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Experimental melting of hydrous peridotite–pyroxenite mixed sources: Constraints on the genesis of silica-undersaturated magmas beneath volcanic arcs

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ABSTRACT

The most primitive arc magmas expressed as melt inclusions in forsteritic olivine display silica-undersaturated, nepheline normative compositions, sometimes associated with high CaO contents. Involvement of a heterogeneous mantle source containing an amphibole-bearing clinopyroxene-rich component is often mentioned to account for the origin of these magmas. However, the proportions and the role of such mantle source component in arc magma genesis remains a matter of debate. To better understand the generation of silica-undersaturated magmas in arcs and the role of clinopyroxenites during arc magma genesis, we have performed melting experiments on a heterogeneous hydrous mantle (hydrous lherzolite mixed with variable amounts of amphibole-bearing clinopyroxenite) at 1 GPa under oxidizing conditions (close to the fayalite–magnetite–quartz: FMQ-buffer). Unlike under anhydrous conditions, pyroxenites and peridotites have similar solidus temperatures under hydrous conditions, but the melt productivity still increases with increasing fraction of pyroxenite in the source. For peridotite-rich sources (up to 50% clinopyroxenite) the presence of orthopyroxene buffers the partial melts to compositions identical in terms of major elements to regular peridotite melts. When orthopyroxene leaves the residue (above 50% of pyroxenite), melts become nepheline-normative, with CaO/Al_2O_3 ratios >1. Comparison between experimental melts produced by melting homogeneous mixed sources (homogeneous melting) and aggregated melts from heterogeneous sources (heterogeneous melting) shows that the later are more silica-undersaturated and richer in CaO. Our experiments confirm that nepheline-normative melt inclusions have sampled pure or poorly-mixed clinopyroxenite melts from a heterogeneous mantle source, while hypersthene-normative lavas are likely to result from a more advanced stage of magma mixing. Amphibole–clinopyroxenite heterogeneities in the mantle wedge could originate by density-driven delamination of lower crustal cumulates consisting of clinopyroxene + amphibole ± olivine. Partial melts of these cumulates can be efficiently extracted and suffer only little interaction with surrounding peridotites before their entrapment as melt inclusions; alternatively, they can react with peridotite to form secondary orthopyroxene-free metasomatic veins, which may also contribute to the source of silica-undersaturated arc magmas.

1. Introduction

Most lavas erupted in subduction zones exhibit calc-alkaline differentiation and are characterized by relatively silica-rich compositions (~55 wt% SiO_2 on average; e.g., Plank and Langmuir, 1988), even for the most primitive compositions. The higher silica content of primary magmas produced in arc environments with respect to those from other geodynamical environments has been ascribed to the addition of water (e.g., Nicholls and Ringwood, 1973; Hirose and Kawamoto, 1995; Gaetani and Grove, 1998), and/or silica-rich slab-derived fluids (e.g., Green and Ringwood, 1967; Nicholls and Ringwood, 1973; Wyllie and Sekine, 1982; Schiano et al., 1995) to their mantle source region. The primary, hydrous arc magmas evolve towards more silica-saturated compositions by fractional crystallization, magma mixing or assimilation processes (e.g., Grove et al., 2003, 2005). Rarely erupted high-Mg basalts in arc settings have generally CIPW norms (Cross et al., 1903) with hypersthene + olivine, while andesites are typified by normative hypersthene + quartz (Gill, 1981).

