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Fractionation of highly siderophile elements in refertilized mantle: Implications for the Os isotope composition of basalts

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ABSTRACT

Highly fertile lherzolite and spinel websterite in the Ronda peridotite massif are enriched in Pt and Pd compared to Os, Ir, Ru and Re. The fractionation of the highly siderophile elements (HSE) in these rocks was produced by reaction of melt with their peridotite and pyroxenite precursors. Modeling indicates that upon reaction primary HSE hosts were dissolved and magmatic sulphides precipitated, largely erasing the original HSE signature of reacting protoliths. The budget of HSE in the melt was controlled by sulphide–silicate partitioning or entrainment of molten sulphide in silicate melt. Rhenium was likely removed from precursor peridotite and pyroxenite by previous melt extraction. Refertilization of peridotite by melts increased Al_2O_3, CaO, Pt, Pd contents and $^{187}Os/^{188}Os$ beyond typical values for mantle peridotite and the primitive upper mantle. The interaction of melts with residual peridotite and pyroxenite, as illustrated in the Ronda massif, can generate radiogenic-Os-enriched domains in the mantle with high melt productivity, higher Pt/Os and Pt/Re than common peridotite, and lower Re/Os than typical pyroxenite. As also previously proposed for pyroxenites, these "hybrid" domains can account for the difference in Os isotope compositions between many basalts (e.g., MORB and OIB) and common depleted mantle peridotites. Moreover, the presence of these enriched hybrid components in the mantle, evolved over sufficient timescales and in geologically reasonable proportions, may account for the ^{186}Os–^{187}Os enrichment of plume lavas without requiring a chemical contribution from the core.

1. Introduction

The compositional variability of primitive basalts partly reflects the geochemical heterogeneity of their mantle source (e.g., Hart, 1971; Sobolev et al., 2005; Zindler et al., 1984). This heterogeneity is exemplified by pyroxenite layers intercalated with peridotite in orogenic ultramafic massifs (e.g., Allègre and Turcotte, 1986; Pearson et al., 1993). Interaction between melts and peridotite further enhances the compositional heterogeneity of the mantle, generating a broad spectrum of lithologies at different P-T conditions (Kogiso and Hirschmann, 2006; Lambart et al., 2012; Yaxley and Green, 1998). Melts produced from pyroxenites and hybrid peridotite–pyroxenite domains may constitute a significant fraction of mantle-derived magmas as these lithologies are more fertile than typical peridotite, with lower solidus temperatures and higher melt productivity (Hirschmann and Stolper, 1996; Kogiso et al., 2004; Yaxley, 2000). Moreover, fertile heterogeneities in the mantle nucleate magmatic channels that focus melts up to the surface and hinder their re-equilibration with ambient peridotite (Katz and Weatherley, 2012). Therefore, melts of pyroxenite and peridotite reacted with pyroxenite may critically influence the composition of mantle-derived basalts.

The geochemical behaviour of both the parent and daughter elements in the ^{187}Re–^{187}Os and ^{190}Pt–^{186}Os systems is governed by their siderophile and chalcophile affinity, and fractionation of these elements during mantle melting and melt–rock reaction is induced mainly by sulphide–silicate and crystalline sulphide–

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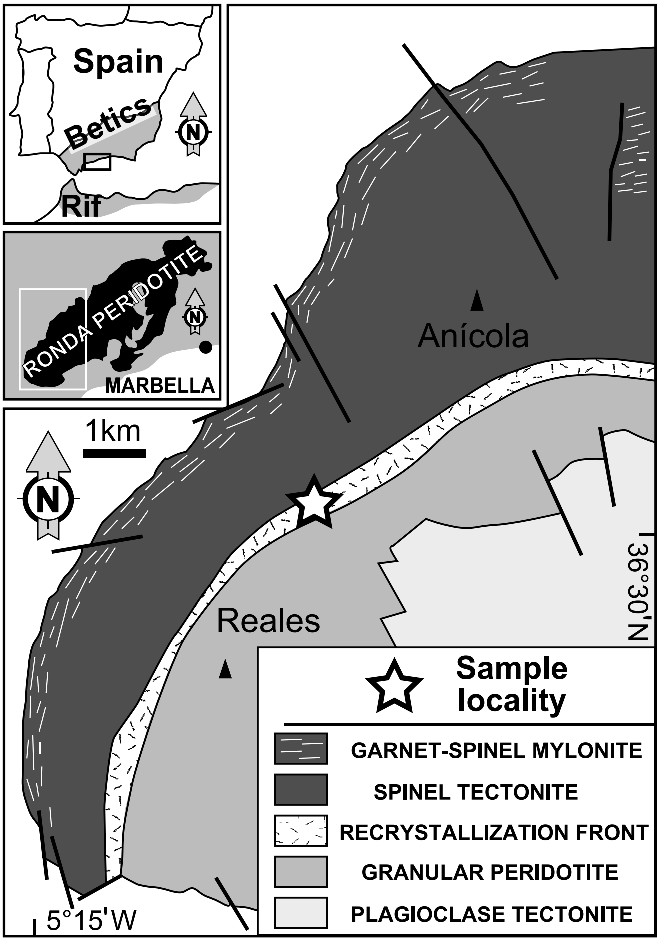

Fig. 1. Geological sketch map of the western Ronda peridotite massif (southern Spain) (see upper left insets for geographic location) with the location of the studied samples (star). Modified from Lenoir et al. (2001).

sulphide melt partitioning (e.g., Bockrath et al., 2004; Brenan, 2008; Fonseca et al., 2007; Mungall et al., 2005). The uniquely large difference in bulk compatibility during mantle melting of the parent elements, Re and Pt (mildly incompatible), compared to the daughter, Os (compatible) (e.g., Brenan, 2008; Fleet et al., 1996; Mallmann and O'Neill, 2007), creates greatly contrasting Os isotope compositions through time between residual peridotite and lithologies crystallized from or reacted with melt. Hence, Os isotopes provide key constraints on magmatic processes in the mantle and allow identification of contributions from melt-enriched domains in the genesis of basalts (e.g., review in Day, 2013; Hauri and Hart, 1993; Reisberg et al., 1993).

