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# $^{186}$Os–$^{187}$Os and highly siderophile element abundance systematics of the mantle revealed by abyssal peridotites and Os-rich alloys

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## Abstract

Abyssal peridotites are oceanic mantle fragments that were recently processed through ridges and represent residues of both modern and ancient melting. To constrain the nature and timing of melt depletion processes, and the composition of the mantle, we report high-precision Os isotope data for abyssal peridotites from three ocean basins, as well as for Os-rich alloys, primarily from Mesozoic ophiolites. These data are complemented by whole-rock highly siderophile element (HSE: Os, Ir, Ru, Pt, Pd, Re), trace- and major-element abundances for the abyssal peridotites, which are from the Southwest Indian (SWIR), Central Indian (CIR), Mid-Atlantic (MAR) and Gakkel Ridges. The results reveal a limited role for melt refertilization or secondary alteration processes in modifying abyssal peridotite HSE compositions. The abyssal peridotites examined have experienced variable melt depletion (2% to >16%), which occurred >0.5 Ga ago for some samples. Abyssal peridotites typically exhibit low Pd/Ir and, combined with high-degrees of estimated total melt extraction, imply that they were relatively refractory residues prior to incorporation into their present ridge setting. Recent partial melting processes and mid-ocean ridge basalt (MORB) generation therefore played a limited role in the chemical evolution of their precursor mantle domains. The results confirm that many abyssal peridotites are not simple residues of recent MORB source melting, having a more complex and long-lived depletion history.

Peridotites from the Gakkel Ridge, SWIR, CIR and MAR indicate that the depleted MORB mantle has $^{186}$Os/$^{188}$Os of 0.1198356 ± 21 (2SD). The Phanerozoic Os-rich alloys yield an average $^{186}$Os/$^{188}$Os within uncertainty of abyssal peridotites (0.1198361 ± 20). Melt depletion trends defined between Os isotopes and melt extraction indices (e.g., $Al_2O_3$) allow an estimate of the primitive mantle (PM) composition, using only abyssal peridotites. This yields $^{187}$Os/$^{188}$Os (0.1292 ± 25), and $^{186}$Os/$^{188}$Os of 0.1198388 ± 29, both of which are within uncertainty of previous primitive mantle estimates. The $^{186}$Os/$^{188}$Os composition of the PM is less radiogenic than for some plume-related lavas, with the latter requiring sources with high long-term time-integrated Pt/Os. Estimates of primitive mantle HSE concentrations using abyssal peridotites define chondritic Pd/Ir, which differs from previous supra-chondritic estimates for Pd/Ir based on peridotites from a range of tectonic settings. By contrast, estimates of PM yield supra-chondritic Ru/Ir. The cause of enhanced Ru in the mantle remains enigmatic, but may reflect variable partitioning behavior of Ru at high pressure and temperature.

*Keywords:* $^{186}$Os/$^{188}$Os; $^{187}$Os/$^{188}$Os; Highly siderophile elements; Primitive mantle; Abyssal peridotite; Os-rich alloys

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## 1. INTRODUCTION

The highly siderophile element (HSE: Re, Os, Ir, Ru, Pt, Rh, Pd, Au) composition of the mantle is a key constraint for understanding terrestrial accretion and differentiation. Core formation is predicted to have efficiently stripped the HSE from the mantle due to the high metal–silicate partition coefficients ($>10^4$) typical of these elements at relatively low pressures and temperatures (e.g., Brenan et al., 2016). This prediction is not matched by mantle peridotite compositions that commonly have HSE abundances only ~150 times less abundant than in chondrite meteorites, and in broadly chondritic relative proportions (Morgan, 1986; Morgan et al., 2001; Becker et al., 2006; Fischer-Gödde et al., 2011). Competing models to explain this discrepancy include late accretion of chondrite-like impactors to Earth (e.g., Kimura et al., 1974; Chou, 1978), lower metal–silicate partition coefficients at higher pressures and temperatures (Murthy, 1991), and outer core addition (Snow and Schmidt, 1998).

