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Rhenium–osmium isotopes in pervasively metasomatized mantle xenoliths from the Bohemian Massif and implications for the reliability of Os model ages

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A B S T R A C T

Peridotite xenoliths brought to the surface by basaltic lavas attest to a variety of mantle processes, including partial melting, melt percolation or refertilization. The whole rock Re–Os concentrations and Os isotopic compositions were determined for 30 xenoliths collected from 11 localities across the northern Bohemian Massif in order to evaluate the Os model ages and attempt to relate the results to major crustal tectonic events during the history. Most samples were affected by variable extent of metasomatic overprint, which is commonly paralleled by very low Os concentrations (<1 ppb). Rhenium concentrations in the whole suite are below the primitive mantle value. A subset of samples shows evidence for Re addition from host basaltic rocks, consistent with the presence of abundant melt pockets with secondary sulphides. The $^{187}Os/^{188}Os$ ratios range from 0.1162 to 0.1330 and cannot be directly related to individual mantle domains, implying the inability of more recent tectonic events to reset the original Os isotopic systematics. The calculated mantle extraction ages (T_{MA}) range from <0.1 to 2.1 Ga, whereas future ages obtained for nine samples indicate metasomatic overprints. The Re depletion ages (T_{RD}) vary between <0.1 and ~1.6 Ga. However, the T_{RD} is not well suited for direct comparison with crustal ages because it represents a minimum age limit rather than specific age estimate. Therefore, a modified model age (T_{RDII}) was calculated assuming a non-zero Re content during the pre-metasomatic stage and using a composition of the most depleted sample in our suite. A prominent peak in the calculated T_{RDII} ages ranges between 0.5 and 0.6 Ga which corresponds to the Cadomian orogenic cycle.

1. Introduction

Highly siderophile elements (HSE: Os, Ir, Ru, Rh, Pt, Pd, Re and Au) are useful geochemical tracers of processes in the Earth's upper mantle such as partial melting, melt percolation or metasomatism (e.g., Aulbach et al., 2013; Barnes et al., 1985; Lorand et al., 2004, 1999, 2013; Luguet and Reisberg, 2016, and references therein; Morgan, 1986; Pearson et al., 1995). Unlike lithophile elements, the HSE budget is largely controlled by Cu–Fe–Ni sulphides and HSE-bearing alloys (e.g., Luguet et al., 2001; Lorand et al., 2013, 2008). During mantle melting, Os is generally highly compatible whereas Re is mildly incompatible (Shirey and Walker, 1998). This leads to subchondritic Re/Os ratios in the residual mantle; as a consequence, the Re–Os isotopic system ($^{187}Re \rightarrow {}^{187}Os$, $t_{1/2} = 41.6 \times 10^9$ y; Smoliar et al., 1996) can be used as a useful tool for age determination of melt extraction events leading to formation of the sub-continental lithospheric mantle (SCLM) and its connection to the overlying continental crust (Carlson, 2005; González-Jiménez et al., 2013; Lee and Walker, 2006; Peslier et al., 2000; Walker et al., 1989). This is due to the generally more robust nature of the Re–Os system against the effects of metasomatism in comparison to lithophile element isotopes, because Os abundances and $^{187}Os/^{188}Os$ ratios are typically much less affected than Re during young melt percolation events (Carlson and Irving, 1994; Pearson et al., 1995; Walker et al., 1989). The temporal relationship of the Re–Os isotopic system in a hypothetical mantle reservoir is approximated by T_{RD} and T_{MA} model ages. The T_{MA} age shows the time of a sample separation from the mantle with the assumption of its closed system behaviour (e.g., Shirey and Walker, 1998). The T_{RD} model age represents the minimum age for a Re depletion event, as it assumes a two-stage

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evolution of the sample Re budget including total Re removal by partial melting and its possible later influx from host lava.

