

Reactive bulk assimilation: A model for crust-mantle mixing in silicic magmas

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ABSTRACT

Bulk assimilation of small (millimeters to ~1 km) fragments of crust—driven and (ultimately) masked by reactions during xenolith melting and magma crystallization—is an important mechanism for crust-mantle mixing. Xenoliths containing mica or amphibole undergo dehydration melting when incorporated into a host magma, yielding mainly plagioclase, pyroxene, Fe-Ti oxides, and hydrous melt. The xenolith is physically compromised by partial melting and begins to disintegrate; xenolithic melt and crystals are mixed into the host magma. Xenocrystic zircon is liberated at this stage. The cryptic character of assimilation is greatly enhanced in any hydrous magma by hydration crystallization reactions (the reverse of dehydration melting). All pyroxenes and oxides (phenocrysts, xenocrysts, or crystals having a hybrid signature) will be subject to these reactions, producing feldspars, amphiboles, and micas that incorporate material from several sources, a particularly effective mixing mechanism. Implicit in the model is a reduced energy penalty for bulk assimilation—much of the assimilant remains in solid form—compared to melt-assimilation models. A large role for bulk assimilation supports stopping as a credible mechanism for the ascent of magmas. While the assimilation of low-density crust and concomitant fractionation provide the isostatic impetus for ascent, the wholesale incorporation and processing of crustal rocks in the magma chamber helps create the room for ascent.

Keywords: bulk assimilation, dehydration melting, heat balance, silicic magma.

INTRODUCTION

Most large-volume continental silicic magmas are complex hybrids of mantle-derived basaltic melts and crustal rocks (e.g., DePaolo et al., 1992). Although physical evidence of hybridization is sometimes preserved in xenoliths and xenocrysts, most arguments for crust-mantle mixing invoke chemical evidence, especially radiogenic isotopes. By the early 1970s, it was recognized that isotopic variations in the Sierra Nevada batholith, for example, correlated with the character of the basement and, implicitly, required mixing of crustal and mantle sources (Kistler, 1974). Most models for the petrogenesis of silicic plutonic and volcanic rocks, especially in continental arcs, are specifically designed to address the problem of integration of crustal and mantle sources (e.g., DePaolo, 1981; Hildreth and Moorbath, 1988; DePaolo et al., 1992; Spera and Bohron, 2001). Until recently, crust-mantle mixing documented by radiogenic isotopes was treated as a purely cryptic process. However, single crystal isotopic studies of plagioclase and other minerals have shown that individual crystals may preserve evidence of magma mixing and other magmatic hybridization processes (e.g., Davidson and Tepley, 1997; Knesel et al., 1999; Gagnevin et al., 2004). Zircon has long been known to preserve evidence of inheritance from crustal sources, and this knowledge is routinely applied to source modeling for granitic and rhyolitic rocks. Experiments have verified that interaction between crustal lithologies (e.g., biotite gneiss) and basalt at high temperature and pressure yields hybrid melts whose compositions are similar to continental arc granitoids and rhyolites (Patino Douce, 1995, 1999).

This paper presents a conceptual model of the physico-chemical mechanisms that lead to the largely cryptic, large-scale mixtures of

crust and mantle materials exemplified by the silicic granitoids of continental arcs. We argue that bulk assimilation of small (millimeter to ~1 km) fragments of crust, driven and ultimately masked by reactions during partial melting of xenoliths and pluton crystallization, is an important mechanism of crust-mantle mixing in silicic volcanic and plutonic rocks.

The model presented here focuses on the assimilation side of assimilation–fractional crystallization processes. Fractional crystallization (which must occur as a consequence of assimilation of crust, especially in relatively fluid basaltic magmas) is not specifically addressed.

CONCEPTUAL MODEL: REACTIVE BULK ASSIMILATION

The reactive bulk assimilation model is based on the chemical and physical behavior of country-rock xenoliths as they are heated, partially melt, disaggregate, mix, and react with the host magma (Fig. 1). Incongruent reactive melting at the time of assimilation and, especially, incongruent reactive crystallization as the magma cools are critical to understanding assimilation and crust-mantle mixing.

