

Osmium isotopes and mantle convection

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The decay of ^{187}Re to ^{187}Os (with a half-life of 42 billion years) provides a unique isotopic fingerprint for tracing the evolution of crustal materials and mantle residues in the convecting mantle. Ancient subcontinental mantle lithosphere has uniquely low Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios due to large-degree melt extraction, recording ancient melt-depletion events as old as 3.2 billion years. Partial melts have Re/Os ratios that are orders of magnitude higher than their sources, and the subduction of oceanic or continental crust introduces into the mantle materials that rapidly accumulate radiogenic ^{187}Os . Eclogites from the subcontinental lithosphere have extremely high $^{187}\text{Os}/^{188}\text{Os}$ ratios, and record ages as old as the oldest peridotites. The data show a near-perfect partitioning of Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios between peridotites (low) and eclogites (high).

The convecting mantle retains a degree of Os-isotopic heterogeneity similar to the lithospheric mantle, although its amplitude is modulated by convective mixing. Abyssal peridotites from the ocean ridges have low Os isotope ratios, indicating that the upper mantle had undergone episodes of melt depletion prior to the most recent melting events to produce mid-ocean-ridge basalt. The amount of rhenium estimated to be depleted from the upper mantle is 10 times greater than the rhenium budget of the continental crust, requiring a separate reservoir to close the mass balance. A reservoir consisting of 5–10% of the mantle with a rhenium concentration similar to mid-ocean-ridge basalt would balance the rhenium depletion of the upper mantle. This reservoir most likely consists of mafic oceanic crust recycled into the mantle over Earth's history and provides the material that melts at oceanic hotspots to produce ocean-island basalts (OIBs). The ubiquity of high Os isotope ratios in OIB, coupled with other geochemical tracers, indicates that the mantle sources of hotspots contain significant quantities (greater than 10%) of lithologically distinct mafic material which represents ancient oceanic lithosphere cycled through the convecting mantle on a time-scale of 800 million years or more.

Keywords: mantle; isotope; geochemistry; eclogite; rhenium; osmium

1. Introduction

Rhenium (Re) and osmium (Os) are two of a class of trace elements which are referred to as the *highly siderophile elements*. As such, most of the Earth's budget of Re and

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Os resides in the Earth's metallic core, yet enough of these elements remain in the silicate portion of the Earth to give concentrations in the Earth's mantle of the order of parts per billion. Scant evidence exists which indicates significant mass exchange between the Earth's core and mantle; this issue will be discussed at the end of the paper. Most of this paper will focus on the behaviour of Re and Os in the silicate portion of the Earth and especially on the use of Os isotopes to trace mass flow in the convecting mantle.

The isotope ^{187}Re decays to ^{187}Os with a half-life of 42 billion years, producing readily measurable changes in the isotopic ratio of $^{187}\text{Os}/^{188}\text{Os}$ (a complete review is given by Shirey & Walker (1998)). Due to the decay of ^{187}Re , the mean $^{187}\text{Os}/^{188}\text{Os}$ ratio of the bulk silicate Earth (BSE, bulk Earth minus the core) has increased by 33% since its formation 4.56 billion years ago. At the same time, partial-melting processes have worked to create mantle and crustal reservoirs with large ranges in Re/Os ratio, with consequent variations in $^{187}\text{Os}/^{188}\text{Os}$ that range over orders of magnitude. These materials are subducted into the Earth's mantle at convergent margins, thus introducing a large Os isotopic dispersion into the convecting mantle. It is the large variability in Os isotopes that is used to examine the chemical differentiation of the Earth's mantle and its modulation by convective motion.

Partial melting is one of the most fundamental processes on Earth, and partial melting of the mantle produces a unique signature in the Re–Os isotope system. During partial melting of the mantle, Re is partitioned preferentially into the melt, while Os is almost quantitatively retained by the residue. The Re/Os ratios of the residues of mantle melting are thus greatly lowered, retarding the growth of radiogenic ^{187}Os . At the same time, mantle-derived melts have Re/Os ratios that are greatly elevated (commonly orders-of-magnitude higher than their sources), with the result that crustal materials rapidly accumulate radiogenic ^{187}Os . The retention of Os by the residues of mantle melting is a property of the Re–Os isotope system that is unique, and this property makes Os isotopes a particularly sensitive tracer of those parts of the mantle which have experienced melting.

These properties of the Re–Os isotope system are most clearly seen in the continental lithosphere, where the variations have not been reduced by convective mixing. The continental lithosphere provides a clear view of how Os isotopes are distributed in a 'frozen' system that is not subjected to large-scale convective motion. It will be shown that mixing and partial melting in the convecting mantle modulates the Os isotope variability but does not homogenize it. The heterogeneity of Os isotopes in the convecting mantle provides unique constraints on the origin of mantle hotspots and the distribution of chemical reservoirs in the deep Earth.

