Mantle refertilization by melts of crustal-derived garnet pyroxenite: Evidence from the Ronda peridotite massif, southern Spain

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A B S T R A C T

Geochemical studies of primitive basalts have documented the presence of crustal-derived garnet pyroxenite in their mantle sources. The processes whereby melts with the signature of garnet pyroxenite are produced in the mantle are, however, poorly understood and somewhat controversial. Here we investigate a natural example of the interaction between melts of garnet pyroxenite derived from recycled plagioclase-rich crust and surrounding mantle in the Ronda peridotite massif. Melting of garnet pyroxenite at ~1.5 GPa generated spinel websterite residues with MREE/HREE fractionation and preserved the positive Eu anomaly of their garnet pyroxenite precursor in whole-rock and clinopyroxene. Reaction of melts from garnet pyroxenite with depleted surrounding peridotite generated secondary fertile spinel lherzolite. These secondary lherzolites differ from common spinel lherzolite from Ronda and elsewhere by their lower-Mg# in clinopyroxene, orthopyroxene and olivine, lower-Cr# in spinel and higher whole-rock Al2O3, CaO, Sm/Yb and FeO* at a given SiO2. Remarkably, secondary spinel lherzolite shows the geochemical signature of ghost plagioclase in the form of positive Eu and Sr anomalies in whole-rock and clinopyroxene, reflecting the transfer of a low-pressure crustal imprint from recycled pyroxenite to hybridized peridotite. Garnet pyroxenite melting and melt–peridotite interaction, as shown in the Ronda massif, may explain how the signature of subducted or delaminated crust is transferred to the mantle and how a garnet pyroxenite component is introduced into the source region of basalts. The efficiency of these processes in conveying the geochemical imprint of crustal-derived garnet pyroxenite to extruded lavas depends on the reactivity of pyroxenite melt with peridotite and the mantle permeability, which may be controlled by prior refertilization reactions similar to those documented in the Ronda massif. Highly fertile heterogeneities produced by pyroxenite–peridotite interaction, such as secondary spinel lherzolite in Ronda, may nucleate magmatic channels that remain chemically isolated from the ambient mantle and act as preferential pathways for melts with the signature of recycled crust.

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1. Introduction

Melting of small scale (~1 km) compositional heterogeneities (pyroxenitic to eclogitic lithologies) in the peridotitic mantle is usually proposed to account for the trace element and/or isotopic variability observed in primitive basalts (e.g., Allegre and Turcotte, 1986; Hauri, 1996; Hirschmann and Stolper, 1996; Hofmann and White, 1982; Meibom and Anderson, 2003; Phipps Morgan and Morgan, 1999). Experimental results for pyroxenite melting indicate that its solidus temperature is 50–200 °C lower than that of peridotite at 1–3 GPa (Hirschmann and Stolper, 1996; Kogiso et al., 2004a; Lambart et al., 2009; Pertermann and Hirschmann, 2003a). Pyroxenite can thus begin to melt ~15–50 km deeper than peridotite and may, therefore, generate considerable melt fractions under conditions where peridotite remains solid (Katz and Rudge, 2011). As a result, the relative contribution of pyroxenite to the composition of mantle-derived melts is ~3–10 greater than its volumetric proportion in the source (Hirschmann and Stolper, 1996; Pertermann and Hirschmann, 2003a; Phipps Morgan, 2001). Thus, pyroxenite
melting may be of great importance in the generation of mantle basalts. However, the significance of a pyroxenitic imprint to the melt budget produced in the mantle and the mechanisms of interaction between pyroxenite melt and surrounding peridotite remain controversial (e.g., Hirschmann and Stolper, 1996; Keshav et al., 2004; Lambart et al., 2009; Niu et al., 2011; Shorttle and Maclennan, 2011; Sobolev et al., 2005, 2007; Stracke et al., 1999).

Sections of orogenetic peridotite massifs are considered natural proxies of the compositionally heterogeneous mantle source of basalts, and their structure laid the foundations for the marble-cake hypothesis for the structure of the upper mantle (e.g., Allègre and Turcotte, 1986; Blichert-Toft et al., 1999; Phipps Morgan, 2001). The Ronda orogenic peridotite massif in southern Spain is the largest (~300 km²) portion of subcontinental lithospheric mantle exposed on the Earth’s surface. One of its most remarkable features is the so-called “recrystallization front” (Van der Wal and Vissers, 1993, 1996), a heterogeneous mantle domain with intercalated pyroxenite that experienced melting and melt–rock reaction at ~1.5 GPa along a transient lithosphere–asthenosphere boundary (Garrido and Bodinier, 1999; Lenoir et al., 2001; Van der Wal and Bodinier, 1996). Melting of pyroxenite at the Ronda recrystallization front therefore represents a valuable analogue for the genesis of magmas in a heterogeneous marble-cake mantle, especially relevant for MORB production which takes place at a mean pressure close to 1.5 GPa (e.g., Künzler and Grove, 1992).

