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Thickening, refertilization, and the deep lithosphere filter in continental arcs: Constraints from major and trace elements and oxygen isotopes

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ABSTRACT

Arc magmatism is a complex process involving generation of primary melts in the mantle wedge and chemical refinement of these melts into differentiated products akin to continental crust. Interaction of magmas (cooling, crystallization and assimilation) with the overlying crust, particularly if it is thick, is one way by which primary basalts are refined into more evolved compositions. Here, we explore the role of the mantle lithosphere as a trap and/or reactive filter of magmas. We use mantle xenoliths from the Sierra Nevada continental arc in California as a probe into sub-Moho processes. Based on clinopyroxene modal abundance and major, minor and moderately incompatible trace element concentrations, the peridotites define a refertilization trend that increases with depth, grading from clinopyroxene-poor (<5%), undeformed spinel peridotites equilibrated at <3 GPa (<90 km) to clinopyroxene-rich (10–20%), porphyroclastic garnet peridotites equilibrated between 3 and 3.5 GPa (90–105 km), the latter presumably approaching the top of the subducting slab. The petrology and geochemistry of the xenoliths suggest that the fertile peridotites were originally depleted spinel peridotites, which were subsequently refertilized. Incompatible trace element geochemistry reveals a pervasive cryptic metasomatic overprint in all peridotites, suggesting involvement of small amounts of subduction-derived fluids from the long-lived Farallon plate beneath western North America. However, bulk reconstructed $\delta^{18}O_{SMOW}$ values of the peridotites, including the most refertilized, fall between 5.4 and 5.9‰, within the natural variability of unmetasomatized mantle (∼5.5 ± 0.2‰). Together with Sm, Yb, and Ca compositional data, the oxygen isotope data suggest that the role of slab or sediment melts in refertilizing the peridotites was negligible (<5% in terms of added melt mass). Instead, binary mixing models suggest that many of the Sierran garnet peridotites, particularly those with high clinopyroxene modes, had up to 30% mantle-derived melt added. Our data suggest that refertilization of the deep arc lithosphere, via melt entrapment and clinopyroxene precipitation, may be an important process that modifies the composition of primary arc magmas before they reach the crust and shallowly differentiate. Comparison of our data with a global compilation of arc-related mantle xenoliths suggests that sub-Moho refertilization may be more extensive beneath mature arcs, such as continental arcs, compared to juvenile island arcs, possibly because of the greater thickness of crust and lithosphere beneath mature and island arcs.

1. Introduction

Island arcs are potential building blocks of continents (Taylor, 1977), but an outstanding problem is how basalts, the dominant product of island arcs, are refined into andesitic continental crust. One end-member mechanism is single-stage differentiation of granitoids from a basaltic parent (Bowen, 1928; Gill, 1981; Grove and Baker, 1984; Lee et al., 2007b; Jagoutz et al., 2009). Another scenario is multi-stage differentiation of a basaltic parent involving re-melting and assimilation of pre-existing lower crust to generate granitoids (White and Chappell, 1977; Tatsumi et al., 2008). Primary magmas are mixed, assimilated, stored, and homogenized in deep crustal magma chambers (Hildreth and Moorbath, 1988; Annen et al., 2006), and upon ascent through shallower crust are further differentiated via lower pressure crystal fractionation and wallrock assimilation (DePaolo, 1981; Blatter et al., 2013; Bohrson and Spera, 2001; Lee et al., 2013; Dufek and Bachmann, 2010). Such deep crustal magma chambers may be favored

