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Rhyolites and their Source Mushes across Tectonic Settings

OLIVIER BACHMANN* AND GEORGE W. BERGANTZ

DEPARTMENT OF EARTH AND SPACE SCIENCES, UNIVERSITY OF WASHINGTON, BOX 351310, SEATTLE, WA 98195-1310, USA

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Evolved magmas, including highly explosive rhyolites, are mainly generated by extraction of viscous melts from solid residues either in (1) partial melting zones within the crust (dominantly up-temperature evolution with newly formed silicic melt), or in (2) long-lived crystallizing mush zones fed by mafic to intermediate magmas (dominantly down-temperature evolution with residual silicic melt). Although both processes undoubtedly occur and are generally coupled, allowing for mixing between mantle and crustal components, we argue that combined field, thermal, geochemical, and geophysical observations favor residual melt extraction from crystalline mushes as the likely scenario in all tectonic settings. Depending on the main melting process in the mantle, two end-member differentiation trends occur: (1) a dry lineage leading to hot-reduced rhyolites and granites in magmatic provinces fueled by decompression melting of the mantle; (2) a wet lineage leading to cold-oxidized rhyolites and granites in subduction zones dominated by flux melting of the mantle.

KEY WORDS: *rhyolite; REE; differentiation; plutonic–volcanic connection; mush*

INTRODUCTION

The origin of rhyolites deserves much attention as they generate some of the largest volcanic eruptions on record (see issue of *Elements on Supervolcanoes*, February 2008). One possible mechanism to produce these high-viscosity, volatile-rich, but generally crystal-poor magmas is by extracting interstitial melt trapped within large, upper crustal mush zones (defined as ‘as mixture of crystals and silicate liquid whose mobility is inhibited by a high fraction of solid particles’ Bachmann & Bergantz, 2004; Hildreth, 2004; Eichelberger *et al.*, 2006; Miller & Wark, 2008). This interstitial melt extraction appears to occur most efficiently when mush zones contain 50–60 vol. % crystals so that chamber-wide convection currents are hindered by the formation of a quasi-rigid crystalline skeleton (rheological transition from liquid to solid behavior occurs at ~50–60 vol. % crystals, Marsh, 1981; Brophy, 1991; Vigneresse *et al.*, 1996; Petford, 2003) but the permeability is still high enough that melt can be efficiently extracted (McKenzie, 1985; Wickham, 1987; Bachmann & Bergantz, 2004). Most of these mush zones end up forming silicic plutons (Lipman, 1984; Bachmann *et al.*, 2007*b*; Hildreth & Wilson, 2007; Lipman, 2007), although some erupt as crystal-rich ignimbrites (Lipman *et al.*, 1997; Lindsay *et al.*, 2001; Bachmann *et al.*, 2002; Maughan *et al.*, 2002).

A potential geochemical test for this hypothesis is to compare the composition of aplites with high-silica rhyolites. Aplites are highly evolved, fine-grained dyke-like structures, commonly found within granitic bodies (*sensu lato*), which are thought to also form by interstitial melt extraction from highly crystalline silicic magmas (e.g. Jahns & Tuttle, 1963; Miller & Mittlefehldt, 1984; Hibbard & Watters, 1985; Eichelberger *et al.*, 2006). This geochemical comparison between aplites and high-silica rhyolites was recently attempted by Glazner *et al.* (2008), who reported significant differences in Sr, Y and rare earth element (REE) concentrations between them, and therefore challenged the hypothesis that voluminous high-silica rhyolites could be derived by melt extraction from large crystalline mushes of granodioritic composition.

The purpose of this paper is to re-examine the relationship between rhyolites, silicic plutons (granite *sensu lato*) and aplites from different tectonic settings (convergent

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*Corresponding author. E-mail: bachmano@u.washington.edu margins, divergent margins, and hotspots, fueled by different mantle melting regimes). When integrating independent lines of evidence from geochemical, geophysical and field observations, we argue that rhyolites, silicic plutons and aplites have a clear genetic connection. This connection appears not to be restricted to any particular tectonic setting as co-magmatic silicic plutons, rhyolites, and aplites in a given magmatic province typically represent respectively the solidified mush zones, and the interstitial liquids extracted from them at different stages of evolution.