Here we present the geochemistry of a unique snapshot of melting of garnet pyroxenite and reaction of pyroxenite melts with host peridotite at the Ronda recrystallization front, forming residual spinel websterite and hybrid, secondary lherzolite. We obtain new insights into the mechanisms responsible for the presence of geochemical components ascribed to crustal-derived garnet pyroxenite in mantle melts.

2. Geological setting

Several studies elucidate the composition, structure and petrological evolution of the Ronda peridotite massif. A detailed summary of these results is presented in Electronic Appendix and here we focus on the geological characteristics most relevant for this study. The Ronda peridotite massif is located in the westernmost Betic Cordillera (southern Spain), and its western region consists of three petrological, structural and geochemical domains (Fig. 1a) (Garrido and Bodinier, 1999; Garrido et al., 2011; Lenoir et al., 2001; Precigout et al., 2007; Soustelle et al., 2009; Van der Wal and Bodinier, 1996; Van der Wal and Vissers, 1993, 1996): (1) foliated spinel tectonite and garnet-spinel mylonite in the NW; (2) coarse granular peridotite in the central area; and (3) plagioclase tectonite in SE. The first domain originally equilibrated in the diamond–stability field (at depth > 150 km, Davies et al., 1993), accreted to the lithosphere in the Proterozoic (Marchesi et al., 2010; Reisberg and Lorand, 1995), and experienced decompression to ~70 km probably related to back-arc extension (Garrido et al., 2011; Marchesi et al., 2012). Garnet pyroxenites, up to 6 m thick, are intercalated with peridotite in this domain (Dickey, 1970; Garrido and Bodinier, 1999; Morishita et al., 2003; Suen and Frey, 1987), which represents the vestiges of an old heterogeneous subcontinental mantle. The central domain of coarse granular peridotite is separated from the overlying spinel tectonite by a narrow recrystallization front (~200 m wide). Annealing and grain growth are evident across this transition as a result of recrystallization of spinel tectonite to secondary granular peridotite. The formation of the coarse granular peridotite and the recrystallization front has been related to the Late Oligocene–Early Miocene uplift of the asthenosphere in the western Mediterranean region, which induced partial melting of the attenuated lithospheric mantle and km-scale migration of basaltic and volatile-rich melts (Garrido and Bodinier, 1999; Lenoir et al., 2001). Melting and melt–rock reaction in a veined subcontinental mantle, now preserved in the spinel tectonite domain, therefore generated the depleted spinel peridotite and spinel websterite that constitute the granular peridotite domain (Garrido and Bodinier, 1999; Lenoir et al., 2001). The third domain, dominated by plagioclase tectonite, was formed at the expense of coarse granular peridotite by low pressure (< 1 GPa) cooling associated with compression and strain localization in shear zones during the Early Miocene emplacement of the Ronda peridotite into the continental crust (Van der Wal and Vissers, 1996).

Garrido and Bodinier (1999) showed that the modal assemblages, (micro)structures, mineral and whole-rock compositions of pyroxenite layers in Ronda are related to the petrological zoning of the massif. In this study we focus on dark greenish spinel websterites cropping out along the recrystallization front, which are interpreted as the melting products of garnet pyroxenite similar to those that remain preserved within the spinel tectonite domain (Garrido and Bodinier, 1999). Spinel websterite at the recrystallization front forms single or composite layers concordant with the foliation of spinel tectonite although they are generally hosted in non-foliated peridotite (Garrido and Bodinier, 1999). Composite layers show a mineralogical and compositional zoning between Al-rich spinel websterite and Cr-rich pyroxenite, due to the progressive replacement of the former by parental melts of the latter (Garrido and Bodinier, 1999).

