

Ages from Re-Os isotopes in peridotites

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We review the application of the Re-Os isotope system to determining the age of mantle lithosphere. The premise behind most Re-Os dating of peridotites is that Re, being a moderately incompatible element, is depleted during melting events whereas Os, being strongly compatible, is retained in the residue. If mantle lithosphere forms during melt extraction events and Re is depleted relative to Os, then Os isotopes can potentially date the timing of lithosphere formation via retardation in the growth of $^{187}\text{Os}/^{188}\text{Os}$ ratio relative to mantle evolution model. Model ages for peridotite melting can be calculated by determining the intersection of the Os isotope evolution of the sample with a model mantle composition. This is generally done either by assuming no Re in the sample (T_{RD} ages, which are minimum ages, Walker et al., 1989), by using the measured Re/Os of the sample (T_{MA} ages, analogous to Nd model ages) or by using linear trends between $^{187}\text{Os}/^{188}\text{Os}$ and immobile indicators of melt depletion (e.g., Al_2O_3 , CaO or Lu) as isochron analogs (e.g., Reisberg and Lorand, 1995).

Each type of model age calculation is subject to assumptions and uncertainties, and over the past decade a number of studies utilizing coupled Re-Os and platinum group element (PGE) whole rock studies, as well as *in situ* analyses (of sulfides and PGE phases) have illuminated several factors that need to be considered when applying the Re-Os system to determining the age of lithospheric mantle. These include 1) the effects of weathering, alteration and late sulfide breakdown (in the case of xenoliths) on Re and Os concentrations, 2) disturbance of the Re-Os system in the mantle by refertilization and melt-rock reaction that may occur long after initial melt depletion, and 3) the variability of $^{187}\text{Os}/^{188}\text{Os}$ in the present-day convecting upper mantle, as recorded in abyssal peridotites and ophiolites. Each of these factors is addressed, in turn.

Serpentinization and weathering

Many mantle-derived peridotites, especially those that crop out on the continents or ocean floor, are heavily serpentinized. In the case of peridotite xenoliths, those carried by kimberlite are generally much more heavily serpentinized compared to those carried by alkali basalts. However, a number of studies of heavily serpentinized peridotites, from both outcrop and xenoliths, have inferred little disturbance of the

Re-Os system due to serpentinization (Büchl et al., 2002, and references therein), likely due to the reducing conditions prevalent during this process.

Since sulfides are the major carrier of both Re and Os in sulfide-saturated (i.e., more fertile) mantle xenoliths, their breakdown via secondary processes may affect Re and Os concentrations and, over time, $^{187}\text{Os}/^{188}\text{Os}$. Oxidative weathering at the Earth's surface causes breakdown of sulfides in many mantle xenoliths ejected in explosive eruptions, whereas xenoliths that are carried in basaltic lavas may be shielded from such weathering effects and, thus, preserve their original sulfides (Lorand, 1990; Lorand et al., 2003). In addition, oxidation of molten sulfides during decompression in the host basalts may alter the PGE chemistry of peridotite xenoliths, particularly for potentially volatile PGE such as Os (Handler et al., 1999; Lorand et al., 2003). Several studies, however, have reported the presence of PGE phases produced by the breakdown of mantle sulfides (Keays et al., 1981; Chesley et al., 1999) and such phases are the main host of Os in highly refractory peridotites (Luguet et al., 2007). Thus, the degree to which secondary sulfide breakdown influences Re and Os concentrations is likely dependent on the $f\text{O}_2$ during breakdown and the stability of secondary PGE phases. In any event, sulfide breakdown due to weathering or oxidative decompression of xenoliths may fractionate Re from Os and warrants consideration when evaluating initial $^{187}\text{Os}/^{188}\text{Os}$ of peridotite xenoliths.

Refertilization and melt-rock reaction

Melts that percolate through residual peridotites can alter the chemical composition of these peridotites, including the Re and PGE abundances, as well as $^{187}\text{Os}/^{188}\text{Os}$. Such melt-rock interactions may be particularly important for interpreting the Os isotope composition of peridotites thus affected, especially when the refertilization occurs long after original melt depletion event(s) and when the process replaces original Os with (typically) more radiogenic Os. There are two settings where such interactions are well documented: 1) at high melt-rock ratios where the formation of melt channels results in the replacement of original lherzolite by dunite and harzburgite (Quick, 1981; Kelemen et al., 1992; Kelemen et al., 1995) and 2) at lower melt-rock ratios where infiltration and recrystallization of asthenospheric melts produces lherzolite from harzburgite (e.g., Le Roux et al., 2007).