TRACE ELEMENTS AND CRYSTAL RESIDUES

The Earth's magmatism can be roughly divided in two main trends on the basis of the dominant melting process in the mantle. In a convergent margin environment, mafic magmas (the primary drive of the Earth's magmatism; e.g. Hildreth, 1981) arise dominantly as a result of flux melting, induced by addition of volatiles to the mantle wedge from the subducting slab (e.g. Davies & Stevenson, 1992; Schmidt & Poli, 1998; Ulmer, 2001; Parman & Grove, 2004), and differentiation trends commonly follow a fairly wet (and oxidized) path. In contrast, drier, more reduced conditions dominate in areas of mantle upwelling characteristic of hotspots, continental rifts, and mid-ocean ridges (MOR), as magmatism is produced by near-adiabatic decompression melting of the mantle (e.g. Kushiro, 2001).

The difference in P_{H_2O} and f_{O_2} that prevails in the source regions of the different tectonic settings leads to different mineral assemblages. For example, the stability of hydrous minerals, clinopyroxene and oxides is enhanced at the expense of plagioclase in subduction zones (e.g. Holloway & Burnham, 1972; Gaetani *et al.*, 1993). Because the mineral assemblage present during magma evolution controls the concentrations of trace elements in igneous rocks (e.g. Rollinson, 1993), silicic magmas produced in wet environments show significant differences in trace element concentrations from those in dry environments at comparable silica contents.

As pointed out by Christiansen (2005) and Christiansen & McCurry (2008), rhyolites can be divided in two categories: (1) the hot–dry–reduced rhyolites, occurring mostly above areas of mantle upwelling (hotspots and continental rifts); (2) the cold–wet–oxidized rhyolites, typically found in subduction zones. This observation appears robust despite the presence of hot–dry–reduced rhyolites in some subduction zones (e.g. Puyehue rhyolite, Gerlach *et al.*, 1988) and cold–wet–oxidized examples in extensional environments (e.g. Bishop Tuff; Hildreth, 1979; even if the Bishop Tuff magma is not as oxidized as most arc rocks, e.g. Scaillet & Evans, 1999). Both types of rhyolites have very similar major element concentrations, but show different trace element contents; in particular, for rare earth elements (REE, Fig. 1). In wet–oxidized environments, crystallization of amphibole and titanite, which sequester middle REE (MREE) and heavy REE (HREE) (+ Y) (Frey *et al.*, 1978; Hildreth, 1979; Lipman, 1987; Wones, 1989; Bachmann *et al.*, 2005; Davidson *et al.*, 2007*a*; Glazner *et al.*, 2008), produces an increasingly pronounced U-shaped pattern with progressive differentiation. A deep Eu negative anomaly is not expected, because (1) plagioclase crystallization (which removes Eu and Sr from the melt) can be delayed in water-rich environments (e.g. Johannes & Holtz, 1996), and (2) titanite and amphibole do not take up Eu as much as the other REE (lower partition coefficient for Eu than adjacent REE; e.g. Bachmann *et al.*, 2005). In contrast, the dry, reduced magmas crystallize abundant olivine, pyroxenes, and plagioclase, which