3. Sampling and petrography

Detailed mapping of the Ronda peridotite massif shows that residual spinel websterites, after melting of garnet pyroxenite, are very rare in the field and especially crop out along the recrystallization front. This scarcity is likely due to their consumption during the melting and melt–rock reaction processes associated with the development of the recrystallization front (Garrido and Bodinier, 1999). For this study we sampled a rare outcrop of residual spinel websterite at the Ronda recrystallization front (Fig. 1a) which preserves textural evidence of garnet breakdown (see below) and is in contact with predominantly fresh peridotite. Spinel websterite in this locality forms a composite layer with Cr-rich pyroxenite (Fig. 1b). We sampled four Al-rich spinel websterites (4/1, 4/2, 5/1, 5/2) and four host lherzolites (P1, P2, P3, P4) located within 1 m of the websterites (Fig. 1b).

Spinel websterite is mainly made up of 1–4 mm subhedral clinopyroxene and orthopyroxene in variable proportions, minor spinel and rare 1–2 cm deformed orthopyroxene; fine-grained (0.2–1 mm) plagioclase is commonly interstitial between pyroxene and occasionally associated with spinel. In addition, plagioclase forms rounded symplectites with orthopyroxene, clinopyroxene, vermicular spinel±olivine (Fig. S.1, Supplementary Material), which are several millimetres in size and the product of garnet breakdown (Garrido and Bodinier, 1999). Towards the contact with the Cr-rich side of the composite layer (from 4/1 to 5/2), the grain size of spinel websterite increases and the modal abundance of spinel and plagioclase decreases.

Host lherzolite has granular microstructure consisting of undeformed coarse grained (1–5 mm) olivine, orthopyroxene, clinopyroxene and spinel and rare smaller (0.3–0.5 mm) olivine grains. Subhedral orthopyroxene, clinopyroxene, spinel and lobate olivine form abundant clusters 1–2 cm in size (Fig. S.1, Supplementary Material). This microstructure strongly supports
the secondary formation of pyroxenes and spinel, concurrent with olivine dissolution. Indeed, these lherzolites are richer in clinopyroxene and poorer in olivine compared to other peridotites from the Ronda massif and the primitive upper mantle (PUM) (Fig. 2).

4. Analytical techniques

4.1. Mineral chemistry

Major element compositions of minerals were obtained in rock thin sections by EMPA using a CAMECA SX 100 instrument at the CIC of the University of Granada (Spain). Excitation voltage was 15 kV and beam current 15 nA. Counting times were 20–40 s. Several analyses of each mineral were performed to obtain representative average compositions and detect possible grain zoning. EMPA data of minerals are presented in Supplementary Material.

In situ trace element analyses of clinopyroxene were carried out by LA-ICP-MS in host lherzolites and in the spinel websterite 4/1. Analyses were performed at the Géosciences Montpellier laboratory (Montpellier, France) at analytical conditions similar to those of Marchesi et al. (2009) using a ThermoFinnigan ELEMENT XR high resolution (HR) ICP-MS, coupled with a Geolas (Microlas) automated platform housing a 193 nm Compex 102 laser from LambdaPhysik. The reference sample BIR-1G was included as an unknown during the analytical runs and shows good agreement with working values for this international standard (Jochum et al., 2005). LA-ICP-MS data of clinopyroxene are given in Supplementary Material.

4.2. Whole-rock composition

Whole-rock powders were made by crushing and powdering each sample in an agate ring mill. Major elements and V, Cr, Co, Ni, Cu and Zn were analysed by XRF at the Universities of Leeds (United Kingdom) and Granada (Spain) using standard sample preparation and analytical procedures (Davidson and Wilson, 2011; Lázaro et al., 2011). Lithophile trace elements (Sc, Rb, Sr, Zr, Nb, Ba, REE, Hf, Ta, Pb, Th and U) were analysed by a VG-PQ2 Turbo+ ICP-MS at the Géosciences Montpellier laboratory. Sample dissolution was performed following the HF–HClO$_4$ digestion procedure described by Ionov et al. (1992) and the element concentrations were determined by external calibration. The detection limits, precision and accuracy of ICP-MS analyses at the Géosciences Montpellier lab are reported in Garrido et al. (2000). Whole-rock major and lithophile trace element data are presented in Supplementary Material.
5. Results

5.1. Mineral chemistry

5.1.1. Major elements

Minerals from lherzolite which hosts spinel websterite typically have lower Mg# \[\text{Mg}/(\text{Mg} + \text{Fe}^{2+})\] than other peridotites from Ronda (olivine: 85.3–86.2, orthopyroxene: 85.5–86.7 and clinopyroxene: 86.9–90.7) (Fig. 3a, b, and c). As well as lower Cr$_2$O$_3$ in clinopyroxene (0.39–0.57 wt%; Fig. 3c). NiO in olivine is rather variable (0.27–0.40 wt%) at relatively constant Mg# (Fig. 3a). Cr# \[\text{Cr}/(\text{Cr}^3+\text{Al})\] and Mg# of spinel vary between 0.06–0.08 and 70.9–73.3 respectively, and plot outside the general trend observed in the Ronda peridotite (Fig. 3d).