Recent studies have identified a population of nepheline-normative, sometimes CaO-rich, primitive arc magmas occurring

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occasionally as whole rocks, but more generally as primary melt inclusions preserved in highly forsteritic (Fo > 85) olivine phenocrysts (e.g., Della-Pasqua and Varne, 1997; Gioncada et al., 1998; Métrich et al., 1999; Schiano et al., 2000; De Hoog et al., 2001; Elburg et al., 2007; Portnyagin et al., 2007; Le Voyer et al., 2008; Bouvier et al., 2010a, 2010b; Sorbadere et al., 2011, 2013). The composition of these melt inclusions cannot be linked to their hypersthene-normative host lavas by simple differentiation processes (e.g., Schiano et al., 2000). Nor can partial melting of anhydrous or hydrous peridotite generate magmas with silica-undersaturated compositions and other properties similar to those observed for these arc melt inclusions (Schiano et al., 2000; Médard et al., 2006). Indeed, only high-pressure melts from peridotite (above 1.5–1.8 GPa; e.g., Hirose and Kushiro, 1993; Kushiro, 1996; Gaetani and Grove, 1998; Falloon et al., 2001; Tenner et al., 2012; Till et al., 2012a) are silica-poor and silica-undersaturated. However, they have lower CaO/Al_2O_3 ratios and nepheline-normative contents than most primitive arc melt inclusions. Moreover, the presence of residual garnet in the source of these melt inclusions has been dismissed according to their flat HREE spectra (e.g., Elburg et al., 2007; Sorbadere et al., 2013). Partial melting of lherzolite in the presence of CO_2 could also generate nepheline-normative melts (e.g., Dalton and Presnall, 1998; Green et al., 2004; Dasgupta et al., 2007). However, experimental melts of carbonated or CO_2-fluxed peridotites are significantly different from nepheline-normative arc melt inclusions (e.g., Elburg et al., 2007). In particular, the melt inclusions have much higher CaO and MgO contents, highly incompatible element concentrations, Zr and Hf contents and LREE/HREE ratios. The most widely cited mechanism for the genesis of the nepheline-normative melt inclusions in arc settings involves partial melting of amphibole-bearing, clinopyroxene-rich pyroxenite lithologies (or melt-rock interactions between such lithologies and peridotite-derived melts) at lower crustal or shallow upper mantle pressures (Gioncada et al., 1998; Schiano et al., 2000; De Hoog et al., 2001; Médard et al., 2004, 2006; Elburg et al., 2007; Bouvier et al., 2010a, 2010b; Marchev et al., 2009; Georgiev et al., 2009; Sorbadere et al., 2011, 2013).

Pyroxenites have been widely described in arc environments as xenoliths or in ultramafic complexes (e.g., Aoki, 1971; Irvine, 1974, 1980; DeBari and Coleman, 1989; Conrad and Kay, 1984; Himmelberg and Loney, 1995; Garrido and Bodinier, 1999; Turner et al., 2003; Greene et al., 2006; Berly et al., 2006). They have been interpreted either as clinopyroxene-rich cumulates from the deep arc crust (Wyllie, 1967; DeBari and Coleman, 1989; Müntener et al., 2001; Berly et al., 2006; Greene et al., 2006), or metasomatic veins in the mantle (e.g., Irving, 1980; Garrido and Bodinier, 1999; Berly et al., 2006). The high temperatures needed to form nepheline-normative arc melt inclusions (up to 1300 °C; Schiano et al., 2000; Sorbadere et al., 2013) are difficult to reconcile with arc crust melting. Additionally, in the case of crustal melting, the derived melts would have a wide range of compositions from nepheline-normative to quartz-normative, reflecting the heterogeneity of crust lithologies, but this is not the case for primitive arc melt inclusions. Hence, melting of lower-crustal cumulates cannot be directly responsible for the common pyroxenitic signature of primitive arc magmas.

Fractional crystallization experiments (Müntener et al., 2001; Müntener and Ulmer, 2006; Alonso-Perez et al., 2009) and modelling (Greene et al., 2006) have shown that cumulate pyroxenites are generated up to 50–60% fractional crystallization of basaltic mantle-melts. However, they represent generally less than 5% of the volume of a mature arc crust and 35% of a young arc crust (DeBari and Coleman, 1989; Kelemen et al., 2003; Greene et al., 2006; Garrido et al., 2007; Smith et al., 2009). To explain this difference, DeBari and Sleep (1991), Müntener et al. (2001), and Greene et al. (2006) proposed that the major part of the dense cumulative pyroxenites has been delaminated into the less dense underlying residual mantle, where they could play a major role in the genesis of nepheline-normative arc magmas. However, the proportions and the role in arc magma genesis of such mantle source component remains a matter of debate.

