Regionally dependent metasomatism of orogenic mantle revealed by highly siderophile elements and Re–Os isotope geochemistry of Variscan lamproites: A pilot study from the Bohemian Massif

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Abstract: Orogenic (high-silica) lamproites represent a group of post-collisional mantle-derived igneous rocks that hold the potential to sample components with extreme compositions from highly heterogeneous mantle. In our pilot study, we explore highly siderophile element (HSE) and Re–Os isotope systematics of Variscan orogenic lamproites sampled from the termination of the Moldanubian and Saxo–Thuringian zones of the Bohemian Massif. Orogenic lamproites of the Bohemian Massif are distinguished by variably high contents of SiO_2, high Mg# and predominant mineral associations of K-rich amphibole and Fe-rich microcline. The HSE show (i) consistently very low contents in all investigated orogenic lamproites compared to the estimated concentrations in majority of mid-ocean ridge basalts, hotspot-related volcanic rocks and arc lavas, and (ii) marked differences in relative and absolute HSE abundances between the samples from the Moldanubian and Saxo-Thuringian Zone. Such a regional dependence in HSE from mantle-derived melts is exceptional. Orogenic lamproites have highly variable and high initial suprachondritic $^{187}Os/^{188}Os$ values (up to 0.631) compared with rather chondritic to subchondritic Os isotope values of the young lithospheric mantle below the Bohemian Massif. The highly radiogenic Os isotope component in orogenic lamproites may be derived from preferential melting of metasomatised vein assemblages sitting in depleted peridotite mantle. This process appears to be valid generally in the petrogenesis of orogenic lamproites both from the Bohemian Massif (Variscan lamproites) and from the Mediterranean area (Alpine lamproites). As a specific feature of the orogenic lamproites from the Bohemian Massif, originally ultra-depleted mantle component correlative with remnants of the Rheic Ocean lithosphere in the Moldanubian Zone was metasomatised by a mixture of evolved and juvenile material, whereas the lithospheric mantle in the Saxo-Thuringian Zone was enriched through the subduction of evolved crustal material with highly radiogenic Sr isotope signature. As a result, this led to observed unique regionally dependent coupled HSE, Rb–Sr and Re–Os isotope systematics.

Introduction

The platinum-group elements (PGE: Os, Ir, Ru, Rh, Pt and Pd), along with Re and Au, are grouped together as the highly siderophile elements (HSE), defined by their strong affinities for metals and sulphides relative to silicates. These elements have variable partitioning behaviour between highly compatible Os, Ir, Ru and Rh relative to mildly compatible Pt and Pd and moderately incompatible Re and Au during melting and mafic melt crystallization (e.g., Day et al. 2013). This exceptional geochemical behaviour serves HSE as a powerful tool for tracing different mantle processes such as partial melting, melt percolation and mantle metasomatism. However, the behaviour of HSE in orogenic mantle is not well constrained because of a limited amount of available HSE data of compositionally highly variable mantle-derived orogenic melts and mantle xenoliths. This is intriguing as orogenic lamproites hold a potential to sample mantle domains with extreme geochemical (including isotope) composition from highly heterogeneous orogenic mantle. In spite of that, there are still only a few papers dealing with incomplete HSE systematics of lamproitic rocks till the present day (e.g., Conticelli et al. 2007; Prelević et al. 2015).

Lamproites are comparatively a rare group of peralkaline, ultrapotassic and perpotassic mantle-derived igneous rocks. Traditionally, lamproites can be found in both anorogenic and orogenic geodynamic settings, and it has been demonstrated that their mantle source can be enriched by interaction with different reservoirs within the lithospheric mantle, including subducted continental and oceanic material (e.g., Prelević et al. 2010, 2015; Krmíček et al. 2016).

Orogenic lamproites in the Bohemian Massif

In the Bohemian Massif, the occurrences of peralkaline dykes of lamproitic composition are almost exclusively restricted to the eastern margin of the Moldanubian Zone and to the West Sudetes Domain of the Saxo–Thuringian Zone (e.g., Krmíček et al. 2011, 2016 and references therein). These dykes are all orogenic in origin, being emplaced after their host geological units collided during the Variscan orogeny (Fig. 1). Spatial distribution of these lamproites in a belt at the eastern termination of the Moldanubian and Saxo–Thuringian zones is genetically connected with the closure of the Rheic Ocean followed by the subduction of the Brunovistulian Terrane (Krmíček et al. 2016).

Orogenic lamproites and their more evolved equivalents (leucolamproites) occur both in the Moldanubian and Saxo–Thuringian zones. Their compositions can be distinguished by predominant mineral associations of K-rich amphibole and Fe-rich microcline, which mineralogically correspond to a new variety of silica-rich lamproite (Krmíček et al. 2011).

The dykes have not been directly dated, however, based on $^{40}Ar/^{39}Ar$ age determinations of other mafic intrusions with lamproitic affinity from the Bohemian Massif, their presumed emplacement age is ~330 Ma (Awdankiewicz et al. 2009; Krmíček et al. 2011).

