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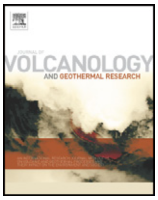

Review

Evaluation of crystal mush extraction models to explain crystal-poor rhyolites

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ABSTRACT

Mush models have become the new paradigm for explaining crystal-poor rhyolites in a variety of settings. Despite this general acceptance, there are cases where this model is problematic. Rhyolites from two specific areas are used to highlight examples where mush extraction models are inconsistent with erupted compositions. Rhyolites from eastern Oregon are used to address a mush origin of hot and dry (or A-type) rhyolites from bimodal volcanic suites and rocks from the San Luis Caldera Complex of the San Juan Volcanic Field in Colorado are used to address crystal-poor rhyolites of calc-alkaline suites.

Crystal-poor A-type rhyolites from Oregon resemble those from the neighboring Snake River Plain–Yellowstone centers. They are Fe-rich and high-field-strength-element enriched in comparison to regional calc-alkaline rhyolites and they vary widely in their degree of fractionation. A compositional assessment between least fractionated A-type rhyolites and a variety of intermediate magmas, including co-genetic intermediate magmas that erupted along with rhyolites during ignimbrite eruptions, indicates that intermediate, calc-alkaline and alkaline crystal mushes are unlikely to be able to generate interstitials melts after >50% crystallization that match observed rhyolites with high Ba/Rb and Ba/Sr as long as alkali-feldspar, low An plagioclase ($\sim<An_{40}$) or biotite are part of the crystallizing magma mush assemblage before extraction. Arguments specifically against granodioritic mush as rhyolitic nursery for Oregon hot & dry, Fe-rich, A-type rhyolites are multifold and strong.

The San Luis Caldera Complex consists of crystal-rich intermediate magmas as well as crystal-poor rhyolites that erupted over a narrow time window. This association allows us to directly apply the mush model by comparing silicic interstitial melts of crystal-rich magmas with erupted rhyolites. REE contents of rhyolitic interstitial melt have MREE depleted patterns relative to bulk rock in all cases where titanite and/or abundant amphibole are observed. On the contrary, erupted San Luis Caldera Complex rhyolites do not show a depleted middle REE pattern but rather have patterns common to typical rhyolite. Consequently, whenever titanite and/or abundant amphibole is part of a mush mineral assemblage of calc-alkaline intermediate magma prior to melt extraction, the interstitial rhyolitic melt is unlikely to represent commonly observed rhyolitic lava or tuff compositions.

Granite bodies have also been invoked as crystal mush sources to produce compositionally zoned high-silica rhyolites upon repeated extraction. This model is tested on two voluminous high-silica rhyolite bodies with strong compositional zoning.

Considering Nb and Rb contents of most enriched rhyolite of both tuffs as the first extracted interstitial melt of the granitic mush constrains the bulk composition of the granite and in turn the second extracted rhyolite using batch melting models. Results indicate the second extracted rhyolite at 50% crystallinity is much more depleted than any observed rhyolite of either of the zoned tuffs. Therefore, a repeated granitic mush extraction scenario as explanation of chemically zoned high-silica rhyolite magmas is doubtful.

While physically attractive, an origin of crystal-poor rhyolites from crystal-rich mushes requires careful testing to determine instances where a mush model is applicable and where it is not.

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1. Introduction

Crystal mush extraction models have been popular in explaining crystal-poor rhyolites of a variety of settings ever since they were introduced (Bachmann and Bergantz, 2004; Hildreth, 2004). In fact, crystal mush models have become the new paradigm of how crystal-poor silicic magmas are generated. Mush models can explain observed basic chemical and mineralogical features of a number of rhyolitic lavas and tuffs. On the other hand, there are examples where a model of interstitial melt extraction from kilometers thick crystal mush (cf. Hildreth and Wilson, 2007) is questionable because of the inconsistencies created (Streck and Grunder, 2008). The composition of aplite dikes, that record late-stage melt extraction in a plutonic environment, has also been used to caution how applicable the original mush model is (Glazner et al., 2008).