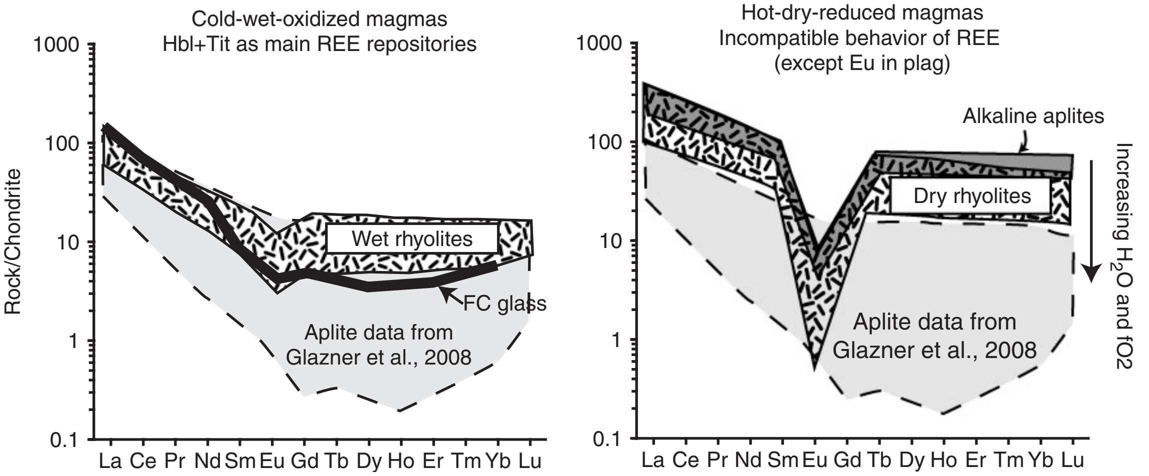

Fig. 1. Typical REE patterns for the two types of high-SiO_2 rhyolite (cold–wet–oxidized and hot–dry–reduced; see text for details) and aplites from different tectonic settings. FC glass refers to interstitial glass from the Fish Canyon magma (Bachmann *et al.*, 2005). Most patterns taken from Glazner *et al* (2008). Other data obtained from the literature (see text) and Appendix 1.

do not host REE (except Eu in plagioclase). This assemblage produces REE patterns that show deep, negative Eu anomalies with otherwise fairly straight and distinctively high light REE (LREE) and HREE concentrations [the 'seagull' pattern of Glazner *et al.* (2008)].

With the exception of garnet, phases other than amphibole, titanite and plagioclase are unlikely to play a major role in the shape of REE patterns. In highly evolved systems (>70 wt % SiO_2), REE-rich mineral phases such as allanite, chevkenite, and monazite are common (e.g. Wolff & Storey, 1984; Bea, 1996), but as they occur late in the evolution of magmas and are always in low modal amounts, they have less opportunity to significantly fractionate REE. Only garnet is known to be an important residual phase in high-pressure hydrous mafic magmas (e.g. Hildreth & Moorbath, 1988; Müntener & Ulmer, 2006) and strongly sequesters HREE.

Rhyolites, silicic plutons, and aplites from similar tectonic environments have REE patterns that match those described above (seagull vs MREE–HREE depleted; Fig. 1). Most arc rhyolites [e.g. data from Andean rhyolites of Glazner *et al.* (2008, fig. 1c) and examples from the Aegean Arc, the Andes and the Taupo Volcanic zone (Fig. 1; see also supplementary data and figure, available for downloading at http//:www.petrology.oxfordjournals.org; Bryant *et al.*, 2006; Wilson *et al.*, 2006)] have lower MREE and HREE than high-silica rhyolites from hotspot systems and continental rifts. Conversely, REE patterns of aplites from titanite-free hosts (Glazner *et al.* 2008, fig. 1d) and alkaline leuco-granite (e.g. Charoy & Raimbault, 1994), are much more 'seagull-like', resembling the patterns of rhyolites from hotspots or continental rifts (e.g. Yellowstone, Coso, and Long Valley systems). Glazner *et al.* (2008) did not reach this conclusion because their focus was on REE (and Sr, Y) concentrations in aplites from the Tuolumne Intrusive Suite, produced by a regional magmatic pulse related to Cretaceous subduction (Bateman & Chappell, 1979), and they compared them with high-silica rhyolites from several magmatic centers not directly resulting from subduction processes [Yellowstone area, Coso volcanic field, SW Nevada volcanic field, Long Valley magmatic system (Glazner *et al.*, 2008, fig. 1b)], although all tectonic settings were compared in their fig. 1c.

Admittedly, some aplites do form more pronounced U-shaped patterns than even the wettest, coldest rhyolites, but this should be expected. Aplites are mostly generated very late in the evolution of large plutonic bodies and are commonly associated with pegmatites, as pointed out by Glazner et al (2008) and several others [at least as far back as Jahns & Tuttle (1963), including those in the Tuolumne Intrusive Suite, studied by Fournier (1968)]. Aplites are typically mobilized after high-silica rhyolites, and therefore record more extreme differentiation patterns (particularly in REE) in water-rich and high-f_{O_2} environments. Highly evolved cupolas in plutonic bodies (leucogranites) present the same characteristics (i.e. U-shaped REE patterns; e.g. Lipman, 1987; Bryant *et al.*, 2006). In addition, we expect a continuum of REE pattern between the two types of rhyolites; the wettest rhyolites from areas of mantle upwelling (e.g. Bishop Tuff) can have patterns that overlap with arc rhyolites (e.g. Glazner *et al.*, 2008, fig. 1b), and the driest arc-related rhyolites can have seagull-like patterns (e.g. Mitropolous & Tarney, 1992).