The model can be divided into three parts: (1) incorporation of the xenolith into the melt, heating, partial melting, and physical weakening of the xenolith; (2) disaggregation and disintegration of the xenolith followed by mixing of both melt and xenocrysts into the host magma; and (3) incongruent hydration-crystallization reactions (Beard et al., 2004) during magma crystallization in which anhydrous xenocrysts and phenocrysts react with melt to yield amphiboles and/or micas. Most of the examples and arguments given here refer to processes that happen at relatively low temperature (<1000 °C). Note, however,

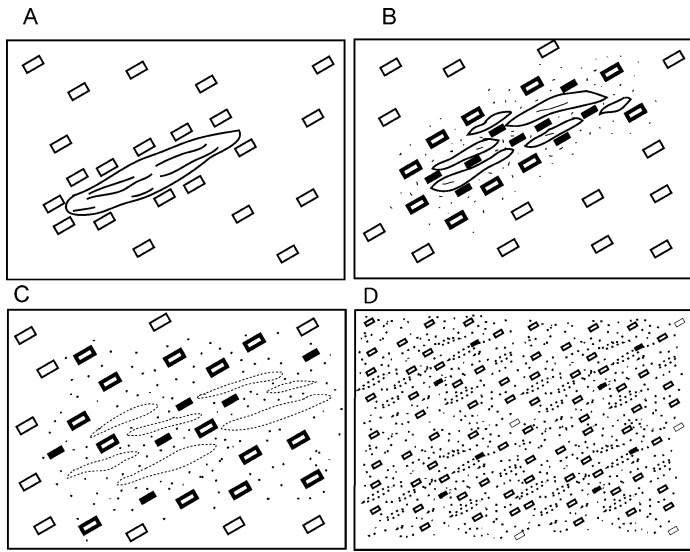


Figure 1. Bulk incorporation of xenolith into magma. A: Heating of xenolith to solidus induces crystallization in surrounding magma. B: Xenolith undergoes dehydration melting and begins to break up. Stippling represents mixtures of melt component of magma and dehydration melt of xenolith. New crystals formed from hybrid liquid have hybrid chemical, including isotopic, compositions (solid symbols). Other crystals (including erstwhile xenocrysts and phenocrysts) will have hybrid overgrowths or rims (thick black mantles). C: Disintegration of xenolith progresses to point where it is only vaguely recognizable. Crystallization continues. D: Swarm of several largely disintegrated xenoliths begins to merge. Former xenoliths are now marked by diffuse heterogeneous regions within magma.

that the first two parts of the model will operate even more effectively at higher temperature (e.g., in basaltic melts).

Incorporation, Heating, Dehydration Melting

At the outset, small fragments of country rock are incorporated into a magma (Fig. 1A). An upper limit for the size of xenoliths that can be effectively heated, partially melted, and disaggregated in a typical magma body is estimated to be on the order of 10^2 – 10^3 m (given typical thermal diffusivities for rocks [$\sim 10^{-6}$ m²/s] and time scales for pluton crystallization [10^4 – 10^5 yr]).

At temperatures of 800–900 °C, any country rock containing mica or amphibole will begin to undergo incongruent dehydration-melting reactions (Fig. 1B) of the general form: amphibole and/or mica + qtz + sodic plag = opx and/or cpx + calcic plag + oxides and/or garnet + hydrous melt.

By 850–950 °C, these reactions result in the formation of an anhydrous mineral assemblage coexisting with a hydrous melt (see review of Veilzeuf and Schmidt, 2001). The melt fraction is a function of mineralogy, rock composition, and temperature, but typically ranges from 20% for amphibolites at 900 °C to >60% for biotite gneisses at 1000 °C (Beard and Lofgren, 1991; Patino Douce and Beard, 1996; Veilzeuf and Schmidt, 2001). At higher temperatures melting will progress beyond the dehydration melting reactions. Wholesale melting of some xenoliths will occur and hot, mafic melts at the base of the crust will be particularly effective agents of assimilation (Reiners et al., 1995). Heat of fusion for the dehydration-melting reaction is drawn locally from the magma, resulting in crystallization in the vicinity of the xenolith.

