Melts, Mush and More: Evidence for the State of Intermediate-to-Silicic Arc Magmatic Systems

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Abstract

Understanding the physical state of intermediate-to-silicic arc magmatic systems is necessary for our petrologic models of these systems. Researchers have generated a plethora of data — geophysical, geochronological, petrological, theoretical — over the past few decades. These data have changed how we view arc magmatic systems, leading to a model of crystal mush that is rejuvenated repeatedly over the lifespan of the magmatic system. However, much of the data is either circumstantial or incomplete. Paterson et al. (2016; this volume) use a combined set of textural, geochemical and temporal data to demonstrate the changing physical state of the Tuolumne Intrusive Complex in California over its ~10 million year history. They offer evidence for magmatic erosion and recycling, along with the potential for a "surge growth" of the batholith that allows for significant volumes of magma to exist ephemerally under arc volcanoes.

Keywords: Geochronology, plutons, arc volcanoes, zircon, Sierra Nevada

What is the state of magma underneath active volcanic arcs? That question has been vexing petrologists for decades and is fundamental to understanding what petrologic processes are at work in arc magmatic systems. Most intermediate-to-silicic arc magmas (henceforth "arc magma") are stored 3 kilometers or more beneath the Earth's surface, so direct observation is impossible. Instead this question has been approached four main ways: (1) geophysical inspections of active arcs; (2) mineral geochronology; (3) field observations of plutons and; (4) thermal and physical modeling of magmatic systems. Each of these four avenues have their own strengths and shortcomings. Unfortunately, many times the interpretation of these data appear to be at odds.

Some overarching observations can be made about what we know of the state of active intermediate-to-silicic arc magmatic systems:

Large bodies of highly molten magma are rare: Geophysical observations (such as seismic tomography) have yielded little evidence for large bodies of fully-molten magma persistently underneath arc volcanoes. If anything, only small lenses of partial melt are observed at depths of 3-18 kilometers (see Chiarrabba et al, 2000; Stankiewicz et al., 2010; Paulatto et al., 2012). Detailed studies, such as the iMUSH study at Mount St. Helens, have revealed areas of potentially partially-molten material in the upper-to-middle crust (Levander et al., 2015; Kiser et al., 2016). Similarly, geodetic data such as InSAR have shown us that volcanic systems are regularly inflating and deflating, but these changes might be related to magma movement, hydrothermal activity or regional fault action (see Pritchard and Simons, 2004; Poland et al., 2006; Parker et al., 2016.)

Diverse interactions are preserved in the texture plutonic and volcanic rocks: The high frequency that mafic enclaves and cognate inclusions are found in both plutonic and volcanic rocks from arc settings betrays the complex mingling and mixing that must occur (see Platevoet et al., 1991; Cole et al., 2001; Wiebe et al., 2007; Paterson 2009 among many others). Many of these textures show the clear sign of liquid-liquid or liquid-mush interacting (e.g., Clynne, 1999; Coombs et al., 2002; Wiebe et al., 2001, Wiebe and Hawkins, 2015), confirming that portions of all large plutonic bodies were likely simultaneously liquid for some period of time.

Intermediate-to-silicic arc magmas are amalgams of crystals from a variety sources: Mineral geochronology studies such as U-Th/U-Pb dating of zircon and Ra-Th dating of plagioclase feldspar (see Cooper, 2015) have added temporal constrain to the subvolcanic magmatic bodies. Crystal cargo for arc magmas are a complex assemblage of pheno-, ante- and xenocrysts collected from active liquid, crystal mush and the host rock that is variably recycled during the lifetime of the magmatic system (e.g., Bacon and Lowenstern, 2005; Miller et al., 2007; Claiborne et al., 2010; Ruprecht et al., 2012; Walker et al., 2012; Klemetti and Clynne, 2014; Pack et al., 2016).

These magmas are incrementally emplaced and ephemerally eruptable but mostly long-lived mushes: Studies of zircon at plutonic systems exposed the incremental nature of pluton emplacement, where large magmatic systems might take millions of years to be formed through multitudes of magmatic pulses (starting with Reid et al., 1997 and Glazner et al., 2004). Looking across all mineral geochronology datasets, Cooper and Kent (2014) demonstrated that for many arc volcanoes, magma is only briefly in an eruptable state — that is, with low enough viscosity to allow eruption.