VOLATILES, MUSH TEMPERATURE AND ERUPTABILITY

Apart from the difference in REE patterns between rhyolites and aplites, other arguments have been raised against the mush extraction model for hot–dry rhyolites (e.g. Streck & Grunder, 2008). For instance, the magmatic temperatures of these rhyolites are generally higher than those recorded for near-solidus, granodiorite mushes; also, the lack of intermediate compositions erupted in bimodal volcanic fields suggests a paucity of potential source mushy reservoirs. These two observations can be reconciled with the mush model if one considers that there are both hot and cold types of crystalline mush and that intermediate magmas have a lower probability of erupting in tectonic environments that produce the driest magmas as volatile saturation is delayed until more evolved compositions are obtained.

As for rhyolites, granites (*sensu lato*) have been categorized as hot–dry or cold–wet on the basis of geochemical arguments and zircon saturation temperatures (e.g. Clemens *et al.*, 1986; Frost & Frost, 1997; King *et al.*, 2001; Miller *et al.*, 2003). Therefore, we propose that in hotspot systems and continental rifts, source mushes have hot–dry granitoïd compositions (e.g. Barbarin, 1990; Frost & Frost, 1997; Frost *et al.*, 1999; Edwards & Frost, 2000; Schmitt *et al.*, 2000), leading to high-silica rhyolites such as those found in Yellowstone, Coso, and SW Nevada, whereas convergent margins have mushes of cold–wet granodioritic composition (which sometimes erupt as large crystal-rich ignimbrites called the Monotonous Intermediates; Lindsay *et al.*, 2001; Bachmann *et al.*, 2002; Maughan *et al.*, 2002; Bachmann *et al.*, 2005) and will lead to arc rhyolites (Bachmann *et al.*, 2007*a*; Hildreth, 2007; Fig. 2).

We concur that magmas with intermediate compositions between basalts and rhyolites, which could act as source mush zones for hot–dry–reduced rhyolites in hotspot systems and continental rifts (Streck & Grunder 2008), are rare in the volcanic record [the 'Daly Gap'; recognized since Daly (1925) in bimodal volcanic fields] but not in the plutonic realm. Although alkaline plutonic bodies of intermediate composition (syenites, alkali granitoids) may be

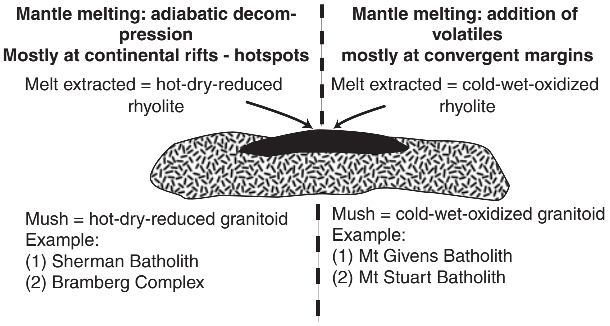

Fig. 2. Relationship between mushes and evolved, crystal-poor caps in different tectonic settings (field examples are from Erikson, 1977, Frost *et al.*, 1999, McNulty *et al.*, 2000, Schmitt *et al.*, 2000).