Analytical methods

The concentrations of HSE and Re–Os isotope data were obtained at the Institute of Geology of the Czech Academy of Sciences in Prague following the methods described in detail by Krmíček et al., in review. Osmium isotope measurements were determined using the Thermo Triton Plus multicollector thermal ionization mass spectrometer (TIMS), while Ir, Ru, Pt, Pd and Re concentrations were analysed by the sector-field ICP-MS (Element 2, Thermo).

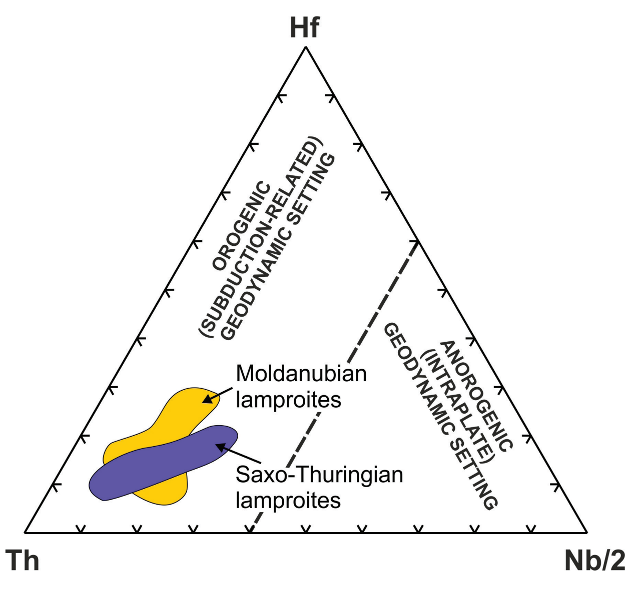

Fig. 1. Position of studied Variscan lamproites from the Bohemian Massif in the Th–Hf–Nb/2 discrimination diagram developed for potassic mantle-derived rocks by Krmíček et al. (2011).

Results

Contents of HSE in all samples show consistently very low values (ΣHSE mostly below 1 ppb; Krmíček et al., in review) with respect to the estimated concentrations both in the primitive upper mantle (PUM; Becker et al. 2006) and in the mantle-derived rocks such as mid-ocean ridge basalts, hotspot-related volcanic rocks (ocean island basalts, continental flood basalts, komatiites, intraplate alkaline volcanic rocks such as kimberlites and anorogenic lamproites) and arc lavas (e.g., Day 2013; Gannoun et al. 2016 and references therein), with the Moldanubian lamproites being recognised by higher values on average than the samples from the Saxo–Thuringian Zone.

The primitive mantle-normalised HSE distributions exhibit fractionated patterns with progressive increase from iridium-PGE (I-PGE; Os, Ir, Ru, Rh) to platinum-PGE (P-PGE; Pt, Pd) with Pt_N/Os_N between 1.5 and 36, feature typical for mantle-derived melts (see Gannoun et al. 2016 and references therein), while Re is mostly similar to or lower than Pt.

The present-day $^{187}Os/^{188}Os$ isotope ratios vary widely within the studied sample suite, ranging between 0.157 and 0.685, corresponding to variable radiogenic initial $^{187}Os/^{188}Os_{(330)}$ values of 0.157–0.631. There is no significant difference between the samples from different zones as they oscillate between the $^{187}Os/^{188}Os$ and $^{187}Re/^{188}Os$ values close to the composition of PUM and a component with highly radiogenic $^{187}Os/^{188}Os$ both at relatively low and high $^{187}Re/^{188}Os$.

Discussion

Due to contrasting behaviour of Os and Re during partial melting, mantle-derived melts should be preferably enriched in Re over Os leaving the mantle residues with subchondritic Re/Os ratios. Indeed, arc lavas and melts derived by partial melting of MORB or OIB sources exhibit Re-enriched compositions (usually >100 ppt of Re; Gannoun et al. 2016 and references therein). For the rest of HSE, during the mantle depletion caused by common partial melting degrees (<20 %), low-melting point (e.g., Cu-bearing) sulphides represent a predominant host for P-PGE, while I-PGE are hosted by highly refractory phases such as alloys or high temperature sulphides leading to characteristic enrichment from Os through Pt to Re in mantle-derived melts (e.g., Day 2013; Gannoun et al. 2016). However, observed Re and other HSE abundances in orogenic lamproites from the Bohemian Massif require a mantle source overall largely replenished in all HSE, especially in Re (Fig. 2). The most possible explanation for these characteristics is a presence of large proportion of recycled, HSE-poor material (e.g., eclogite, pyroxenite; Ackerman et al. 2013; Aulbach et al. 2016) in the parental source of lamproitic magmas, which would be consistent with observed variable, but radiogenic $^{187}Os/^{188}Os$ signatures. Moreover, there is a unique regional dependence between relatively Re-enriched Moldanubian lamproites and those from the Saxo–Thuringian Zone (Fig. 2). This difference can be primarily caused by the presence of regionally contrasting depleted/enriched mantle source and/or by variable oxygen fugacity during partial melting or metasomatism of depleted mantle source by regionally contrasting material. Additionally, Tertiary orogenic lamproites from the Mediterranean area display relative Re and Os enrichment compared to Variscan orogenic lamproites from the Bohemian Massif (Fig. 2). Such enrichment could be related to the interaction with a component derived from the convective mantle via volatile-rich carbonatite fluids (Prelević et al. 2010).