To better understand the generation of nepheline-normative magmas in arc and the role of clinopyroxenites during arc magma genesis, we have performed melting experiments on mixes of amphibole clinopyroxenite and variable proportions of hydrous peridotite at 1 GPa between 1150 and 1300 °C. Our experiments refer to an end-member melting model (homogeneous melting) involving a homogeneous mixed source. Hence, they are probably not directly applicable for a natural melting system occurring in the sub-arc mantle. Our experiments can also be used to quantify the compositions of melts derived from another end-member case where source components melts independently, and the resulting liquids mix afterwards (heterogeneous melting). Our results also help improve the petrogenetic model for silica-undersaturated (i.e., nepheline- and hypersthene-normative) arc magmas, and clarify the relationship between nepheline-normative melt inclusions and their hypersthene-normative host lavas.

2. Experimental and analytical procedures

2.1. Starting materials

Our synthetic starting materials consist of an olivine–amphibole clinopyroxenite (OCA2) and a peridotite (KLB-1) (Table 1). MIX25, MIX50 and MIX75 are homogeneous mixtures of 25 wt% OCA2 + 75 wt% KLB-1, 50 wt% OCA2 + 50 wt% KLB-1, and 75 wt% OCA2 + 25 wt% KLB-1, respectively. The composition of the olivine–amphibole clinopyroxenite OCA2 (45 wt% clinopyroxene, 36 wt% amphibole, 19 wt% olivine, Médard et al., 2006) is based on the phase proportions and compositions of several amphibole–clinopyroxene–olivine cumulative rocks found in arc settings. It is representative of the lower crustal layered complexes beneath exhumed volcanic arcs that constitute the arc roots (e.g., Aoki, 1971; DeBari and Coleman, 1989; Conrad and Kay, 1984; Himmelberg and Loney, 1995; Turner et al., 2003; Berly et al., 2006). The composition of the spinel lherzolite KLB-1, used in various experiments as an analogue for the composition of the bulk upper mantle, was taken from Hirose and Kawamoto (1995), with 0.2 wt% H_2O added. Oxygen fugacity in arc settings is generally higher than in other environments (e.g., Osborn, 1959; Carmichael, 1991; Arculus, 1994; Parkinson and Arculus, 1999; Rowe et al., 2009; Kelley and Cottrell, 2009; Malaspina et al., 2010). Thus, in order to ensure more oxidizing conditions in the partial melting experiments, 5 mol% of total iron was added as Fe^{3+} in the composition of OCA2 and KLB-1.

OCA2 and KLB-1 starting materials were obtained by mixing analytical grade oxides together with synthetic pseudowollastonite, fayalite, and hydrous glasses. The use of hydrous glasses allows a better control on water and alkali concentrations in the starting materials. The compositions of the hydrous glasses were chosen in order to create dacitic/rhyolitic glasses, which melt at ∼800 °C in the $NaAlSi_3O_8–KAlSi_3O_8–SiO_2–H_2O$ system (Tuttle and Bowen, 1958). To form hydrous glasses, dry glasses were produced at 1 atm from analytical grade oxides and carbonates, then loaded in a gold capsule along with water. Samples were then fused at 1000 °C and 1.0 GPa in a 19.1 mm piston-cylinder.

2.2. Experimental techniques

Partial melting experiments were performed in a 12.7 mm end-loaded piston-cylinder at 1 GPa between 1150 and 1300 °C using thick-walled (0.75 mm) $Au_{80}Pd_{20}$ containers, in order to minimize