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Two models for the formation of magma reservoirs by small increments

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ABSTRACT

It is now clear that magma reservoirs develop over long time intervals out of a large number of individual intrusions. Evidence from some large volcanic deposits, including those of the Bishop Tuff, California, and Fish Canyon Tuff, Colorado, indicates that such reservoirs may experience pervasive and rapid heating before catastrophic eruptions. Injection of hot primitive melt in the reservoir is often invoked to explain these observations, but this requires the rapid emplacement of a large magma volume (at least 25 km^3 in less than 100 years for the Bishop Tuff) and efficient heat transfer through a thick cumulate pile. Within a magma body that grows incrementally, temperatures rise progressively and may eventually lead to a permanent volume of melt. Temperature and crystallization follow two completely different paths depending on the thickness of individual intrusive sheets. In one limit, corresponding to thick sheets, crystallization proceeds at equilibrium. Initial magma batches crystallize completely and a permanent body of melt develops progressively once ambient temperatures in the complex rise above the solidus. In the other limit, corresponding to thin sheets, crystallization is kinetically-controlled, such that initial intrusions do not crystallize completely and preserve a glassy residue. Once temperatures within the growing magma pile reach a certain threshold value, nucleation and growth of crystals get reactivated in the residual glass. Crystallization then proceeds catastrophically in a positive feedback loop involving latent heat release and temperature rise. Thus, an initial phase with no evolved melt present ends with the sudden formation of a large volume of evolved melt in a crystal mush. After this initial phase, new intrusions get emplaced in heated surroundings and follow a thermal path similar to that of the equilibrium case, with melts that become increasingly more primitive with time. Evidence for kinetic controls on crystallization in the natural environment is provided by the significant amounts of glass (up to 40%) that are found in thin isolated basaltic sills and dykes. Owing to sluggish crystallization kinetics, more glass should be generated in andesitic and dacitic magmas emplaced in similar conditions. Devitrification of such quantities of glass accounts for the rapid heating of a thick sill complex.

The two models of magma reservoir formation involve different requirements: the intrusion thickness must be smaller than a critical value in the kinetic model and the average magma input rate must exceed a threshold value in the equilibrium model. For a given injection rate, a permanent magma reservoir forms in a shorter time interval and over a smaller cumulative magma thickness in the kinetic model than in the equilibrium one. The kinetic model is such that the amount of evolved melt generated increases with decreasing injection rate, in contrast to the equilibrium model for which the opposite relationship holds.

1. Introduction

Crustal magma reservoirs may feed eruptions over long time intervals that exceed one million years (Halliday et al., 1989; Davies et al., 1994; Simon and Reid, 2005). This has challenged our understanding of how such reservoirs form and evolve thermally. If a large volume of magma is emplaced rapidly with little further melt input, the bulk compositional and thermal evolution is monotonic. Convective motions in the melt are unavoidable, implying that cooling is effected rapidly, typically in less than a thousand years (Worster et al., 1990; Sparks et al., 1990). One must therefore consider that magma reservoirs grow in small increments, with initial magma batches providing a heated crustal environment that allows later intrusions to remain partially molten (Petford and Gallagher, 2001; Annen and Sparks, 2002; Glazner et al., 2004; Annen et al., 2006). Detailed geological and petrological observations show indeed that large batholiths and plutons have developed out of sill and dyke complexes (Sisson et al., 1996; McNulty et al., 1996; Coleman et al., 2004). On a smaller scale, mixing and mingling figures, primitive magma enclaves as well as cycles of cooling and heating recorded by crystal zoning provide evidence for the repeated injection of primitive magma in the same storage zone. Mahood (1990) has envisioned phases of cooling

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and differentiation followed by the remelting of older cumulate assemblages depending on the balance between cooling during repose periods and heating due to recharge events.

In a magma body that grows by small increments, temperatures rise progressively, so that the residual melt becomes increasingly more primitive with time. In contradiction with this prediction, several eruption deposits provide evidence for the rapid formation of large volumes of evolved magma (Murphy et al., 2000; Bachmann and Bergantz, 2003). Zoning in quartz phenocrysts from the Bishop Tuff indicates that temperatures rose by about 100 °C in less than 100 yr just before eruption (Wark et al., 2007). Similar heating events prior to major eruptions have been documented in other volcanic systems (Table 1).

Taken together, the different pieces of evidence available seem contradictory. In a reservoir that has grown in small increments, rapid rejuvenation of a thick cumulate pile requires a major change in the intrusion sequence and the sudden emplacement of a large primitive magma volume elsewhere. For example, emplacement of at least 25 km^3 of primitive magma is required for the Bishop Tuff (Wark et al., 2007). In that particular case, the injection process must have lasted less than the duration of the heating phase, indicating that the input rate was at least 0.25 $km^3 yr^{-1}$, which is much larger than known rates in active and fossil systems (Crisp, 1984; Fialko and Simons, 2000). Furthermore, heating of an essentially solid cumulate pile can only be achieved by conduction, which cannot be efficient over more than a few tens of meters in such a short time. To overcome these difficulties, Lipman et al. (1997) and Bachmann and Bergantz (2006) have proposed that rejuvenation is achieved through gas sparging, which involves pervasive gas flow due to the degassing of an underlying magma body. Bachmann and Bergantz (2003) find that about 3000 km^3 of volatile rich basaltic magma is required to reheat the Fish Canyon cumulate pile in this manner, implying the accumulation of at least 2 km of magma beneath it. Another requirement is that the cumulate pile must be highly permeable.