2. Osmium in the continental lithosphere

The lithospheres of the continents are strong, mechanical boundary layers at the top of the mantle that are resistant to mixing by convective motion. In particular, the net buoyancy of Archean cratons makes them highly resistant to subduction. As a result, the Re–Os systematics of continental rocks provides a view into the distribution of Os isotopes among rocks that are not mixed by mantle convection. This view shows a clear dichotomy between partial melts (e.g. mafic and silicic crust) and mantle residues (e.g. peridotites).

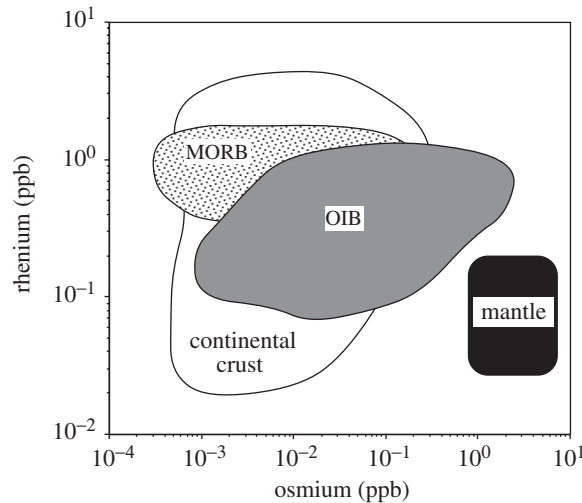


Figure 1. Rhenium (Re) and osmium (Os) abundances for mantle rocks, oceanic basalts (MORB, OIB), and continental sediments. Concentrations are in parts per billion (ppb). All crustal rocks are characterized by Re/Os ratios much higher than those for mantle rocks, mainly due to mild enrichment in rhenium and strong depletion in osmium.

(a) *Continental crust and sediments*

All crustal rocks have Re/Os ratios much higher than the mantle, with the result that continental crust and sediments have highly elevated $^{187}\text{Os}/^{188}\text{Os}$ ratios (see, for example, Esser 1991). Silicic crust and sediments, which have been reworked by surficial and tectonic processes, have highly variable abundances of Re and Os. By contrast, mafic crust generally retains Re and Os abundances more similar to direct partial melts of the mantle, such as mid-ocean-ridge basalt (MORB) (Hauri & Hart 1997; Shirey & Walker 1998). In general, the high Re/Os ratios of most crustal rocks are due to Re abundances 1–10 times higher than mantle abundances, coupled with low (but variable) Os concentrations (figure 1). In comparison with other Earth reservoirs, the continental crust is also characterized by high ratios of rubidium/strontium (Rb/Sr) and neodymium/samarium (Nd/Sm), such that silicic crust and sediments have ‘enriched’ Sr- and Nd-isotope signatures coupled with their elevated Os isotope ratios (see, for example, Taylor & McLennan 1985).

(b) *Subcontinental mantle*

Mantle xenoliths contained in basalt and kimberlite magmas, as well as tectonically exposed peridotite massifs (so-called ‘alpine peridotites’), provide a valuable sampling of the lithology and geochemistry of the subcontinental mantle. The vast majority of mantle xenoliths breaks down into two categories: peridotites (olivine-dominated mineralogy) and so-called ‘eclogites’ (pyroxene-dominated mineralogy). In this paper, we will use the term ‘eclogites’ in a generic sense, to indicate any rock of dominantly mafic lithology with a low abundance of olivine (less than 30%).

There exists a remarkable distinction among peridotites and eclogites in their Re–Os data (e.g. Walker *et al.* 1989; Pearson *et al.* 1995; Shirey & Walker 1998; Pearson & Nowell 2002). Figure 2 shows a near-perfect separation of these two rock