In spinel websterite, the Mg# of orthopyroxene increases from 4/1 to 5/2 and is inversely correlated with TiO$_2$ (Fig. 3b). Similarly, Cr$_2$O$_3$ in clinopyroxene and the Cr# of spinel increase from samples 4/1–5/1 to 5/2 (Fig. 3c and d). Olivine in spinel websterite has Mg# = 82.3–82.8 and NiO = 0.17–0.23 wt% (Fig. 3a), and the anorthite content of plagioclase varies between 73 and 82 wt%.

5.1.2. Trace elements in clinopyroxene

Primitive mantle-normalized trace element patterns of clinopyroxene in lherzolite are mostly homogeneous and show LREE depletion (La/Sm$_N$ = 0.3), positive Eu and Sr anomalies (Eu$/^{*}$ = 1.3–1.4, Eu$_{N}/^{*}$ = $\text{Sm}_{N} + \text{Gd}_{N}/2$; Sr$_{N}/^{*}$ = 2.4–2.8, Sr$_{N} = (\text{Pr}_{N} + \text{Nd}_{N})/2$) and unfractionated HREE segments (Sm$_{N}/\text{Yb}_{N}$ = 1.1–1.2) (Fig. 4a). Clinopyroxene in spinel websterite similarly presents a positive Eu anomaly (Eu$_{N}/^{*}$ = 1.4) but is more depleted in U and Pb and more fractionated in HREE (Sm$_{N}/\text{Yb}_{N}$ = 1.8–5.8) than clinopyroxene in lherzolite. In addition, clinopyroxene in spinel websterite shows variable MRREE/HREE and both positive and negative spikes of Sr (Fig. 4b) which indicate compositional disequilibrium at the thin section scale. Concentrations of HREE are correlated with those of other trace elements: in particular, grains which are most depleted in HREE are also most depleted in Zr and Y, most enriched in Sr and show slight positive spikes in Ti. These patterns are similar to those of clinopyroxene in Ronda garnet pyroxenites with the inferred imprint of primary plagioclase (Morishita et al., 2003, 2009), but the latter have lower REE concentrations (Fig. 4b).

5.2. Whole-rock composition

5.2.1. Major and transition elements

Host lherzolite has extremely fertile whole-rock compositions in terms of major and transition elements, with higher Al$_2$O$_3$ and TiO$_2$.
CaO and lower MgO and Ni than other mantle peridotites from the Ronda massif and the PUM (Fig. 5). These lherzolites also present clearly higher Cr contents than other Ronda peridotites and the PUM (Fig. 5c).

Spinel websterite has decreasing Al$_2$O$_3$ and increasing CaO from 4/1 to 5/2 (Fig. 5a and b). In terms of major and transition elements, these rocks are similar to other residual spinel websterites along the recrystallization front and fill the compositional gap between garnet pyroxenite and peridotite from the Ronda massif (Fig. 5).

5.2.2. Lithophile trace elements

Except for the lack of Pb depletion, the primitive mantle-normalized trace element patterns of clinopyroxene follow those of its clinopyroxene, including the positive Eu and Sr anomalies (Fig. 5a). In spite of the exceptionally fertile modal and major element compositions of these peridotites (Figs. 2 and 5), their whole-rock trace element concentrations overlap those of other lherzolites from the Ronda massif and are mostly lower than in the PUM (Fig. 5a). We remark that the coupled positive whole-rock Eu and Sr anomalies of these lherzolites are distinctive within the Ronda suite.