Physical models of a reservoir that grows incrementally have been developed by several authors (Petford and Gallagher, 2001; Annen and Sparks, 2002; Glazner et al., 2004; Annen et al., 2006). Successive injections progressively warm up the crust until temperatures become large enough to sustain a melt body. Tens to hundreds of thousand years must elapse before the formation of a permanent melt body and the magma input rate must be larger than a threshold value of a few centimeters per year per unit area (Annen et al., 2008), which is larger than values that have been determined for a large number of magmatic/plutonic systems (Crisp, 1984; Fialko and Simons, 2000). One observation that is not accounted for by these models is a late and rapid heating event. A recent model accounts for this peculiar feature. According to this model, magma emplacement proceeds through thin intrusive sheets which cool so rapidly that crystallization is kinetically-controlled. In such conditions, early magma batches do not crystallize completely and leave a substantial amount of residual glass. With time, as the amount of magma emplaced increases, temperatures rise in the reservoir, which eventually acts to reactivate the nucleation and growth of crystals in the glassy interstitial parts of the cumulate pile (Michaut and Jaupart, 2006). Such crystallization releases latent heat at near solidus temperatures, which thermally rejuvenates the magma pile and leads to a rather homogeneous crystal mush containing chemically evolved melt. In this model, thermal rejuvenation is an intrinsic feature of the thermal sequence and proceeds fast because it operates quasi simultaneously over a large magma thickness. This can reconcile the two features of reservoir evolution invoked above, with slow growth due to small magma increments leading to a late and rapid heating/rejuvenation event. Like the other models, the kinetic model has specific requirements because it only works if individual magma additions are sufficiently thin.

In this paper, we reevaluate the kinetic model and compare it to the equilibrium crystallization model of (Annen and Sparks, 2002; Annen et al., 2006). We assess its validity using recently published laboratory experiments (Pupier et al., 2008). We review field observations of glassy residues in sills and dykes as well as data on magma emplacement rates and intrusion thicknesses. One criticism of the kinetic model is that field evidence for thin intrusive sheets is difficult to find because chilled margins and contacts between intrusive units get obliterated in the interior of magma bodies (although they can be found, *e.g.* (Wiebe et al., 2007)). In a similar fashion, the other models for the formation of magma reservoirs have specific requirements that are difficult to test in the field. For example, direct physical evidence for pervasive gas sparging is lacking. Also, it is currently impossible to verify that the average input rate in a fossil magmatic system was indeed above the threshold value needed for a permanent melt body. Thus, we resort to indirect evidence, *i.e.* predictable consequences, to assess the merits, likelihood and limitations of the different models.

2. Crystallization kinetics

There is plenty of evidence for some kinetic control on crystallization in geological conditions. These include crystal size variations away from chilled margins, as well as quench textures and crystal morphologies that may be found even in the deep interior of plutons (Moore and Lockwood, 1973; Tegner et al., 1993; Sisson et al., 1996). In some cases, the order of appearance of certain mineral phases is kinetically-controlled (Gibb, 1974). Such evidence has already been reviewed by Brandeis et al. (1984) and Michaut and Jaupart (2006) and need not be repeated here. A few kinetic data are available from different types of measurements, either in the laboratory or in the natural environment, but they do not allow construction of full kinetic functions over a whole crystallization interval. Calculations demonstrate that the nucleation rate is the critical input (Brandeis and Jaupart, 1987a). For our present purposes, what is important is how crystallization kinetics can be included in a large-scale thermal model and specifically how the nucleation and growth rates of crystals depend on temperature and composition.

Table 1
Heating of magma reservoir before an eruption.

Eruption	Volume	Heating	Timescales	Authors
Santorini, Greece, Minoan rhyodacite	30 km^3	35 to 85 °C		Cottrell et al. (1999)
Soufriere Hills, Montserrat, 1995–1999 andesitic eruption		20 to 200 °C	3 yr	Murphy et al. (2000)
Ceboruco, Mexico, Jala pumice eruption, 1000 yr	~0.3 km^3 mixed dacite (+ ~3 km^3 rhyodacite)	~70 °C	34 to 47 days	Chertkoff and Gardner (2004)
Mount Unzen, Japan, 1991–1995 rhyodacitic eruption		60 to 110 °C	Few weeks Few months	Venezky and Rutherford (1999) Nakamura (1999)
La Garita Caldera, Colorado Fish Canyon Tuff, 28 Ma	5000 km^3	~40 °C		Bachmann et al. (2002)
Bishop tuff magma system	500 km^3	~100 °C	<100 yr	Wark et al. (2007)
Campanian Ignimbrite, Italy	200 km^3		~100 yr	Pappalardo et al. (2008)