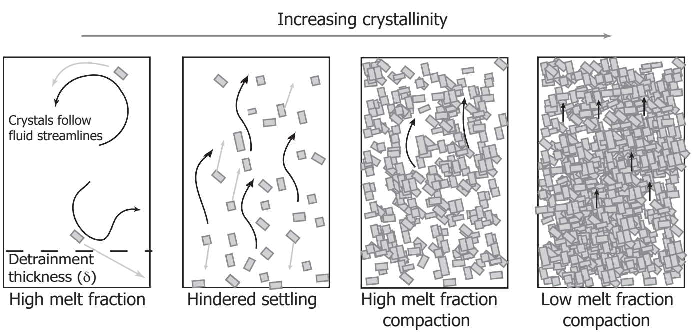

Figure 2. Conceptual model of crystal-melt dynamics at range of melt fractions. At high melt fraction, crystals follow magmatic streamlines and only segregate from melt in narrow region at base of flow (detrainment thickness). As crystals approach lock-up (i.e., interconnected crystalline network), melt can separate from crystals relatively efficiently through hindered settling and high melt fraction compaction. At even higher crystal fraction, very low permeability of mush inhibits crystal-melt separation. Time spent at any point in crystallization sequence will modulate total extracted volume, and this is controlled by thermal parameters such as geothermal gradient and latent heat of crystallization.

[1]GSA Data Repository item 2010192, multiphase modeling approach, is available online at www.geosociety.org/pubs/ft2010.htm, or on request from editing@geosociety.org or Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301, USA.

RESULTS OF MELT EXTRACTION SIMULATIONS

Although initial composition and thermal environment induce variations, a generalized set of dynamics evolves (shown conceptually in Fig. 2): at low crystallinity, cooling and associated crystallization generate convection currents due to the induced density variations. Most crystals remain in suspension, as millimeter-sized particles in intermediate- to high-viscosity silicate melts follow fluid streamlines (Brophy, 1991; Burgisser et al., 2005; Thompson, 1972), except near the boundaries, where some crystals can settle out (Koyaguchi et al., 1990; Martin and Nokes, 1988). At high crystallinity (>70 vol% crystals), crystal-liquid separation mainly occurs by low melt fraction compaction, and in such conditions, low permeability impedes melt separation (Bachmann and Bergantz, 2004; McKenzie, 1985). The most favorable window for crystal-melt separation to occur is at a crystallinity between ~50 and 70 vol%. This is a consequence of (1) the relative velocities that can be initiated between crystals and melt and (2) the small amount of time the magma body spends at high temperature. Intruding magmas are typically much hotter than surrounding country rocks. The initially high thermal gradients drive rapid cooling and the magma body will spend relatively little time near its liquidus. The probability for finding a specific composition in nature depends both on the amount of time that a given melt composition is thermally viable and the relative velocity between melt and crystals. Even though extraction rates can be slow at high crystallinity (~1–10 mm/yr), the magma spends a large amount of time at these thermal conditions relative to the crystal-poor situations in nearly all crustal thermal environments due to the decreasing thermal gradients and buffering due to the latent heat of crystallization (Dufek and Bergantz, 2005a). The melt extraction probability is also relatively insensitive to the depth of intrusion, unless the wall-rock temperature is near to the solidus temperature of the composition under consideration, which allows for much greater time periods (and greater extraction) at low melt fraction.

A key feature of these coupled thermal and mechanical calculations is that the crystallization process drives the dominant fluid motion (Fig. 3). Density variations induced (1) by the thermal expansion of the silicate melt or (2) by compositional variation between melts of different compositions are nearly always much smaller than the density difference between silicate melt and newly formed crystals. Therefore, convection patterns in these sill-like reservoirs are dominated by crystal plumes falling from the roof (Bergantz and Ni, 1999).