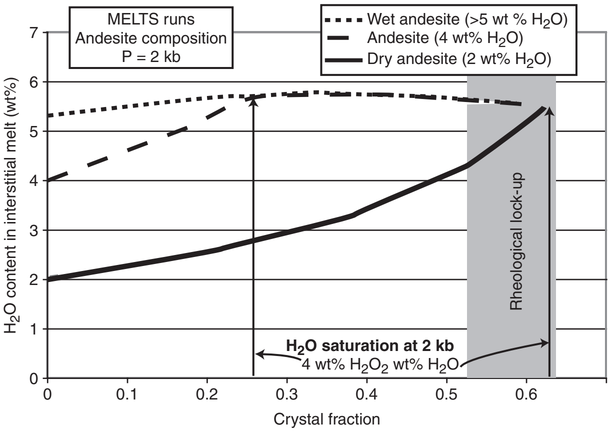

Fig. 3. Curves obtained by MELTS (Version 5.0, Ghiorso & Sack, 1995) of crystal fraction vs H_2O content in interstitial melts for an andesite composition crystallizing at 2 kb pressure for different initial H_2O contents, illustrating the delayed water saturation in drier system, leading to a reduced eruptability.

scarcer than calc-alkaline granodiorites, they cannot be considered rare (e.g. Clemens *et al.*, 1986; Eby, 1990; Chappell *et al.*, 1998; Frost *et al.*, 2001) and are typically found in the same tectonic settings as the hot–dry–reduced rhyolites.

The paucity of erupted intermediate magmas is a likely consequence of the same fundamental difference that generates distinct types of REE patterns: abundance of volatiles in the magmatic crustal column. As demonstrated by the seminal work of Geist *et al.* (1995) on rhyolites from Volcàn Alcedo (Galapagos Archipelago), evolved magmas are expected to be eruptible only after they become saturated with volatiles (either by progressive enrichment as a result of crystallization of anhydrous phases and/or addition from the surrounding crust). In both tectonic settings, basalts generally erupt from deep sources by processes independent of volatile saturation, but when these mafic magmas stall in the crust (triggering differentiation), the compositions of subsequently erupted magmas depends on the relative timing of volatile saturation and rheological lock-up, as follows.

In volatile-rich systems, under upper crustal conditions, volatile saturation is reached at intermediate compositions, increasing the likelihood that such compositions will be erupted (Fig. 3). Therefore, andesite–dacitic compositions dominate the volcanic record in subduction zones (e.g. Gill, 1981). More evolved compositions (rhyolites) are rare in subduction zones (Hildreth, 2007) because (1) their parental magmas (andesite or dacite) erupt, and (2) when they do form, rapid crystallization induced by volatile exsolution renders these volatile-laden systems generally too crystal-rich to erupt (Cashman & Blundy, 2000; Miller *et al.*, 2003).

In drier systems, rheological lock-up by cooling-induced crystallization is reached before volatile saturation for the intermediate compositions. Therefore, most alkaline andesites and dacites do not erupt. More differentiation is required for volatiles to accumulate and eruption to occur (Fig. 3), leading to the observed bimodal distribution of chemical compositions of erupted products in hotspots and continental rifts.

DISTILLING RHYOLITES

Silicic magmas can form either by partial melting of metaigneous and metasedimentary supracrustal materials (see recent references e.g. Bindeman *et al.*, 2008; Bryan *et al.*, 2008; Glazner *et al.*, 2008; Streck & Grunder, 2008) or by fractional crystallization (± assimilation) of mafic parents [countless references since Daly (1914) and Bowen (1928)]. The mush model favors neither of them, as the 50–60 vol. % crystal window can be achieved by either partial melting (up temperature) or progressive crystallization (down temperature). As discussed above, trace (and major) element geochemistry mostly reflects P–T–P_{H_2O} and f_{O_2} conditions in the magma source zones, but has generally been unsuccessful in discriminating between the two processes (see Brophy, 2008). However, by examining lines of evidence that are largely independent of geochemistry, we conclude that crustal melting will be typically less important than fractional crystallization in producing high-SiO_2 magmas. We also stress that magma columns will be dominated by mush zones (e.g. Marsh, 2004) and interstitial liquid extraction when magmas reach intermediate crystallinities.