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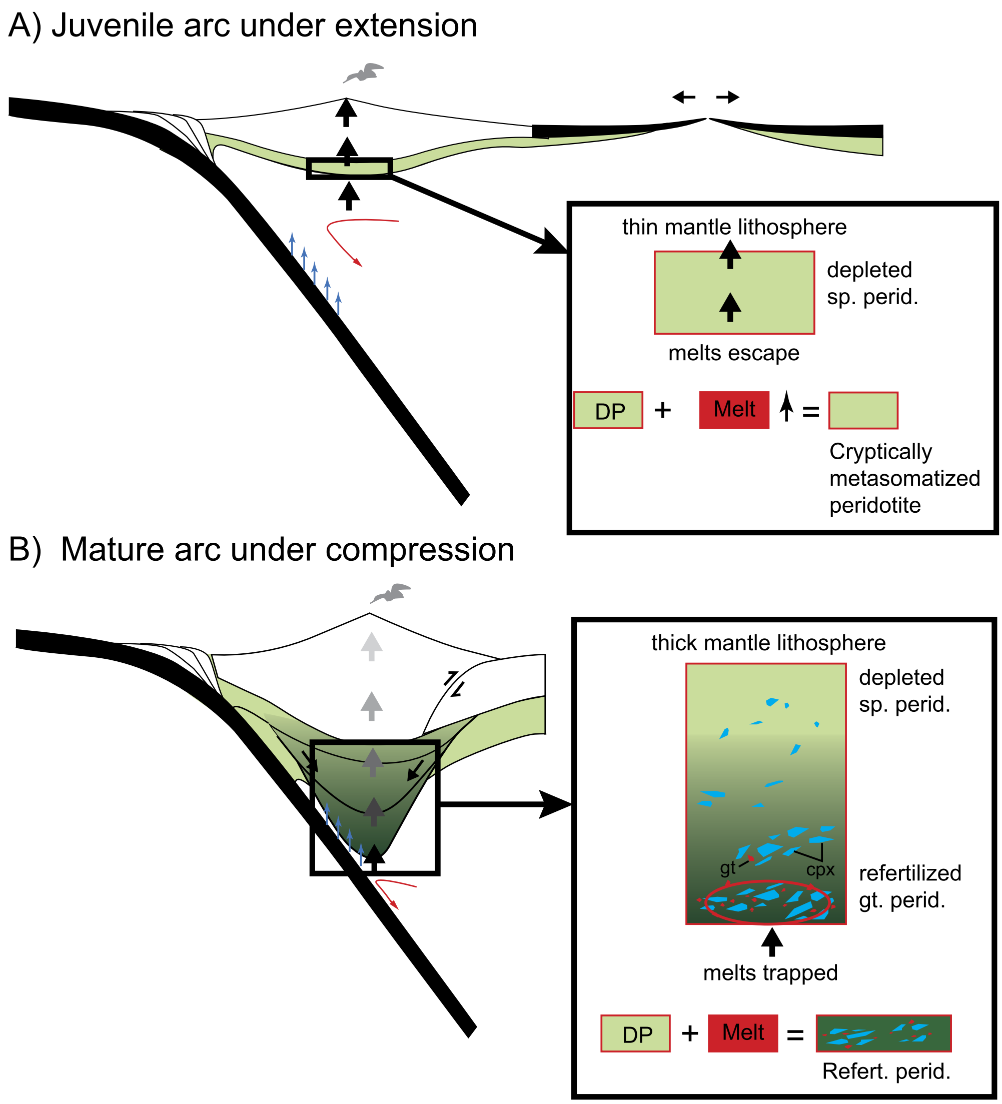

Fig. 1. Cartoon illustrating refertilization of the mantle lithosphere in juvenile and mature arcs. In A), mantle lithosphere is thin beneath juvenile arcs under extension. Primary magmas from the mantle wedge do not stagnate extensively beneath the lithosphere, bypassing it and erupting as basaltic magmas (black arrows). However, cryptic metasomatism of the mantle could occur, but this would not result in the formation of new mineral phases. In B), mantle lithosphere is thick beneath mature arcs under compression. Primary magmas from the mantle wedge might stagnate extensively beneath the lithosphere and undergo increased differentiation (black to gray arrows), and also experience high-pressure crystal fractionation which results in clinopyroxene-enrichment of the mantle. This type of modal metasomatism results in refertilization.

beneath thick, mature island and continental arcs, because primary magmas may be more easily trapped beneath thick crust, enhancing differentiation to more felsic compositions (Leeman, 1983). Indeed, crustal deformation studies of arc volcanoes suggest that deep crustal magma chambers are more prevalent beneath compressional, thick continental arcs compared to extensional, thin island arcs (Chaussard and Amelung, 2012). As a consequence, continental arc magmas may experience greater differentiation and processing through thicker crustal columns, erupting a larger proportion of andesites, compared to their island arc counterparts where the crust is thinner and the magma flux is dominated by basalt (Fig. 1).

Despite the focus on the crust and its effect on magmatic differentiation in arcs (Plank and Langmuir, 1988; Wallace and Carmichael, 1999), comparatively few studies have addressed the role of the mantle lithosphere. One important question in the study of arc magmatism (and magmatism in general) is how much differentiation of a primary melt occurs below the crust? This question is important because in some arcs, particularly mature continental arcs, such as the Andes in South America and Sierra Nevada in the Western USA, the deep sub-Moho arc lithosphere can reach considerable thickness (Kay et al., 1994; Ducea and Saleeby, 1996; Lee et al., 2001a; Haschke and Gunther, 2003; Chin et al., 2012). Field and xenolith studies from paleo-arcs such as the Sierra Nevada (Lee et al., 2006), Talkeetna (Greene et al., 2006), and Kohistan (Jagoutz et al., 2009, 2011) reveal an abundance of mafic cumulates at lower crustal depths. While these cumulates provide evidence for deep crustal crystal fractionation of primitive arc magmas, how much crystal fractionation occurs within the underlying mantle lithosphere is not well known. Because thicker crust favors fractionation of high-pressure phases (e.g., pyroxene over olivine; Chen and Presnall, 1975), it might be expected that thicker lithosphere would also promote the fractionation of such phases. As a consequence, “primary” arc magmas may undergo crystal fractionation at greater depths than previously recognized. Furthermore, melts passing through depleted arc mantle can react with and modally metasomatize (refertilize) the mantle, transforming it back into fertile lherzolite (Fig. 1B).