Studied orogenic lamproites have high and variable suprachondritic initial $^{187}Os/^{188}Os$ values, much higher than predominantly only slightly superchondritic to subchondritic values found in the Bohemian upper mantle rocks (e.g., Ackerman et al. 2013; Kochergina et al. 2016) but similar to those found in pyroxenites (cf. Ackerman et al. 2016). The highly radiogenic $^{187}Os/^{188}Os$ component is sampled both by lamproites (with high Mg#) and leucolamproites, which, together with absence of xenoliths, excludes the possibility that radiogenic $^{187}Os/^{188}Os$ component is related to low-pressure contamination by continental crust with high $^{187}Os/^{188}Os$. The observed variability in $^{187}Os/^{188}Os$ can be explained by binary mixing between clinopyroxenite and ambient mantle. This process seems to be valid generally in the petrogenesis of orogenic lamproites both from the Bohemian Massif and from the Mediterranean area. On the other hand, $^{187}Os/^{188}Os$ variations in combination with Os abundances alone do not have sufficient sensitivity to distinguish possible variations in mantle sources (and thus the nature and extent of mantle metasomatism) of orogenic lamproites from the Moldanubian and Saxo–Thuringian zones. Therefore, we introduce the combination of $^{187}Os/^{188}Os$ and $^{87}Sr/^{86}Sr$ as the latter is very sensitive indicator of subduction-related (fluid-enhanced) metasomatism. Using this approach, the composition of Moldanubian and Saxo-Thuringian lamproites is best explained by vein/wall-rock melting model requiring 60–70 % contribution from the metasomatised mantle with different (regionally dependent) Sr-isotope composition. This is in agreement with assumption of Krmíček et al. (2016), that the originally ultra-depleted mantle component (correlative with subducted Rheic Ocean lithosphere) was metasomatised by a mixture of evolved and juvenile material (thinned continental crust?) in the Moldanubian Zone, whereas the lithospheric mantle in the Saxo-Thuringian Zone underwent subduction-related metasomatism by evolved (with pronounced negative Eu anomaly and highly radiogenic $^{87}Sr/^{86}Sr$) crustal material.

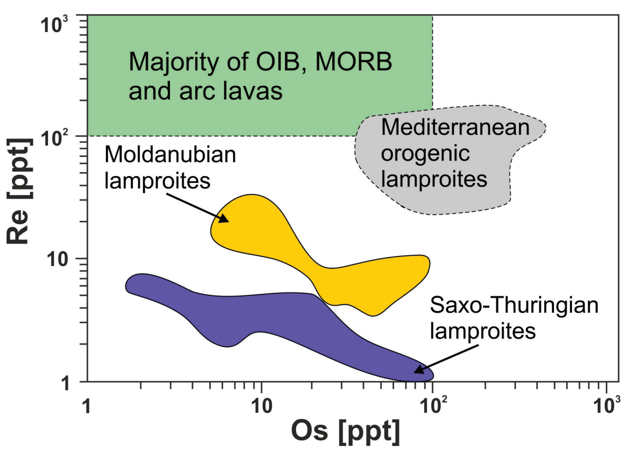

Fig. 2. Re and Os abundances (ppt) of the studied Variscan lamproites in comparison with the Mediterranean orogenic lamproites and majority of OIB, MORB and arc lavas (Krmíček et al., *in review* and references therein).

Conclusions

Based on our pilot study of highly siderophile elements and Re–Os isotope geochemistry of orogenic lamproites from the Bohemian Massif, we present the following conclusions:

- All HSE show consistently very low contents in all samples compared to the other mantle-derived volcanic rocks as the result of high proportions of HSE-depleted material (e.g., pyroxenite, eclogite) in the source parental for orogenic lamproitic magmas.
- There are remarkable differences in relative and absolute HSE abundances between the samples from the Moldanubian and Saxo–Thuringian zones.

- Studied orogenic lamproites have highly variable and suprachondritic $^{187}Os/^{188}Os$ values overlapping the values found in mantle pyroxenites from the Bohemian Massif. Therefore, the highly radiogenic Os isotope component in orogenic lamproites may be derived from preferential melting of metasomatised mantle rich in clinopyroxenite vein assemblages sitting in depleted peridotite mantle.
- Based on the combination of Os–Sr isotope signature, the composition of Moldanubian and Saxo–Thuringian lamproites can be best explained by vein/wall-rock melting model requiring 60–70 % contribution from the metasomatised mantle with different (regionally dependent) $^{87}Sr/^{86}Sr$ composition.

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