Melting of pre-existing crustal rocks has been a popular hypothesis for decades, and has become the paradigm for generating silicic magmas following the recognition of 'restitic material' (xenoliths and xenocrystic material) in most large silicic units (e.g. Friedman *et al.*, 1974; Worner *et al.*, 1985; Chappell *et al.*, 1987; Gunnarsson *et al.*, 1998; Charlier *et al.*, 2007; Bindeman *et al.*, 2008; Bryan *et al.*, 2008). In addition, unambiguous isotopic evidence for recycling of crustal material (e.g. Faure, 2001; Davidson *et al.*, 2007*b*) indicates that silicic magmas are open to mass exchange with surrounding crust, and the presence in the rock record of peraluminous felsic rocks suggests that some evolved magmas may be pure partial melts of pelitic material (Munksgaard, 1984; Pichavant *et al.*, 1988; Mahood *et al.*, 1996; Zeck & Williams, 2002; Clarke *et al.*, 2005). Lastly, at least since the publication of the famous memoir by Tuttle & Bowen (1958), crustal melting is thought to alleviate the heat and room problems associated with the emplacement of large bodies of silicic magmas in the mid- to upper crust.

However, modeling efforts to better constrain the heat budget in basalt–crust interaction (Barboza *et al.*, 1999; Babeyko *et al.*, 2002; Dufek & Bergantz, 2005; Annen *et al.*, 2006) has led to different views, particularly for the large and abundant metaluminous units. State-of-the-art numerical simulations of the energy balance between mafic magmas and the pre-existing crust illustrate how difficult it is to form volumetrically significant amounts of pure crustal melts, even in the deep crust (Barboza *et al.*, 1999; Babeyko *et al.*, 2002; Dufek & Bergantz, 2005; Annen *et al.*, 2006). A very high heat flow from the mantle is required (>60 mW/m^2; Babeyko *et al.*, 2002), and even in these hot conditions, only the lowermost crust can melt in any significant amounts (using the well-constrained melting behaviors of pelites and amphibolites; Barboza *et al.*, 1999; Babeyko *et al.*, 2002; Dufek & Bergantz, 2005; Annen *et al.*, 2006). Even remelting young intrusive rocks requires large amounts of enthalpy and volatiles (Brown, 2007). Heat and water that inevitably escape during solidification must be replenished by the incoming magmas (e.g. Miller *et al.*, 2003).

In addition to the numerical models of heat and mass transfer within the crust, field observations in exposed crustal sections (the natural laboratories) are also in disagreement with crustal melting being the dominant process in producing voluminous silicic magma bodies. Crustal sections, although sparse (Barboza & Bergantz, 2000; Greene *et al.*, 2006; Jagoutz *et al.*, 2007; Hacker *et al.*, 2008), suggest that widespread crustal melting does not occur even when large pools of mafic melts intrude the lower to mid-crust (Barboza & Bergantz, 2000). Careful investigations of these sections (Voshage *et al.*, 1990; Barboza *et al.*, 1999; Greene *et al.*, 2006; Jagoutz *et al.*, 2007) all conclude that fractional crystallization of mantle-derived basalts occurring synchronously with some assimilation (energy-constrained AFC; e.g. Reiners *et al.*, 1995; Bohrson & Spera, 2001; Thompson *et al.*, 2002) is the dominant differentiation process.

We argue that, by analogy to basaltic lenses in mid-ocean ridges (e.g. Sinton & Detrick, 1992), magmas feeding upper continental crust reservoirs are also generated by interstitial liquid extraction from crystalline mushes (Fig. 4; see also Wickham, 1987; Quick *et al.*, 1994). The presence of crustal 'restitic' material in silicic magmas (including xenocrysts) can be reconciled by partial assimilation of wall-rocks (both in the lower and upper crust; e.g. DePaolo, 1981; DePaolo *et al.*, 1992; Bohrson & Spera, 2001; Beard *et al.*, 2004, 2005), and does not necessarily require an origin by pure crustal melting. Most silicic magmas bodies unquestionably undergo open-system behavior and can blend components from both the mantle and the crust [many decades of references, at least since Daly (1914) and Bowen (1928)]. Energy-efficient reactive bulk assimilation has been recognized in both plutonic (Voshage *et al.*, 1990; Beard *et al.*, 2004, 2005) and volcanic (Charlier *et al.*, 2007) environments.