The combination these observations has lead to the now ubiquitous “crystal mush," a body of mainly crystals with low percent melt (<30%?) that can reside for long periods under an arc volcano before rejuvenation that may lead to eruption. The duration of construction, the timing of rejuvenation and the percent of the entire magmatic system involved is unclear and likely varies across different arc volcanic systems. However, these data support the geophysical evidence that magma under arc volcanoes is not in the form of large, long-lived fully-molten bodies (see Reid and Coath, 2000; Vazquez and Reid, 2002; Claiborne et al., 2010; Klemetti and Clynne, 2014; Deering et al., 2016; Eddy et al., 2016.)

Although the petrologic and temporal evidence support abundant crystal recycling within a relatively viscous magma mush, physical models have yet to agree if this is possible. Glazner (2014) argues that the high viscosity of these liquids would prevent processes that require turbulent flow (such as sedimentary-like structures) as the Reynolds number is too small. However, Annen (2009) suggested that a high rate of magma emplacement can allow for larger magma bodies to exist for brief periods. Bergantz et al. (2015) suggest a “mixing bowl” within magma bodies where heating from new injections permits for more turbulent-like flow behavior (and crystal recycling).

Ideally, combining the different lines of petrologic, textural and temporal data could offer the cohesion to the interpretation of all these observations and allow for more robust inputs for physical models. Paterson et al. (2016, this volume) present a fount of information from the Tuolumne Intrusive Complex (TIC) in the Sierra Nevada of California. By combining detailed field observations, compositional data (whole rock and mineralogical) for each magmatic pulses and lobes of the TIC and zircon geochronology, they have documented what they think is the physical state of the TIC magmatic body as each successive pulse of magma intruded.

Paterson et al. (2016) identify features that they interpret as magmatic erosion and recycling during the emplacement and growth of the TIC. These evidence include highly variable contact types between different petrologic units and magmatic structures bounded by schlieren within the TIC that exhibit truncation and erosive features. Additionally, complex compositional relationships are found in xenoliths, cognate inclusions and mafic enclaves that are abundant in the TIC, supporting the idea that magmas in varying states of solidification were eroded and recycled during new intrusions. They argue that these features betray the sediment-like behavior of crystals in a silicic mush.

Beyond these textural observations, Paterson et al. (2016) bring in a temporal and compositional argument for recycling of older magmatic material. Antecrystic zircon that are temporally correlated with older intrusions within the TIC are common in the younger magma bodies. They observe changes in zircon populations, with the proportion of antecrystic zircon increasing within each successive pulse of magma. Additionally, mixed populations of major phases such as amphibole and potassium feldspar from different TIC magmatic pulses of major phasesare found combined at hand-sample scale.

Their interpretation is not one of a profusion of small intrusions across the 10 million year history of the TIC, but rather periods of 0.5-1.5 million years where significant volumes of the magma body was hypersolidus. This could be considered a “surge growth” of the batholith rather than “incremental growth,” where the thermal state of the magmatic system waxes and wanes as each new pulse intrudes the previous batch, creating a dynamic magma body during “surges” of magma emplacement.

Overall, Paterson et al. (2016) suggest that between 35-55% of the original plutonic material has been recycled into newer batches of magma as they intruded. When considering the volume of such magmatic bodies (>10,000 km^3), that is a remarkable amount of crystals and liquid that become incorporated into the latter intrusions. In order to remobilize these crystals, Paterson et al. (2016) invoke the buoyancy of younger, hotter intrusions into cooling crystal mush, avalanches along solidification boundaries and localized convection in the magma body.

The question of the state of intermediate-to-silicic arc magmatic systems is far from resolved. The apparent disconnect between the models of such viscous mushes and the field, temporal and composition data has yet to be resolved. Further studies like Paterson et al. (2016) are needed at a wide variety of plutons across locations and compositions to collect the rich and deep datasets required to interpret the features and patterns in arc plutonic bodies. Until then, we will have tantalizing and sometimes contradictory evidence and models for the physical state of magmatic bodies under arc volcanoes.

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