Disaggregation and Disintegration

The physical integrity of the xenolith is compromised by partial melting. As the xenolith moves through the surrounding magma, it begins to disaggregate (Figs. 1B–1D). The xenolith-derived melt mixes

with the host liquid and magmatic phenocrysts come into contact with this mixed melt. Similarly, xenolith crystals come into contact with the host and/or mixed magmas. Zoning (including isotopic zoning, e.g., in plagioclase), resorption, and reaction are all likely consequences of this stage of host-xenolith mixing. Note that the solid phases derived from partially melted xenoliths (plagioclase, pyroxenes, Fe-Ti oxides) will be phases already present as phenocrysts in many host magmas. Disintegration of partially molten xenoliths and/or melting and disaggregation of wall rock has been documented in extrusive and shallow intrusive rocks and in experiments (Kovach and Marsh, 1981; Grove et al., 1988; Green, 1994; Rushmer, 1995).

In a convective, eruptive, or otherwise physically active magma, stirring of disintegrated xenoliths into the magma may be effective enough to reduce heterogeneities to the scale of a single crystal. If stirring is less complete, local heterogeneities will persist. These may take the form of regular and irregular mesoscale concentrations of minerals (pods, wisps, schlieren) as well as larger features, such as outcrop- or even map-scale layering or compositional variability. Note that in sampling plutons, petrologists usually avoid these features, especially at the mesoscale.

Perhaps the most compelling and commonly recognized consequence of xenolith disintegration is the presence of xenocrystic zircon in silicic plutonic and volcanic rocks. Miller et al. (2003) showed that granitic rocks that contain xenocrystic zircon must incorporate it at relatively low temperature (i.e., below the zircon dissolution temperature [~ 800 °C]; zircon incorporated above this temperature will dissolve in the melt). Given that the higher the degree of partial melting, the weaker a rock becomes (Rushmer, 1995), it follows that if xenoliths incorporated into a magma at 800 °C disaggregate and release zircon to the melt, xenoliths incorporated into higher-temperature magmas must disaggregate as well.

Hydration Crystallization

The cryptic character of assimilation is greatly enhanced, especially in plutons, by reactions that are essentially the reverse of dehydration-melting reactions (hydration crystallization; Beard et al., 2004): opx + cpx + oxides + calcic plag + hydrous melt = amphibole and/or mica + quartz + sodic plagioclase. These reactions will occur as any hydrous magma cools and crystallizes. All anhydrous phases in the system, whether original phenocrysts, xenolith-derived xenocrysts, or crystals having a hybrid signature, are subject to these reactions. Late-crystallizing amphiboles, micas, and feldspars formed during hydration crystallization reactions may incorporate material from several sources.

Note that hydration crystallization is different from simple crystallization during assimilation. Crystallization during assimilation preserves an ongoing record of mixing processes (e.g., Knesel et al., 1999; Gagnevin et al., 2004). Hydration crystallization affects crystals that once preserved the mixing record, obscuring and obliterating evidence that might be preserved, for example, in zoned pyroxenes.

Textural evidence for hydration crystallization is common in many calc-alkaline and other plutonic suites (Fig. 2). Most would agree that, for example, partial replacement of pyroxene by amphibole results from nonisochemical reactions involving melt. In many plutonic suites, the replacement of pyroxene and/or oxide minerals by amphibole and/or biotite can be tracked from incipient to complete (Figs. 2 A–D). In most tonalitic to granitic plutons, any pyroxene originally present is replaced by amphiboles and micas.