We further illustrate this extraction window using a simple analytical model that does not explicitly calculate the full multiphase effects. Using a one-dimensional, three-layer (intrusion with crust on either side) analytical thermal model that incorporates latent heat release, we examine the time-temperature profile in different thermal environments and for different sill thicknesses (Wallace et al., 2003). On the basis of prior experiments (Martin and Nokes, 1988), we assume that crystal separation occurs in a region near the wall (detrainment thickness) where fluid motions diminish, but particle inertia still enables sedimentation. Here detrainment thickness refers to the region near the magma chamber bottom where the

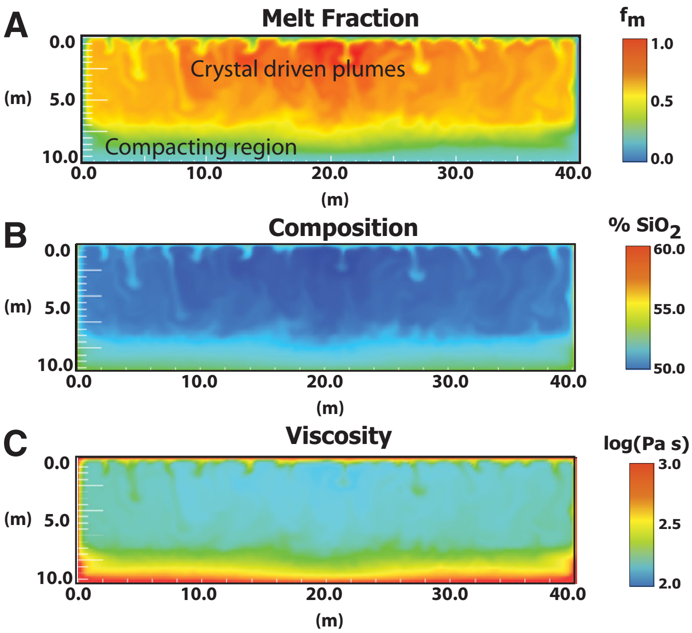

Figure 3. A: Snapshot of cooling and convecting magmatic sill in a typical simulation. Convection is driven primarily by crystallization (due to large density variation between crystals and melt). Hence process of crystallization generates largest scales of fluid motion (variable f_m denotes melt fraction). This intrusion was initially surrounded by crust at half the solidus temperature of basalt (at ~24 km modeled depth). Note that crystals accumulating at floor of intrusion form layer where melt extraction is more efficient. B: Compositional evolution of magma using wt% SiO_2 as proxy. C: Viscosity of melt phase based on composition and temperature of melt.

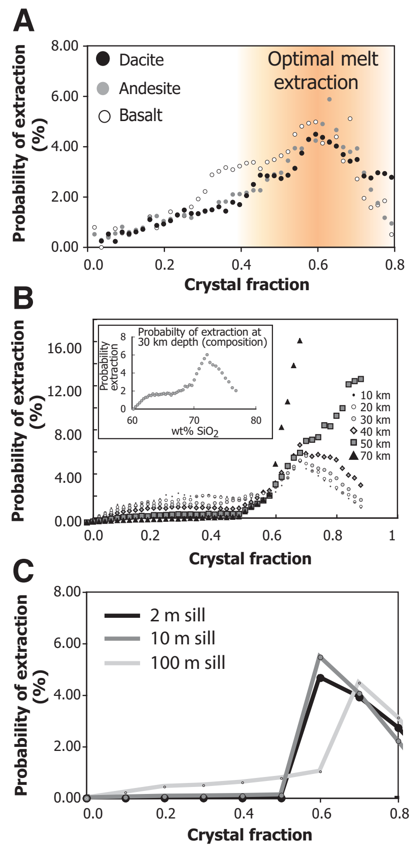

Figure 4. A: Probability for extracting interstitial melt from crystalline residue for different compositions (and viscosities) using multiphase numerical model. Compositions have been normalized so that integrated probability for extracting melt is equal to 100%. These numerical results considered sill thicknesses of 10 m intruded at reference depth of 20 km. B: Melt extraction probability versus crystal fraction for andesitic magma. Andesite is initially intruded in 100-m-thick sills with aspect ratio of 4:1 at different depths and permitted to cool and crystallize. In all cases, probability of extraction is much greater below crystal lock-up than at low crystallinity. For thicker crust, long residence times can result in increasing probability of extraction at high crystallinity (>70% crystallinity). Thin crust results in peak of probability of extraction at 70%. Inset: Probability of occurrence of wt% SiO_2 magmas for example of initially andesitic magma intruded at 30 km depth. C: Analytical calculation for melt-crystal separation in basaltic magma for detrainment thicknesses 10 times the radii of crystals. Dark lines denote sills 2 m thick, dark gray are 10 m thick, and light gray are 100 m thick.