Several studies dealing with mantle xenoliths from European Volcanic Province have provided the evidence for heterogeneous nature of the SCLM. These include well characterized peridotite xenoliths from the Massif Central (Harvey et al., 2010; Lorand and Alard, 2001) and Montferrier (Alard et al., 2011) in France, Eifel (Fischer-Gödde et al., 2011; Meisel et al., 2001; Schmidt and Snow, 2002; Schmidt et al., 2003), and Vogelsberg (Schmidt and Snow, 2002) in Germany, Calatrava in Spain (González-Jiménez et al., 2013; González-Jiménez and Villaseca, 2014) or Kozákov in the Czech Republic (Ackerman et al., 2009). The effects of melt–rock percolation–reaction processes and the implications for asthenospheric and lithospheric mantle have been extensively studied for peridotite occurrences across Europe. The presence of sulphides and their role in distribution of Os and other HSE, as well as possible age perturbations are key factors in deconvolving the true temporal information (e.g., Harvey et al., 2010; Lorand et al., 2008; Lorand et al., 2003a, 2003b; Lorand, 1989). Marchesi et al. (2010) implied that sulphides extracted from the massif peridotites of the Ronda massif may record ancient magmatic events in SCLM. These authors also provided evidence for the uptake of secondary Re at reaction front of the peridotite body, invoking a susceptibility of some model ages to disturbance.

The Bohemian Massif represents a well-suited territory for the study of age relationships between SCLM and overlying crustal units (Babuška and Plomerová, 2010, 2013; Schulmann et al., 2014) as there are numerous occurrences of Cenozoic volcanic rocks in the Bohemian Massif which brought mantle xenoliths to the surface. Some of these xenoliths were previously extensively studied in terms of petrography, mineral chemistry, whole-rock/mineral trace element geochemistry and Sr–Nd–Li isotopes (Ackerman et al., 2015, 2013b, 2009, 2007; Matusiak-Małek et al., 2014, 2010; Medaris et al., 2015a; Puziewicz et al., 2011; Špaček et al., 2013). All these studies documented unequivocally that much of the SCLM beneath the Bohemian Massif was moderately depleted through partial melting and substantially modified through metasomatic processes by melts with basaltic to alkaline–carbonate-rich affinities. However, the structure of lithospheric mantle beneath Central Europe remains rather enigmatic with suggested complex development (e.g., Christensen et al., 2001; Medaris et al., 2015a, 2005; Puziewicz et al., 2015). The Re–Os isotopic data for mantle xenoliths from the Bohemian Massif are largely missing with the exception of the dataset from the single locality Kozákov (Ackerman et al., 2009) and preliminary data from NE Bavaria (Ackerman et al., 2013a). In this study, the Re–Os elemental and isotope systematics together with major element compositions of selected minerals and whole rock trace element compositions are presented for a carefully selected suite of mantle xenoliths, collected from 11 localities in the Bohemian Massif, in order to (i) collect regionally representative dataset for characterization of the Re–Os fingerprint of SCLM beneath the Bohemian Massif, (ii) characterize possible Re–Os fingerprint of SCLM beneath Central Europe, (iii) evaluate the validity of T_{MA} and T_{RD} ages for regional studies, and (iv) compare the T_{MA} and T_{RD} ages with major crust-forming events and determine the reflection of these processes in the lithospheric mantle.