Spinel websterite presents LREE-depleted whole-rock patterns (La/Sm$_n$ = 0.3–0.5) with variable positive Eu anomalies (Eu$n$/Eu$^*$ = 1.1–1.5) and MREE/HREE fractionation (Sm$_n$/Yb$_n$ = 1.1–1.8), and positive and negative Sr spikes (Fig. 5b). Decoupling of Sr and Eu is most probably controlled by variable modal abundances of clinopyroxene with different trace element compositions (Fig. 4b). As with clinopyroxene, these whole-rock patterns are similar to those of Ronda garnet pyroxenites from a plagioclase-rich crustal protolith (Morishita et al., 2003) (Fig. 4b).

6. Discussion

6.1. Origin of spinel websterite by melting of crustal-derived garnet pyroxenite

Based on the presence of symplectites after garnet breakdown (Fig. 5a), and structural and petrological observations, Garrido and Bodinier (1999) concluded that spinel websterite along the Ronda recrystallization front (their group B) originated by partial melting of garnet pyroxenite and reaction with peridotite-derived...
The whole-rock trace element compositions of Ronda garnet pyroxenites (Fig. 8) can be divided into two groups: (1) those with positive Eu and Sr anomalies in whole-rocks and garnet pyroxenite with the imprint of primary plagioclase (b) are from Frey et al. (1985), Garrido et al. (2000), Morishita et al. (2003) and the same sources as Figs. 3 and 5.

The clinopyroxene and whole-rock compositions of spinel websterite record the geochemical evidence of these processes and better constrain the composition of the reacting protolith. In the pseudoternary system forsterite (Fo)–CaTs–quartz diagram projected from diopside (Di), using the method of O’Hara (1968), An—anorthite; En—enstatite. Symbols as in Figs. 1 and 5.

At pressures <2 GPa the subsolidus assemblage of moderately silica-oversaturated and forsterite-enstatite poor mafic rocks consists of clinopyroxene ± garnet ± plagioclase ± orthopyroxene (Kogiso et al., 2004a). Pyroxenite with these compositions is expected to significantly melt above 1200 °C at 1.5 GPa and has a lower solidus and higher melt productivity than more silica-rich pyroxenite (Lambart et al., 2009), confirming that garnet pyroxenite in the Ronda massif underwent important melting.

The whole-rock trace element compositions of Ronda garnet pyroxenites (Fig. 8) can be divided into two groups: (1) those with negative or absent Eu anomalies and higher HREE (e.g., Yb), coupled with generally higher MREE (Gd = 1.6–4.1 ppm) and Zr (10–42 ppm), and lower LREE/HREE (La/YbN = 0.01–0.23) and Sr (5–110 ppm); and (2) those with positive Eu anomalies and lower HREE, as well as generally lower MREE (Gd = 0.1–1.1 ppm) and Zr (0.6–13 ppm), and higher LREE/HREE (La/YbN = 0.10–0.83) and Sr (69–244 ppm). These different compositions support different primary mineral assemblages and in particular a higher modal abundance of primary plagioclase in the second group (Garrido and Bodinier, 1999; Morishita et al., 2003). This conclusion has also been inferred for similar pyroxenites in the Beni Bousera peridotite massif (Gysi et al., 2011; Kornprobst et al., 1990; Pearson et al., 1993) and Northern Apennine ophiolites (Montanini et al., 2012).

Clinopyroxene in garnet pyroxenite with a strong plagioclase imprint is relatively depleted in Zr, HREE and Y (Fig. 4b), owing to equilibration with garnet under granulite facies conditions (T > 900 °C, P > 1.5 GPa) (Morishita et al., 2003). On the other hand, the positive Eu and Sr anomalies in whole-rocks and clinopyroxenes from these pyroxenites have been interpreted as primary signatures indicating a low-pressure crustal origin for these rocks (Morishita et al., 2003, 2009), similar to high-pressure eclogite derived from oceanic gabbro (Yaxley and Sobolev, 2007).
These same compositional features are shown by spinel websterite at the Ronda recrystallization front (Figs. 4b, 6b and 8), thus supporting that its protolith consisted of crustal-derived garnet pyroxenite with a strong plagioclase imprint. The melting reaction of garnet pyroxenite to spinel websterite probably occurred at low melt/rock ratios, as suggested by the compositional disequilibrium preserved at the thin section scale (Fig. 4b), which points to limited diffusive exchange of trace elements between minerals and melt (Agrarian and Lee, 2007). Progressive Sr and Pb depletion in clinopyroxene (Fig. 4b) was possibly caused by crystallization of secondary plagioclase. Whole-rock major and transition elements are consistent with this melting model, as Ca, Al and Ti are generally lower (Fig. 5a and b) and Mg, Cr, Ni (Fig. 5a and c) and Ce/Sm (Garrido and Bodinier, 1999) are higher in spinel websterite compared to garnet pyroxenite. This is in agreement with an open system melting reaction consuming garnet and clinopyroxene and crystallizing orthopyroxene and spinel ± olivine (Garrido and Bodinier, 1999).