DISCUSSION

Fate of a Biotite Crystal

As an example of how reactive bulk assimilation can promote intimate mixing through both chemical and physical processes, let us examine a biotite crystal in a biotite gneiss xenolith. The biotite un-

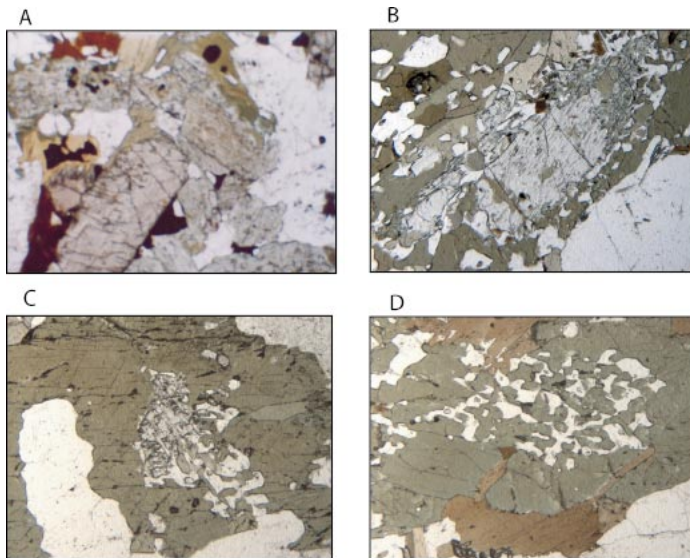


Figure 2. Petrographic evidence for hydration crystallization in plutonic rocks. **A:** Late-stage formation of biotite and amphibole at expense of orthopyroxene, clinopyroxene, and ilmenite. Gabbro, Pilot Peak pluton, California (Beard and Day, 1988). **B:** More extensive replacement clinopyroxene by amphibole and minor biotite. Note formation of quartz at amphibole-pyroxene contact. **C:** Relict clinopyroxene with quartz at amphibole. **D:** Quartz-amphibole intergrowth from same sample as B and C. This texture is interpreted as marking site of now entirely consumed pyroxene. B–D are from Bell Island tonalite, Alaska (Beard et al., 2003).

dergoes dehydration melting when the xenolith is incorporated into the magma, yielding orthopyroxene, plagioclase, Fe-Ti oxides, and melt (e.g., Patino Douce and Beard, 1996). Components of the biotite are redistributed to all of these phases (Fig. 3). Radiogenic Sr is redistributed to the melt and, especially, to any neoblastic plagioclase (Fig. 3). As the xenolith disintegrates, melt and crystalline phases carrying material derived from the original xenolith biotite are dispersed into the magma (e.g., Fig. 1). Finally, during cooling and reactive crystallization, the crystalline and melt components of the original biotite crystal are chemically reassigned to a number of product phases, which may include amphibole, feldspar, quartz, or even biotite (Fig. 3). Original country-rock biotite can eventually become part of final igneous biotite, and of a variety of other phases—a phenomenally effective means for cryptic incorporation of crustal material into a magma. Together, reaction and disintegration can serve to mask the assimilation process to the point that physical evidence of assimilation may be difficult to recognize (and easy to overlook) when the final plutonic product is examined.

Traces of Reactive Bulk Assimilation and a Prediction

Xenocrysts, inherited zircon in particular, provide compelling evidence for the bulk assimilation of crustal xenoliths. Simply put, it is difficult to envision a mechanism better suited to release inherited zircon to the melt than the disintegration of partially molten xenoliths. The detection and analysis of inherited zircon, however, is a costly and time-consuming process. There may be more accessible evidence for reactive bulk assimilation in plutonic rocks.

Almost all plutons (and eruptive sequences) are heterogeneous on scales ranging from zoned crystals to mafic enclaves to map-scale zoning. These heterogeneities have revealed chemical and isotopic signatures of a variety of mixing and assimilation processes (e.g., Reid et al., 1983; Kistler et al., 1986; Davidson and Tepley, 1997). Other common (ubiquitous?) heterogeneities have received less attention. Indistinct patches, clots, stringers, and other concentrations of minerals