THE CHEMICALLY AND THERMALLY OPEN-SYSTEM MUSH MODEL AS THE EARTH'S WAY OF PRODUCING SILICIC MAGMAS

The varieties of physical processes that produce distinct trends of magmatic differentiation are rarely fully expressed through a single chemical index or line of evidence. The mush model discussed herein is based on specific and explicit links between plutons and volcanic systems, and much of the supporting evidence, including field relationships, temporal–compositional relationships and geophysical observations, has been summarized elsewhere (Bachmann & Bergantz, 2004; Hildreth, 2004; Marsh, 2004; Bachmann *et al.*, 2007*b*; Lees, 2007). Hence, we stress, using all the lines of evidence we could assemble, that interstitial liquid extraction from highly crystalline, long-lived mushes that are open to additions of mass and heat can provide a rationalizing framework to explain compositional diversity among magmas. Crystal mushes physically and chemically control magmatic differentiation and can produce the distinct characteristics observed in rhyolites, from the hot and dry conditions in continental rifts and hotspots, to the colder and wetter magmas more typical in subduction zones.

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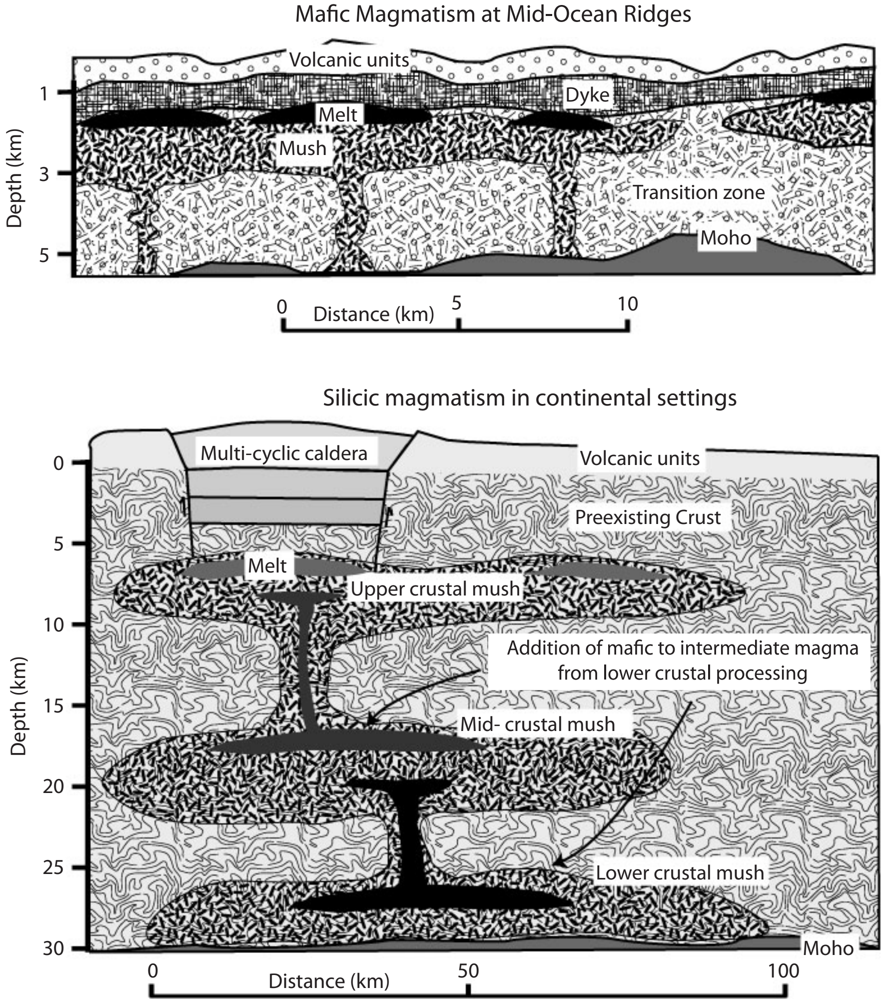

Fig. 4. A schematic comparison of the mush model for (a) mid-ocean ridge (modified from Sinton & Detrick, 1992) and (b) silicic magma chambers in mature continental arcs (modified from Hildreth & Moorbath, 1988, Bachmann & Bergantz, 2004, Marsh, 2004, Hildreth, 2007).

SUPPLEMENTARY DATA

Supplementary data for this paper are available at *Journal of Petrology* online.

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