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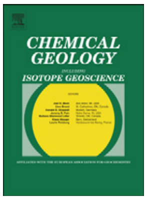

Magnesium isotope systematics of endoskarns: Implications for wallrock reaction in magma chambers

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ABSTRACT

We measured the magnesium isotopic compositions of endoskarns (i.e., the metasomatically altered interior margin of the pluton) generated by contact metamorphism between granodioritic magma and dolomitic wallrock. The endoskarns were sampled as crustal xenoliths in Pleistocene basaltic cinder cones erupted in eastern California and provide a record of pluton–wallrock interactions at depth. The endoskarns consist of an outer zone made of pyroxenite (Mg-rich) and an inner zone represented by a plagioclase–quartz lithology with relict plutonic textures and minor pyroxene. The inner and outer zones are separated by a thin selvage of phlogopite. The Mg isotopic compositions of these endoskarns are all significantly lighter (δ^{26}Mg < −0.8‰ relative to the Dead Sea magnesium (DSM-3) standard) than canonical peridotitic mantle (δ^{26}Mg = −0.25‰). In particular, the outer pyroxenite zones of the endoskarn are consistently >1‰ lighter (−1.69 to −2.09‰; mean = −1.74‰; SD = 0.07‰; n = 8) than the mantle, and Mg isotopic values increase in the inner, Mg-poor and plagioclase–quartz dominated zone (δ^{26}Mg of −0.82‰). Because of the high temperatures associated with endoskarn formation, it is unlikely that the light Mg isotopic compositions result from equilibrium isotopic fractionations between mineral phases. The Mg isotopic signatures of the endoskarns are most easily interpreted by the mixing of Mg between Mg-rich and ^{26}Mg-depleted dolomitic wallrock with Mg-poor and ^{26}Mg-enriched magma. Mg isotopes may thus be useful in tracking magma–carbonate interactions in magmas.

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1. Introduction

Crustal assimilation of wallrock or anatectic melts derived from the wallrock is an important process in the origin and differentiation of magmas. Of interest here is the assimilation of crustal carbonates, such as limestones and dolostones, which could lead to extensive decarbonation (Kerrick, 2001). Examples in which carbonate assimilation is thought to be a significant source of CO_2 in volcanoes come from Merapi in Indonesia (Chadwick et al., 2007) and Etna and Vesuvius in Italy (Allard et al., 1991; Fulignati et al., 2000). To place these types of volcanoes in context, Etna and Vesuvius ($1.3 \pm 0.3 \times 10^{13}$ g/yr CO_2) combined make up 20% of the modern day global CO_2 production from arcs ($<3.1 \times 10^{13}$ g/yr C) (Allard et al., 1991; Dasgupta and Hirschmann, 2010). If carbonate assimilation is widespread, then there are important implications for the long-term global carbon cycle and climate change (Kerrick, 2001; Berner, 2003; Lee et al., 2013).

The extent to which magmas interact with crustal carbonates, however, is difficult to constrain because the interaction zones are often poorly exposed. In many cases, crustal carbonates can be assimilated by magmas, leaving behind little physical evidence (Liao et al., 2012). Detecting carbonate assimilation in magmas using conventional radiogenic isotopes may be difficult because limestones and dolostones are typically characterized by unradiogenic Sr isotopes (and hence, similar to juvenile magmas), and their Nd concentrations are so low that they may not influence the Nd isotopic composition of the magma. Therefore, it is possible that the extent of carbonate assimilation in the evolution of magmas has been under-estimated. Diagnostic tools for identifying carbonate interaction/assimilation by magmas are thus necessary.