The mantle has been sampled from oceanic and continental settings, with a strong bias towards continental lithospheric mantle and massif peridotites. These peridotites all come from the upper mantle and we refer to estimates of the upper mantle based on the HSE as primitive mantle (PM). Some prior studies (e.g., Meisel et al., 2001; Becker et al., 2006; Fischer-Gödde et al., 2011) have also referred to this as primitive upper mantle (PUM). The PM composition in this instance is broadly analogous to the bulk silicate Earth (BSE), since the immense majority of the HSE reside in the mantle relative to the crust. To obtain estimates of the PM composition, studies have used peridotite suites to extrapolate to compositions by accounting for melt-depletion (Morgan, 1986; Meisel et al., 2001). In the most recent iterations, Becker et al. (2006) and Fischer-Gödde et al. (2011) proposed a PM composition with Pd/Ir and Ru/Ir ratios significantly higher than in bulk chondrite meteorites. Similar 'non-chondritic' HSE patterns have also been observed in mantle peridotites from different settings (Pattou et al., 1996; Snow and Schmidt, 1998; Rehkamper et al., 1999), as well as in the mantle sources of some lavas (Peters et al., 2016). However, the reliability of using massif peridotites compositions has been called into question, due to refertilization processes that these samples may experience (e.g., Marchesi et al., 2014; Lorand and Luguet, 2016).

The oceanic mantle is the largest of the accessible terrestrial reservoirs. Despite the volume and extent of this reservoir, it is poorly studied compared with continental mantle peridotites, largely due to accessibility and sampling issues. The most common samples from the oceanic mantle are abyssal peridotites, which are widely interpreted as the depleted mantle residues of mid-ocean ridge magmatic processes (see Warren, 2016 for a review). Abyssal peridotites are typically sampled at oceanic transform faults or at ridge segments, where mantle has been tectonically exhumed. Unfortunately, abyssal peridotites are not pristine samples of the mantle, as most have been modified by secondary alteration processes (e.g., Snow and Dick, 1995; Snow and Reisberg, 1995; Malvoisin, 2015). Additionally, during upwelling and partial melting beneath the ridge, abyssal peridotites may be infiltrated by associated melts (Niu, 2004; Warren, 2016). Nonetheless, abyssal peridotites can be used to help to unravel the composition of the PM, as they are not subject to complex melt refertilization from exotic melts and fluids, as may occur in the continental lithospheric mantle (Becker and Dale, 2016).

Here we report new high-precision $^{186}$Os/$^{188}$Os and $^{187}$Os/$^{188}$Os data for abyssal peridotites from three ocean basins (Indian, Atlantic, Arctic), as well as Mesozoic to Proterozoic-aged Os-rich alloys from ophiolites. We compare these data with $^{186}$Os/$^{188}$Os data obtained for the mantle from prior studies (Walker et al., 1997, 2005; Brandon et al., 2000; Chatterjee and Lassiter, 2016), using identical normalizations and reporting uncertainties as 2 standard deviations (2SD), unless otherwise stated. For convenience, we report uncertainties given on the last digits of the reported value (i.e., $0.1198388 \pm 0.0000029$ is abbreviated to $0.1198388 \pm 29$). These data are coupled with whole-rock HSE, trace-element and major-element data for abyssal peridotites, allowing a refined assessment of Earth's mantle composition from the view point of the oceanic mantle. In addition to providing extrapolations of HSE data to indices of melt depletion (e.g., Morgan, 1986), the Pt–Os and Re–Os isotope systems provide robust constraints on ratios of these elements in the mantle due to the long-lived $^{187}$Re–$^{188}$Os ($\lambda = 1.67 \times 10^{-11}\ y^{-1}$) and $^{190}$Pt–$^{186}$Os ($\lambda = 1.54 \times 10^{-12}\ y^{-1}$) decay schemes (Smoliar et al., 1996; Walker et al., 1997). We use these results to investigate melt depletion processes in the mantle and to estimate the PM composition for the highly siderophile elements.

## 2. SAMPLES AND METHODS

### 2.1. Samples

Abyssal peridotites (Fig. 1) were analyzed from the ultraslow (<20 mm/yr full rate) spreading Oblique Segment at 9–16°E on the Southwest Indian Ridge (SWIR), the slow-spreading (46 mm/yr) central Indian Ridge (CIR) at the Marie Celeste transform fault, the ultraslow spreading (11–14 mm/yr) Gakkel Ridge from 5°W to 85°E, and from the Mid-Atlantic Ridge (MAR) south of the Kane transform fault (MARK area). Full details of sample locations and sample preparation protocols are given in the Supplementary Information.

### 2.2. Major and trace element abundance analyses

Major element compositions were measured by X-ray fluorescence (XRF) at Franklin and Marshall College using a PW 2404 *PANalytical* XRF vacuum spectrometer following the procedures outlined in Boyd and Mertzman (1987). Major element analyses by XRF involved standard lithium tetraborate fusion techniques using 3.6:0.4 g $LiBO_4$:sample powder. Ferrous iron concentrations were determined by titration with potassium dichromate. Precision and accuracy are estimated using repeat analyses of standards, with long-term reproducibility (in wt.% and 2σ absolute stan-