The first process, which has been documented in ophiolites and is considered important in the oceanic setting, produces dunites and harzburgite from lherzolites. The effects on the Re-Os system is to lower the concentrations of both elements due to breakdown of the original sulfide and to increase $^{187}\text{Os}/^{188}\text{Os}$ due to precipitation of new sulfides from radiogenic melts, which were likely derived from recycled basaltic components (Becker et al., 2001; Büchl et al., 2002). This process results in peridotites with relatively low Os, fractionated PGE patterns showing enrichment of the incompatible PGE relative to Os, Ir and Ru and suprachondritic $^{187}\text{Os}/^{188}\text{Os}$.

The second process, which has been documented in peridotite massifs (Saal et al., 2001; Le Roux et al., 2007) and some xenoliths (Chesley et al., 1999; Alard et al., 2002; Reisberg et al., 2004), may be important in the continental mantle lithosphere and produces lherzolites from harzburgites at lower melt-rock ratios. Because most mantle melts are enriched in Re and the incompatible PGE, Pt and Pd, and have low compatible PGE contents (including Os), refertilization should typically result in enrichment of Re. The $^{187}\text{Os}/^{188}\text{Os}$ of the refertilized lherzolite will be a function of the mass balance between the new sulfides precipitated from the basalt and the original Os in the harzburgite, as well as the length of time that the peridotite has evolved with higher Re/Os. Thus, $^{187}\text{Os}/^{188}\text{Os}$ in refertilized lherzolites may show no change (Becker et al., 2001), a small increase (Chesley et al., 1999; Reisberg et al., 2004) or significant increase (Alard et al., 2002), depending on the ratio of original to metasomatic sulfides, Re/Os ratio and time. This process can produce peridotites with “normal” Os contents and enrichment of Re and incompatible PGE, with or without an increase in $^{187}\text{Os}/^{188}\text{Os}$. The participation of this process may, in some instances, be deduced on the basis of elevated Pd/Ir or Pt/Ir ratios in bulk samples, or the presence of sulfides with appreciably suprachondritic $^{187}\text{Os}/^{188}\text{Os}$ (e.g., Alard et al., 2005). Thus, the veracity of Os ages can be evaluated from coupled Os isotope and PGE analyses.

$^{187}\text{Os}/^{188}\text{Os}$ of the convecting upper mantle

It is clear that the depleted upper mantle beneath the ocean basins (DMM) is isotopically heterogeneous with respect to Os, and some abyssal peridotites have T_{RD} ages as old as 2.0 Ga (Alard et al., 2005; Harvey et al., 2006; Liu et al., 2008). For this reason it is not advisable to equate lithosphere formation ages with model ages for the oldest sulfides in a rock (c.f. Griffin et al., 2004; Pearson and Wittig, 2008). However, whole rocks with such ancient provenance appear to be relatively minor components of the DMM, and several studies suggest that random sampling of the convecting upper mantle is dominated by materials with a near chondritic upper mantle isotopic composition (e.g., Meibom et al., 2002; Frei et al., 2006). So while a single sample in a continental setting with a depleted Os isotopic composition is not strong evidence for the

presence of ancient lithospheric mantle, a group of xenoliths from a single locality that show correlations between $^{187}\text{Os}/^{188}\text{Os}$ and indicators of melt depletion are unlikely to represent recent addition from the DMM.

In addition, the average Os isotopic composition of the modern DMM is still poorly known, so the mantle evolution model with which to compare the compositions of peridotites can vary by several percent at present (e.g., Snow and Reisberg, 1995; Walker et al., 2002). This means that Os model age determinations for peridotites with melt depletion ages less than about 1 Ga are poorly constrained. Consequently, the resolution for dating lithospheric melting events during the Phanerozoic is very poor. This is much less of a problem for older systems because variance from chondritic evolution was likely compressed in the past.

Synthesis

Since the 1989 inception of using Os isotopic data to date the residues of mantle melting events, it has become increasingly evident that the interpretation of Os isotopic data requires consideration of multiple complex processes. Nearly 20 years later, it is now clear that model Os melt depletion ages must be interpreted within a framework of supporting evidence, such as chemical evidence of extent of melt depletion (via examination of immobile element concentrations in bulk samples and minerals), trends defined by multiple samples within a suite, and careful assessment of associated PGE data. *In situ* isotopic and PGE data for sulfides, as well as whole rock PGE data, are important for detailing the complex melting and refertilization processes affecting some mantle peridotites. Through judicious use of these methods it may be possible to distinguish melt depletion vs. refertilization/melt-rock reaction trends and, thus, determine reliable ages of lithosphere formation.

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