2. Geological setting

The lithosphere of present-day Central Europe, including its upper mantle section, developed in a series of tectonic cycles which culminated with Devonian–Carboniferous Variscan orogeny, a successive accretion of several microplates and relics of magmatic arcs during the collision of Laurussia and Gondwana supercontinents (see McCann, 2008; Cháb et al., 2010, for a recent review). The Bohemian Massif (Fig. 1) represents the most prominent exposure of the Variscan basement in Central Europe (e.g., Dallmeyer et al., 1995; Žák et al., 2014). Its formation started with a Late Silurian to Devonian (~430–350 Ma) Andean type south-east verging subduction of the Saxothurigian oceanic domain beneath the Teplá–Barrandian and Moldanubian Units (Schulmann et al., 2009). This was followed by continent–continent collision (Franke, 1989; Matte, 2001) with extensive deformation, metamorphism and magmatism mainly within the Moldanubian Unit (Lardeaux et al., 2014; Schulmann et al., 2014), and also significant perturbation and refertilization of the lithospheric mantle (Becker et al., 2001; Janoušek and Holub, 2007; Kusbach et al., 2015; Medaris et al., 2015b). Several authors (e.g., Henk et al., 2000; Ziegler and Dèzes, 2005) also speculate about the late-Variscan lithospheric mantle delamination and asthenospheric mantle upwelling, which should at least partly replace the older lithospheric mantle roots of the Variscan orogeny.

During the Cenozoic, the Bohemian Massif underwent asthenospheric doming and subsequent incipient continental rifting (resulting in the major NE–SW trending Ohře/Eger rift) associated with intraplate alkaline volcanism (Late Cretaceous–Pleistocene, 79–0.26 Ma; Cajz et al., 1999; Downes, 2001; Ulrych et al., 2011). These lavas commonly carry mantle peridotite xenoliths (Ulrych and Adamovič, 2004), similarly to other coeval volcanic systems in Central and Western Europe (e.g., Eifel, Vogelsberg, Massif Central, Calatrava).

3. Samples

The suite of mantle xenoliths selected for this study includes occurrences from distinct parts of the Ohře/Eger Rift (western, central, north-eastern) as well as from off-rift settings across the Bohemian Massif. Petrology and geochemistry of several localities of mantle xenoliths described here were already studied elsewhere, whereas other occurrences are documented for the first time. The xenoliths predominantly consist of protogranular/equigranular (following the classification of Mercier and Nicolas, 1975) spinel harzburgites and lherzolites which underwent variable degrees of partial melting from ~5 to ~35%, followed by metasomatism by basaltic and/or alkaline/CO_2-rich melts (Ackerman et al., 2015, 2013b, 2007; Matusiak-Małek et al., 2014, 2010; Medaris et al., 2015a; Puziewicz et al., 2011; Špaček et al., 2013).

Five localities were sampled in the Ohře/Eger Rift: Dobkovičky (locality #4, $n = 3$), Prackovice (locality #2, $n = 1$), Medvědický vrch (locality#3, $n = 1$), Plešný (locality #1, $n = 4$), and Kraslice (locality #5, $n = 2$) (Fig. 1). For off-rift settings, 19 samples were collected in six localities: Kozákov (locality #6, $n = 4$), Krzeniów (locality #7, $n = 7$), Sproitz (locality #8, $n = 1$), Lutynia (locality #9, $n = 2$) Provodín (locality #10, $n = 4$), and Luže (locality #11, $n = 1$). The xenoliths from off-rift settings exhibit largely variable compositions from spinel-bearing or spinel-free lherzolites to harzburgites and dunites. More details can be found in Supplementary material.

4. Methods

The whole-rock major element composition was calculated from distribution maps obtained using a Tescan MIRA 3GMU scanning electron microscope fitted with SDD X-Max 80 mm^2 EDS detector (Czech Geological Survey), using the AZtecEnergy QuantMap and AutoPhaseMap software. Large Area Mapping tool, covering the whole area of the standard thin section was applied. Multiple EDS maps were individually acquired with the step size of 16 μm, accelerating voltage of 15 kV, WD 15 mm and 6 nA probe current, and subsequently stitched together to enable the phase identification calculations for each peridotite specimen. This methodology was used due to a limited size of most xenoliths which prevented to apply classical wet analysis. Major element concentrations in olivine (ol), orthopyroxene (opx), clinopyroxene (cpx) and spinel (spl) in most samples were determined using a Cameca SX 100 electron microprobe, housed at the Institute of Geology of the Czech Academy of Sciences, using WDS at an accelerating voltage of 20 kV and 2 μm beam size.