6.2. Formation of secondary lherzolite by melt refertilization

Several textural and compositional features indicate that lherzolite hosting spinel websterite was generated by melt refertilization. Host lherzolite has undeformed clusters of pyroxenes and spinel overprinting deformed olivine (Fig. S.1) which are clearly secondary in origin (see also Lenoir et al. (2001)). The modal abundance of clinopyroxene and the whole-rock contents of CaO and Al₂O₃ are higher in these lherzolites than in the PUM and in common peridotite from the Ronda massif (Figs. 2 and 5a, b). Furthermore, host lherzolite has a high Cr content (Fig. 5c), which is a compatible element during partial melting of mantle peridotite at common conditions of oxygen fugacity (Liu and O'Neill, 2004); if governed by the degree of melt extraction, chromium is thus expected to be abundant in depleted (Al-poor) harzburgite and not in highly fertile (Al-rich) lherzolite. Peridotite hosting spinel websterite thus resembles refertilized rocks from Lherz that also have high coupled Cr–Al abundances related to crystallization of secondary pyroxene+spinel clusters from Cr-rich (peridotite-derived) melts (Le Roux et al., 2007). Finally, mineral (Fig. 3) and whole-rock (Figs. 5, 7 and 8) compositions of lherzolites are intermediate between those of other Ronda peridotites and the spinel websterites 4a/4b, 4c/4d, supporting their generation by refertilization of depleted peridotite by melts derived from garnet pyroxenite. Lherzolite hosting spinel websterite thus represents fertile (Clinopyroxene-rich) (Figs. 2 and 7) mantle domains with a pyroxenite–peridotite hybrid affinity, whose mineral and whole-rock compositions support they were refertilized by melts with both peridotite and garnet pyroxenite components.

Relatively low contents of highly incompatible elements (Ba–Th–U–LREE) in host lherzolite (Fig. 6a) argue against refertilization (Fig. 6a) argue against refertilization by entrainment and in situ crystallization of melts (Rampone et al., 1997), as these processes normally induce strong enrichment in incompatible elements (Bedini et al., 1997). Refertilization may have occurred by peritectic melt-consuming reactions (Kellemen et al., 1992) or percolative fractional crystallization (Hart et al., 1993).

6.3. Transfer of the geochemical signature of crustal-derived garnet pyroxenite to secondary lherzolite

Melts of silica-excess garnet pyroxenite have Si-rich compositions at pressures > 2 GPa (Kogiso et al., 2004a) and their reaction with peridotite forms orthopyroxene wall rock (Yaxley and Green, 1998). However, at 1.5 GPa the enstatite–Ca-tschermak join in the pseudoternary Ca-tschermak–forsterite–quartz–diagram (Fig. 7) does not constitute a thermal divide (Kogiso et al., 2004a) and melts of garnet pyroxenite oversaturated in silica can evolve towards the forsterite apex. Hence, partial melts of silica-excess pyroxenite at this pressure are not particularly rich in silica (Kogiso et al., 2004a), and can generate clinopyroxene-rich lherzolites as intermediate products of interaction with peridotite (Bodinier et al., 2008; Lambart et al., 2012).

Crysoal-derived garnet pyroxenite in the Ronda massif displays positive Eu and Sr anomalies (Figs. 6b and 8) which are the geochemical imprint of primary plagioclase transferred to clinopyroxene (Fig. 4b) by high-pressure metamorphism (Morishita et al., 2003, 2009; Yaxley and Sobolev, 2007). Positive Eu and Sr anomalies in plagioclase-free host lherzolites (Fig. 4a, 6a and 8)—a so-called “ghost plagioclase” signature, similar to melt inclusions in Hawaiian basalts (Sobolev et al., 2000)—strongly support refertilization by a melt which preserved the signature of an original plagioclase-rich source. This source was most likely the Ronda garnet pyroxenite derived from recycled crustal gabbro. Additional evidence for the presence of garnet pyroxenite in the source of the refertilizing melts comes from the Sm/Yb ratio in host lherzolite. Indeed this ratio, which is elevated in melts where garnet is residual (Hirschmann and Stolper, 1996), ranges from 0.92 to 0.99 in host lherzolite, which is at least as high as in the PUM (0.92–0.93, McDonough and Sun, 1995; Palme and O'Neill, 2003) and notably higher than more depleted mantle reservoirs such as the depleted MORB mantle (DMM, Sm/Yb = 0.65–0.67; Salters and Stracke, 2004; Workman and Hart, 2005).