The stable isotopes of Mg may have potential in tracking carbonate wallrock and magma interactions. Significant Mg isotopic variations are observed in low temperature environments, ranging from +1‰ to ~−5.5‰ (Galy et al., 2002; Tipper et al., 2006a; Buhl et al., 2007; Brenot et al., 2008; Pogge von Strandmann et al., 2008; Tipper et al., 2008; Immenhauser et al., 2010; Li et al., 2010; Teng et al., 2010b; Wimpenny et al., 2010; Huang et al., 2012). For example, river waters vary from −2.6‰ to +0.8‰(Tipper et al., 2006a,b; Pogge von Strandmann et al., 2008; Tipper et al., 2008), weathering residues are between −0.3‰ and +0.6‰ (Teng et al., 2010b; Huang et al., 2012), seawater is globally homogeneous at ~−0.8‰ (Ling et al., 2011), and carbonates are between −1‰ to −5.5‰ (Galy et al., 2002; Pogge von Strandmann, 2008; Higgins and Schrag, 2010). In contrast, igneous

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rocks and minerals generally exhibit a more limited range in Mg isotopic compositions (Handler et al., 2009; Liu et al., 2010; Teng et al., 2010a), although inter-mineral isotopic fractionations are also observed in high temperature rocks (Li et al., 2011; Liu et al., 2011; Wang et al., 2012).

Thus, given the sharp contrast in Mg isotopic behavior during low and high temperature processes, low temperature isotopic signals can be preserved during high temperature processes. As shown in recent studies by Shen et al. and Teng's group (Shen et al., 2009; Liu et al., 2010), some granitic rocks are isotopically heavy in Mg, which can be explained by the assimilation of pelitic metasediments, which are enriched in ^{26}Mg (Li et al., 2010). However, assimilation of carbonate rocks, such as dolostones or Mg-bearing limestones, should drive Mg isotopes towards light signatures.

As a step towards testing the effect of carbonate assimilation on the Mg isotopes of magmas, we investigated rocks formed by the interaction of granodioritic magma with a dolomitic wall rock derived from the deep crust of the late Cretaceous Sierra Nevada batholith in California, USA (Ducea, 2001; Lee et al., 2007). These metasomatic interior margins of plutonic rocks are called endoskarns. These rocks were sampled as xenoliths hosted in Quaternary basaltic lavas associated with Basin and Range extension (Dyer et al., 2011). Previous detailed petrographic and geochemical analyses of these samples show that their protoliths are granodiorite plutonic rocks that have been metasomatized by CO_2-bearing fluids released from dolomitic wall rock due to decarbonation of the wall rock during skarn formation. Specifically, these CO_2-bearing fluids were also enriched in Ca and Mg, leading to Ca and Mg enrichment of the pluton margins, resulting in the formation of an endoskarn. In this paper, we investigate the Mg isotopic composition of endoskarns in order to assess the extent to which they inherit an isotopic signature from the carbonate wallrock. Because most endoskarn outcrops are poorly exposed or highly weathered, we examined Cretaceous endoskarn xenoliths in Pleistocene volcanoes. These endoskarns were sampled from depth during eruption, providing some of the freshest samples of endoskarn available.

2. Geological setting and sample description

The xenoliths analyzed in this study were collected from the Fish Springs alkali basalt cinder cone (N 37.0712, W 118.2550), which erupted ~0.314 million years ago (Martel et al., 1987; Blondes et al., 2008) on the eastern flank of the Sierra Nevada in the Big Pine volcanic field (0.1–0.5 m.y.) (Fig. 1) (Beard and Glazner, 1995; Mordick and Glazner, 2006; Blondes et al., 2008). The exposed basement rock through which the Big Pine volcanic field was emplaced is composed of Cretaceous granitoids to the west and Paleozoic metasediments to the east (Bateman, 1961; Kistler et al., 1965). Crustal xenoliths are abundant in the Fish Springs cinder cone. Petrographic and geochemical observations suggest that a subset of these crustal xenoliths is represented by endoskarns, formed by the interaction between granodioritic magmas and carbonate wallrocks (Dyer et al., 2011). The endoskarn xenoliths range in size from a few cm up to 30 cm. Notable features in these endoskarns include original igneous minerals that have been replaced by Ca-rich plagioclase and pyroxene (diopside), replacive pyroxenes preserving plagioclase trace-element signatures, and phlogopitic reaction zones between the pyroxene-rich skarn and magma (Dyer et al., 2011).