The original mush model is based on melt extraction from voluminous granodioritic magmas. In order to deal with inconsistencies in applying the original mush model, the model has been expanded to include either compositionally different intermediate mushy magmas (cf. Bachmann and Bergantz, 2008) or to start out with a silicic mush from the beginning (e.g. Campbell et al., 2009; Wolff et al., 2012). Despite these modifications, there are still examples of rhyolites where the observed petrological framework is difficult to reconcile with the supply of interstitial melts from masses of silicic or intermediate mushes. In this contribution, I will discuss cases where application of the “mush model” is problematic using specific examples from Oregon and Colorado, USA. The discussion here is restricted to mushy magmas originating from crystallization of magma or melting of preexisting plutonic bodies as this is at the heart of the mush extraction model (Bachmann and Bergantz, 2004; Hildreth, 2004). It is evident that any partial melting process will result in a crystalline residue–liquid system and thus represents a crystal mush system (cf. Bachmann and Bergantz, 2008). This has been a well appreciated condition ever since crustal partial melting was first invoked to generate rhyolitic magmas through escape of rhyolitic melt from crystalline residues (e.g. Read, 1948).

2. Geological synopsis of primary areas discussed

2.1. Rhyolites from Oregon

Significant volumes of rhyolite erupted as ignimbrites and lava flows in Oregon as early as ~40 Ma and as recent as 1.3 ka (MacLeod et al., 1975; Jordan et al., 2004; McClaughry et al., 2009; Ferns and McClaughry, 2013; Ford et al., 2013). Rhyolites with ages of ~40 to ~24 Ma are concentrated in the north-central to northeastern portion of the Oregon, however, this may be largely a function of exposures (Fig. 1). Between 17 and 15 Ma, the distribution of rhyolitic vents and outcrops define a north–south trending corridor east of 120° (Cummings et al., 2000; Streck and Ferns, 2012). This is followed by a northwestern migrating trend of rhyolite volcanism along the High Lava Plains from ~12 Ma to recent eruptions at Newberry volcano and beyond, to a position within the arc (MacLeod et al., 1975; Jordan et al., 2004; Ford et al., 2013). The age-progressive trend of the High Lava Plains is mirrored by the well-known Snake River Plain–Yellowstone trend of rhyolites (e.g. Pierce and Morgan, 2009) (Fig. 1b).

Tuff exposure correlations, chronological refinements, and petrological investigations are currently in progress in several areas to detail rhyolite petrogenesis and occurrences in Oregon. However, it is clear to date that erupted rhyolites over this 40 million year long period are dominated by Fe-rich, A-type, presumably hot and dry compositions with a lesser proportion of calc-alkaline (or magnesian) types (Fig. 2). High silica (≥75 wt.% SiO_2) compositions apparently predominate over low silica rhyolites that tend to be more common among domes/lava flows and at the youngest centers near or in the volcanic arc of the Cascades. Independent of type, rhyolites are typically phenocryst poor (≤8%) to nearly aphyric (≤1%) and are associated mostly with only sparse intermediate magmas. Compositions of A-type rhyolites are diverse but can usually be distinguished from calc-alkaline rhyolites by higher Ba/Sr, lower La/Yb and generally higher HFSE (e.g. Zr, Nb) and HREE abundances (Fig. 2). Rhyolites vary from those that show chemical signs of strong degrees of fractionation (low Eu/Eu* ≤0.3, low Ba <500 ppm) to those where Eu/Eu* and Ba are high (≥0.4, ≥1400 ppm, respectively) indicating lesser degrees of fractionation (Fig. 3). Rhyolites with high Ba and high Eu/Eu* can be parental magmas to more fractionated rhyolites because both Ba and Eu behave as compatible trace elements when alkali feldspar crystallizes (Streck and Grunder, 2008). Ba tends to remain mildly incompatible when alkali feldspar does not crystallize.

For the evaluation here, focus is placed on three voluminous Fe-rich ignimbrites, each with an eruptive volume estimated at a minimum of 300 km^3 but other A-type rhyolites of this area will be included as well. The ignimbrite units are the 7.1 Ma Rattlesnake Tuff (Streck and Grunder, 1995), the 9.7 Ma Devine Canyon Tuff (Greene, 1973; Jordan et al., 2004; Wacaster et al., 2011), and the ~16–15 Ma Dinner Creek Tuff (Streck et al., submitted for publication; Streck et al., 2011a,b) (Fig. 1). All three tuffs erupted in eastern Oregon within a basalt–rhyolite suite representing ‘hot-dry-reduced’ rhyolites of bimodal settings. The Rattlesnake Tuff and Devine Canyon Tuff are related to extensional tectonics and the Dinner Creek Tuff is related to flood-basalt volcanism of the Columbia River Basalt province. These tuffs are particularly valuable for this discussion because two of the units erupted strongly trace-element zoned high-silica rhyolites but all three of the tuffs erupted co-magmatic components of intermediate to mafic, crystal poor magmas (Fig. 4). This allows a direct petrological and geochemical