In terms of major elements, melts derived from pyroxenite layers intercalated in the mantle can be indistinguishable or significantly different from peridotite melts depending on the source compositions, P–T conditions and degrees of partial melting (e.g., Hirschmann et al., 2003; Keshav et al., 2004; Kogiso and Hirschmann, 2001, 2006; Kogiso et al., 2003, 2004a; Lambart et al., 2009; Pertermann and Hirschmann, 2003a). In particular, SiO₂ and FeO concentrations in pyroxenite-derived melts significantly depend on the normative composition of the source (Hirschmann et al., 2003; Kogiso et al., 2004a; Lambart et al., 2009). The SiO₂–FeO variations obtained in melting experiments of peridotite and pyroxenite with different whole-rock compositions and at different pressures are compared in Fig. 9. Melts...
derived from peridotites and pyroxenites largely overlap, but pyroxenite melts at 1–2 GPa can be characterized by fairly low SiO$_2$ and high FeO abundances (Fig. 9). Only a few peridotite melting experiments at high pressure (3–7 GPa) reproduce similar compositions, but these melts are expected to re-equilibrate and evolve by fractional crystallization of dominant olivine, thus increasing their silica content during the ascent (Kogiso et al., 2003). Rather low SiO$_2$ and high FeO contents at relatively low pressure thus probably constitute distinctive features of melts with an important pyroxenitic component.

In spite of remarkably lower modal abundances of olivine (Fig. 2), host lherzolite has similar SiO$_2$ coupled to higher FeO contents than other peridotites in the Ronda massif, including peridotite cropping out ~10 m away from the pyroxenite layer (sample RPD 07-7B) (Fig. 9). These compositions corroborate a significant contribution of garnet pyroxenite to the melt that refertilized these rocks. However, precipitation of secondary orthopyroxene and dissolution of olivine (Fig. S.1) argue against extremely low silica contents in the refertilizing melt.

6.4. Implications for the presence of a garnet pyroxenite component in mantle melts

Reaction between pyroxenite-derived melts and peridotite creates hybridized olivine-rich lithologies that may preserve the major, trace element and isotopic signatures of garnet pyroxenite (Kogiso and Hirschmann, 2006; Yaxley and Green, 1998; Yaxley, 2000). These fertile peridotite–pyroxenite mixtures have lower solidus temperature and higher melt productivity than normal peridotite (Kogiso et al., 1998; Yaxley, 2000) and may produce melt compositions similar to MORB, OIB, island arc and continental basalts that show the important geochemical imprint of garnet pyroxenite (e.g., Kogiso et al., 1998, 2003, 2004a; le Roux et al., 2002; Schiano et al., 2000; Shorttle and Maclennan, 2011; Sobolev et al., 2005, 2007; Takahashi et al., 1998).

The pressure of garnet pyroxenite melting in the Ronda massif (~1.5 GPa) is within the relevant range for the genesis of present-day basalts, especially MORB (Kinzler and Grove, 1992), in the upwellling mantle. Melts produced preferentially from garnet pyroxenite during adiabatic ascent beneath a mid-ocean ridge will interact with surrounding peridotite, and melting of the highly fertile lithologies hence generated may explain the presence of garnet in the source of MORB without requiring anomalously thick oceanic crust (Hirschmann and Stolper, 1996). Moreover, the transfer of the geochemical signature of plagioclase-rich crustal gabbros to mantle peridotite (Figs. 4a, 6a and 8) by their transformation into high-pressure garnet pyroxenite, pyroxenite melting and peridotite refertilization by this melt may be appropriate mechanisms to recycle oceanic crust into the source region of oceanic island basalts (Sobolev et al., 2000). Melting of garnet pyroxenite and peridotite refertilization by pyroxenite melts in the Ronda massif are thus equivalents to processes conceived for the mantle below mid-ocean ridges, ocean islands, continents and subduction zones. Indeed, the presence of garnet-rich pyroxenitic lithologies in the sources of OIB and MORB is inferred by low SiO$_2$–high FeO compositions and higher Sm/Yb compared to values predicted by melting models of spinel peridotite (Hirschmann and Stolper, 1996; Kogiso et al., 2003; Lambart et al., 2009; Pertermann and Hirschmann, 2003a; Sobolev et al., 2005). Peridotite similar to the lherzolite hosting spinel websterite of the Ronda massif may thus constitute suitable sources for these magmas if refertilization reactions akin to those described in this study occur widely in the mantle.