In this study, we focus on two xenolith samples. Sample A (Fig. 2) consists of four reaction zones with distinctive mineralogies. In the direction of wallrock to magma, these zones are: a pyroxenite zone (Px), a phlogopite-rich zone (Phl), a pyroxene-rich (~30%) plagioclase–quartz zone (Px–Q–Pl), and a plagioclase–quartz zone with <5% pyroxene (Pl–Q). This entire reaction zone occurs over a distance of ~10 cm and is typical of magma–wallrock contacts described in Dyer et al. The Px zone is considered the contact itself and all other zones are considered the endoskarn. Zone Pl–Q contains relict igneous textures and represents the outer margin of the pluton body (Dyer et al., 2011). The original plutonic mafic minerals (e.g., hornblende and biotite) are not present in zones Pl–Q and Px–Q–Pl, suggesting that they have been replaced by pyroxene. Sample B (Fig. 3) is a large (20 cm) plagioclase–quartz rock containing small amounts of pyroxene and occurring as finely

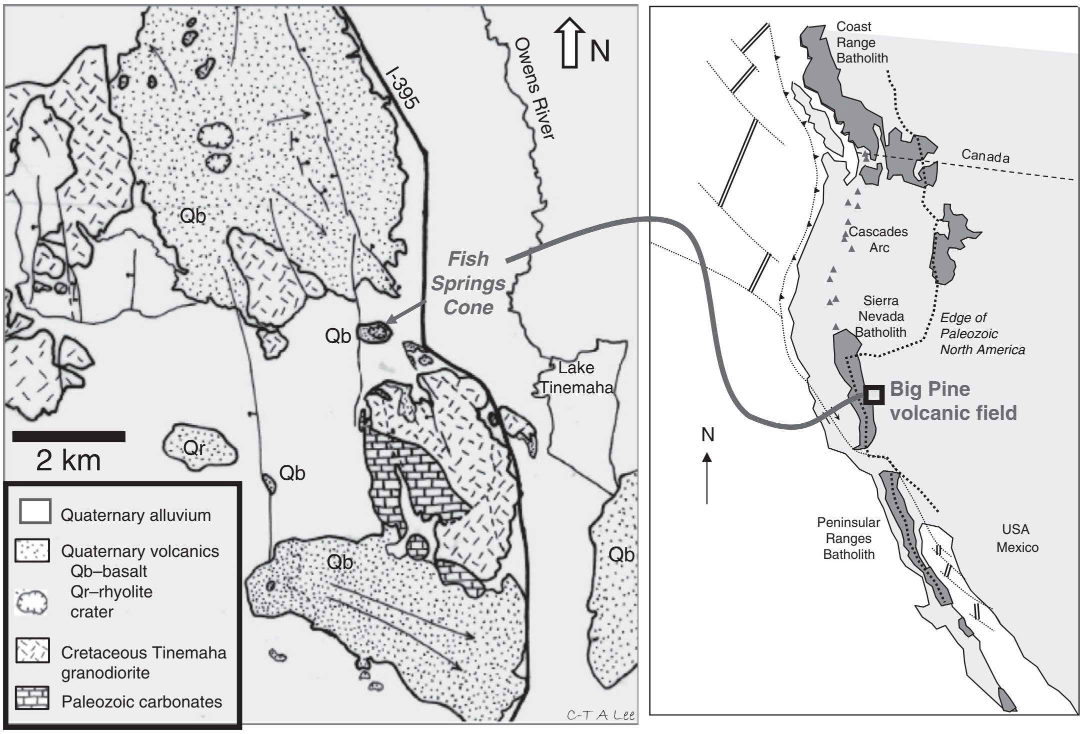

Fig. 1. Geological map showing the sample locality, the Fish Springs cone in the Big Pine volcanic field in the eastern edge of Sierra Nevada.

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