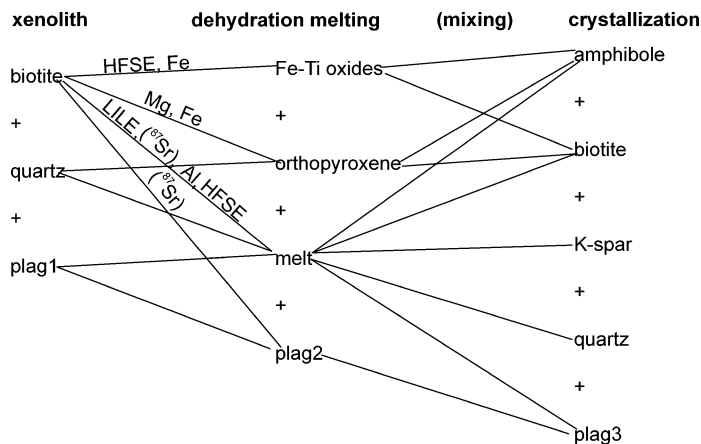


Figure 3. Flow chart showing redistribution of elements from xenolith biotite during dehydration melting and subsequent processes. Note that constituents of original biotite end up in all major subsolidus phases. Although material contribution of biotite to plagioclase will be small, its contribution of radiogenic Sr will be large. LILE—large ion lithophile elements, HFSE—high field strength elements. See text for discussion.

(commonly minerals like biotite and amphibole) on the hand-specimen or thin-section scale and vague wispy or layered structures on an outcrop scale are generally avoided (or ignored) during the study of plutonic rocks. Features of this sort are the expected result of incomplete mixing during reactive bulk assimilation. The reactive assimilation model predicts that many of these features are remnants of incompletely assimilated material and should retain a relict crustal isotopic and/or chemical signature.

SOME IMPLICATIONS OF REACTIVE BULK ASSIMILATION

Heat and Mass Constraints on Assimilation

Most assimilation models (e.g., Reiners et al., 1995; Spera and Bohrsen, 2001) assume that country rocks are assimilated as melts and that the required heat of fusion is derived from crystallization and cooling of the host magma. If, instead of entirely melting the country rocks or even partially melting them and extracting melts, country rocks are incorporated in toto, melt, crystals, and all into host magmas, heat requirements for assimilation are significantly reduced (Grove et al., 1988). Quantifying the importance of this reduction in required heat awaits thermodynamic analysis of the very complex incongruent melting reactions. However, the tacit assumption that bulk assimilation is equivalent to bulk melting places unnecessary and unrealistic constraints on the amount of assimilant that a magma can incorporate. Reactive bulk assimilation provides the mechanism to explain results that suggest ratios of mass assimilated to mass crystallized on the order of 1 or even greater than 1 (e.g., Grove et al., 1988; Vigneresse, 2004), which is difficult to conceive if assimilation requires complete melting.

Stoping and Ascent

A large role for bulk assimilation of crust in the genesis of large-volume silicic magmas gives credence to the idea of ascent by stoping. Stopping and assimilation together can provide a powerful ascent mechanism for magmas in the crust. While the assimilation of low-density crust and concomitant fractionation provides the buoyancy necessary for ascent, the removal of overlying crustal rocks into the magma chamber creates the room for ascent. Some crustal material remains with the magma until emplacement, but some becomes part of a hybridized crystal-rich residue (Patino Douce, 1995), perhaps similar to the Rb-poor, ⁸⁷Sr-rich gabbroic xenoliths reported from western Mexico and elsewhere (Ruiz et al., 1988; Cameron and Robinson, 1990).

Stopping in the context of reactive bulk assimilation would imply that components from all levels of crust traversed by the magma be present and that the final pluton composition represents a summation of interactions during ascent. Although material may be incorporated up to the time of emplacement (and, the zircon evidence suggests, cryptically incorporated if the magma temperature is $> \sim 800$ °C), there is no reason to expect an obvious or distinct chemical signature from country rocks at the level of emplacement. In general, input from rocks at the level of emplacement is likely to be less important than input from rocks traversed at higher temperature deeper in the crust (Reiners et al., 1995). The obvious crustal xenoliths in plutons reflect only the last stages of assimilation and/or refractory lithologies; xenolithic material that is truly relevant to the bulk evolution of the magma is likely to be much less obvious (e.g., Barnes et al., 2005).

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