Crystallization of secondary pyroxenes and spinel in lherzolite indicates that the refertilizing melt in Ronda was significantly reactive with peridotite adjacent to spinel websterite. The presence of an important melt component likely derived from silica-oversaturated pyroxenite (Fig. 7) probably enhanced the disequilibrium of migrating melt with peridotite according to experimental predictions (Pertermann and Hirschmann, 2003a; Yaxley and Green, 1998; Yaxley, 2000). Significant melt reactivity argues against the possibility of transferring the signature of silica-oversaturated garnet pyroxenite over great distances. However, crystallization of reactive melt would reduce the peridotite permeability thus hindering further infiltration and enhancing the retention of the pyroxenitic signature at melt/rock ratios sufficiently high for segregation in melt-rich lenses and subsequent expulsion into veins or channels (Kogiso et al., 2004b). Peridotite refertilization by garnet pyroxenite melt, as documented in lherzolite hosting spinel websterite in the Ronda massif, may thus inhibit extensive re-equilibration of pyroxenite melts with enclosing peridotite, and promote transfer of their geochemical signature to extruded lavas.

Moreover, melting of fertile heterogeneities in the mantle may create a halo of reduced temperature around them, suppressing partial melting and favouring melt–rock reaction in surrounding peridotite (Katz and Weatherley, 2012). Such a process may explain the formation of secondary lherzolite around the residues of garnet pyroxenite melting at the Ronda recrystallization front. These secondary lherzolites preserve the geochemical imprint of crustal-derived garnet pyroxenite and may preferentially melt and nucleate magmatic channels in the mantle (Katz and Weatherley, 2012), thus favouring the preservation of a garnet pyroxenite signature by focused melt transport up to the surface.

7. Conclusions

Spinel websterite in the Ronda peridotite massif was generated at ~1.5 GPa by open system melting of garnet pyroxenite derived from a plagioclase-rich crustal precursor. This process occurred at relatively low melt/rock ratios thus preserving, in the melting residues, the positive Eu anomaly of their garnet pyroxenite protolith and variable MREE/HREE fractionation at the thin section scale.

Enclosing peridotite was strongly refertilized by melts with both garnet pyroxenite and peridotite components, leading to crystallization of pyroxenes and spinel and enrichment in Al, Ca and Cr. The presence of a garnet pyroxenite melt component derived from recycled plagioclase-rich crust (i.e., cumulitic gabbro) imparted positive Eu and Sr anomalies to the whole-rock and clinopyroxene without clearly increasing the concentrations of other trace elements in secondary host lherzolite. In addition, the presence of garnet pyroxenite in the source of the reacting melt caused higher Sm/Yb and FeO$^+$ at a given SiO$_2$ in host lherzolite compared to other peridotites from the Ronda massif.

Highly fertile mantle peridotite that has acquired the geochemical imprint of crustal-derived garnet pyroxenite, similar to the lherzolite hosting spinel websterite in the Ronda massif, may transfer this geochemical imprint to melts produced in different tectonic settings. In particular, these processes may explain the presence of garnet in the source region of MORB and the signature of recycled plagioclase-rich crustal gabbros in oceanic basalts. The reactivity of pyroxenite melt with surrounding peridotite will limit the transfer of its geochemical imprint to melts produced in porous flow through the mantle, but at reduced peridotite permeability, for instance following prior refertilization, the retention of a pyroxenite signature would be favoured by focused melt transport into veins or channels. Moreover, hybrid pyroxenite–peridotite fertile lithologies with the geochemical imprint of garnet pyroxenite may preferentially melt upon decompression and concentrate the
melt flux into channels, thus imparting the geochemical signature of garnet pyroxenite to extruded lavas.

Further isotopic studies of pyroxenite–peridotite composite layers at the Ronda recrystallization front are necessary to infer how melting of garnet pyroxenite and related refertilization of host peridotite are recorded by these geochemical tracers.

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Appendix A. Supporting information

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References