Here we present Os isotope compositions and whole-rock abundances of highly siderophile elements (HSE: Os, Ir, Ru, Pt, Pd, Re) in spinel websterites and their host lherzolite from the Ronda peridotite massif (southern Spain). The western Ronda massif is mainly composed of spinel peridotite tectonite and $\sim$5 vol.% garnet pyroxenite in the NW, whereas the SE of the massif contains their melting and melt–rock reaction products, i.e. granular peridotite and spinel websterite (Fig. 1) (Garrido and Bodinier, 1999; Lenoir et al., 2001). This heterogeneous mantle section properly represents the lithological variability expected in the convecting mantle (Allègre and Turcotte, 1986; Lambart et al., 2012). We show that melting and melt–rock reaction of a pyroxenite–peridotite sequence produced fractionated Pt–Re–Os and radiogenic Os compositions in spinel websterite and refertilized peridotite. Over time, melting of different proportions of these fertile lithologies in the ascending mantle can produce a range of radiogenic Os enrichment, as seen in mid-ocean ridge (MOR) and ocean island basalts (OIB), and also provides an alternative mechanism to core–mantle exchange for the generation of ^{186}Os–187Os-rich plume lavas.

2. Geological background

The Ronda peridotite massif (Betic Cordillera, southern Spain) is a large $\sim$300 km^2 section of upper mantle mainly composed of lherzolite and harzburgite with minor dunite and pyroxenite, locally forming layers ranging in thickness from $<$1 to 100 m (e.g., Garrido and Bodinier, 1999; Lenoir et al., 2001). The western part of the massif is petrologically zoned (Fig. 1) owing to the presence of a "recrystallization front" (Van der Wal and Vissers, 1993). This front represents the frozen boundary between Proterozoic subcontinental lithospheric mantle (the spinel tectonite and garnet-spinel mylonite domain) (Reisberg and Lorand, 1995) and its partial melting – melt percolation products (the granular peridotite domain) generated by Late Oligocene asthenospheric upwelling in the western Mediterranean region (Lenoir et al., 2001). Sulphides in peridotite from across the massif have similar Os isotope compositions that preserve the signature of Proterozoic lithosphere, suggesting that the Re–Os radiometric system was resistant to resetting during lithospheric thermal erosion (Marchesi et al., 2010). The latter tectonic event caused heating of thinned lithospheric mantle at $\sim$1.5 GPa and $\geq$1200 °C and melting of Ronda garnet pyroxenite and peridotite, producing spinel websterite and refertilized lherzolite by the reaction of melts with depleted residues (Bodinier et al., 2008; Garrido and Bodinier, 1999; Lenoir et al., 2001; Marchesi et al., 2013). Spinel websterite at the recrystallization front is concordant with the garnet pyroxenite now preserved in the upper spinel tectonite domain (Garrido and Bodinier, 1999). Moreover, spinel websterites have high Eu and Sr contents in both whole-rocks and clinopyroxene, similar to garnet pyroxenites (Garrido and Bodinier, 1999; Marchesi et al., 2013). These structural and compositional features, along with the presence of pseudomorphic clusters of orthopyroxene, clinopyroxene, plagioclase and spinel from precursor garnet, indicate that spinel websterite was formed by the reaction of infiltrating melt with garnet pyroxenite derived from plagioclase-rich crustal gabbros (Garrido and Bodinier, 1999; Marchesi et al., 2013). Peridotite at the recrystallization front is more fertile than in the other petrological domains at Ronda, supporting the assertion that it reacted with melts infiltrated from lower granular peridotite (Lenoir et al., 2001).

3. Sampling and petrography

Spinel websterites that represent the melt–rock reaction products of former garnet pyroxenites rarely crop out in the Ronda massif, owing to their consumption during melting and melt–rock reaction processes associated with the recrystallization front (Garrido and Bodinier, 1999). These rocks and, especially, the enclosing peridotite are a valuable record of melt interaction with a heterogeneous mantle (Garrido and Bodinier, 1999; Marchesi et al., 2013). Here, to investigate these processes, we sampled two spinel websterites from the Ronda recrystallization front (4/1–4/2, Fig. 1) which have field relations, microstructure and lithophile element compositions representative of spinel websterite after garnet pyroxenite across the Ronda massif (Garrido and Bodinier, 1999; Marchesi et al., 2013). In particular, these samples retain textural evidence of garnet breakdown (see below) and are in contact with predominantly fresh peridotite. Sampling also focused on the adjacent reacted host lherzolites (P1–P2–P3–P4) located within one metre of the websterites. Whole-rock HSE concentrations and ^{187}Os/^{188}Os isotope ratios are presented for both lithologies (Table 1).