magma decelerates, but where crystals continue to settle and sediment at the margin. We consider this detrainment thickness (δ) as a free parameter in these calculations. However, fluid velocities and particle-fluid coupling decrease by roughly 1/distance from the crystal at magmatic conditions (Martin and Nokes, 1988), and δ for high viscosity magmas is likely only tens of crystal radii (*r*). Crystal-melt separation in the detrainment layer is calculated using hindered settling relations and compaction velocities after the melt fraction has decreased sufficiently for the crystals to reach close packing arrangements (Rabinowicz and Vigneresse, 2004). At realistic detrainment thickness values (e.g., 10–100 *r*), crystal-melt separation probabilities sharply peak at 60–70 vol% crystals (Fig. 4C), mimicking the results of the multiphase numerical simulations.

IMPORTANCE OF COMPOSITIONAL GAPS IN CRUSTAL CONSTRUCTION

The compositional gaps between the extracted melt and the crystalline residue left behind is ~5–15 wt% SiO_2 (depending on the mineral phases present). An example for a magma with an initial andesitic composition is shown in the inset of Figure 4B. In the basaltic situation, where mineral phases (mainly pyroxene and plagioclase) that precipitate are similar in composition to the host magma, the compositional gap (with respect to SiO_2) generated after 50%–70% crystallization is typically not large (hence the presence of differentiated basalts in the rock record). For these mafic magmas compositional gaps in other oxide species, such as MgO and Al_2O_3, are more likely. However, when low SiO_2 mineral phases such as Fe-Ti oxides and amphiboles crystallize, the residual melt is rapidly driven away from the initial composition and its SiO_2 content increases as much as 15 wt% after half of the magma has crystallized.

Models of interstitial melt extraction from highly crystalline magma reservoirs (referred to as crystal mushes) that generate evolved, dominantly liquid caps have been suggested for both extremes of the compositional spectrum (from basalts in mid-ocean ridges to rhyolites in continental arcs; Bachmann and Bergantz, 2004; Fornari et al., 1983; Perfit et al., 1994). Analytical and modeling results using compaction and hindered settling equations suggest that, even in the most viscous cases, interstitial melt extraction by upward migration occurs rapidly enough at the 50–70 vol% crystals window to generate nearly aphyric cupolas in a geologically reasonable time scale (Bachmann and Bergantz, 2004; Rabinowicz and Vigneresse, 2004). Our simulations suggest that this process is likely to occur throughout the compositional spectrum from basalt to rhyolite.

As pointed out by Daly (1925), lithospheric magmatism is thought to be dominantly controlled by production of basalt in the Earth's mantle, while the bulk continental crust is crudely layered, from mafic lower crust to silicic upper crust (Christensen and Walter, 1995). Our new results suggest that Earth's crust may have evolved compositionally by selective removal of melt in narrow composition ranges (quanta) from deep to shallow and from basaltic to rhyolitic. Based on the probability of melt extraction from cooling magma bodies for a range of compositions and pressure typical of the Earth's magmatism, we propose the following simplified scenario for crust evolution: basalts, produced in the upper mantle, pond at the base of the crust, crystallize, and release buoyant andesite melt within the extraction window that escapes upward, either to erupt or form andesitic mushes. These mushes with intermediate composition, that transform upon freezing into diorite-tonalite plutons, will generate dacitic interstitial melt after ~50–60 vol% crystallization. These melts, in turn, escape their production sites, ascend, and transform into dacitic volcanic rocks and/or granodiorite plutons. Dacitic mushes end the Earth's compositional ladder by producing the most compositionally evolved and explosive rock type on our planet, rhyolite.

The inherent details of each situation will render the trend more complex, and individual volcanic centers may not always record this step-wise evolution in composition. Open-system magmatic processes, such as magma mixing and crustal assimilation, undeniably occur, particularly in areas of thick continental crust. These processes play a role in generating magmatic diversity, but cannot account for the chemical distillation to progressively more silicic magmas (e.g., high SiO_2 rhyolite cannot be produced by mixing or assimilation); they will overprint the crystal fractionation signature imparted to the magmas by crystal-liquid separation that mostly occurs within the extraction window, and obscure initially existing compositional gaps.

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