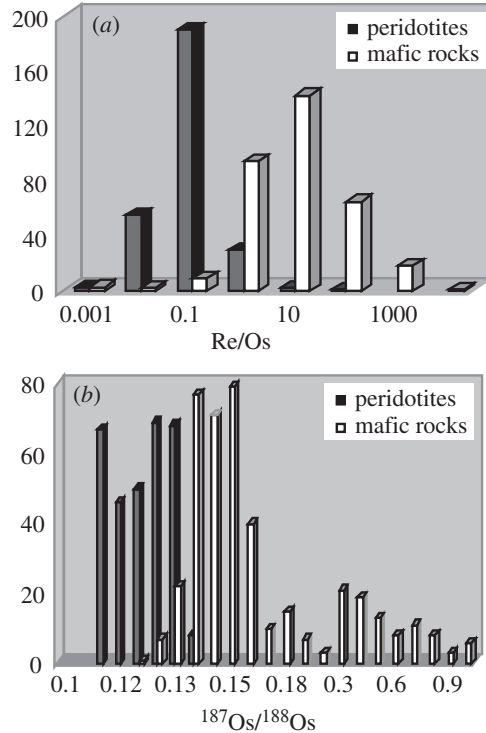


Figure 2. Histograms for (a) Re/Os ratios and (b) $^{187}\text{Os}/^{188}\text{Os}$ ratios for mantle peridotites (black bars) and mafic rocks (open bars). Peridotites include xenoliths from kimberlite and basalt, as well as alpine massifs. Mafic rocks include eclogite and pyroxenite xenoliths, pyroxenites from alpine massifs, and mantle-derived basaltic volcanics. The data exhibit nearly perfect separation of Re/Os and Os isotope ratios between these two rock types. The overlap in Os isotopes is due almost entirely to data for basalts from oceanic hotspots.

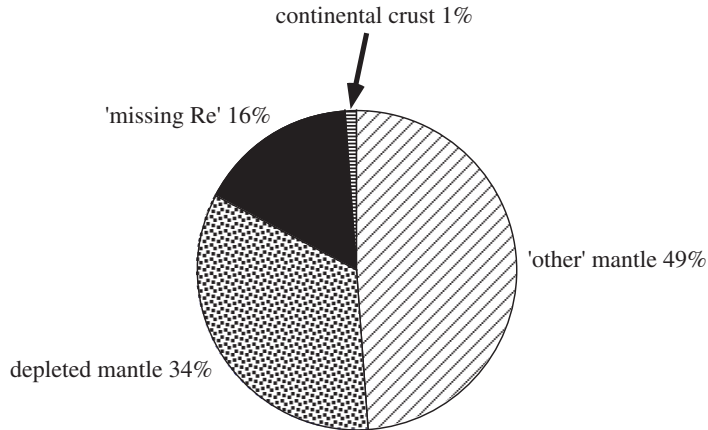


Figure 3. Mass balance of rhenium in the silicate Earth (see § 3). The depleted mantle is assumed to represent 30–50% of the total mantle mass. The continental crust does not balance the amount of Re depleted from the upper mantle, requiring an additional reservoir to account for the amount of 'missing Re'.

types by Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios; this discrimination is the result of partial-melting processes. Extraction of melt from peridotite leaves the residue with low Re/Os ratios, as the Re is preferentially lost to the melt, while the Os is almost entirely retained by the peridotite. Mantle-derived melts have high Re/Os ratios that complement those of the peridotites. Because the continental lithosphere is not subjected to large-scale mixing, the Re–Os systematics of mantle samples (peridotites and eclogites alike) provide good age constraints, which date the timing of partial melting, and record ancient melting events as old as 3.2 billion years (see Shirey & Walker (1998) for a review).

The lack of large-scale convective mixing in the continental lithosphere permits the growth of radiogenic ^{187}Os , which directly reflects the melting-induced variability in Re/Os ratio, with the result that $^{187}\text{Os}/^{188}\text{Os}$ (like Re/Os ratios) shows nearly perfect separation between peridotites and eclogites. Importantly, these relationships persist down to the centimetre scale in exposed alpine peridotites, where pyroxene-dominated layers of mafic composition contain very high $^{187}\text{Os}/^{188}\text{Os}$ ratios with ages as old as 1.3 billion years (e.g. Reisberg *et al.* 1991). These centimetre- to metre-sized mafic layers typically constitute 5% of the mass of any given alpine peridotite body, though their distribution is highly variable at the kilometre scale. The preservation of lithologically distinct mafic components in the ancient lithosphere, as exemplified by eclogite xenoliths and mafic layers, may be reflective of a similar heterogeneity in the convecting mantle. Though deformation rates are undoubtedly higher in the convecting mantle, much larger mafic heterogeneities are introduced into the mantle at convergent margins in the form of 7 km thick oceanic crust.

3. Osmium in the convecting mantle

The generation of basalt at mid-ocean ridges is the most important on-going process by which the Earth is chemically differentiating, and it is likely that a similar mode of rift-induced volcanism has persisted on the Earth for nearly its entire history. Today mid-ocean-ridge volcanism creates a mafic crust 7 km thick, and leaves a depleted mantle residue which is approximately 10 times as thick; the mean oceanic crustal thickness was undoubtedly higher in the hotter, ancient Earth. If the current production rate of oceanic crust is integrated over 4.5 billion years, a minimum of 2.6×10^{26} g of mafic material has been produced at ridges and re-introduced into the mantle at subduction zones, equivalent to 6.5% of the mantle mass. The complementary mass of depleted residue is 10 times this amount. Subduction thus introduces into the mantle a large-amplitude Re/Os heterogeneity; the degree to which this heterogeneity is preserved in the convecting mantle can only be estimated by studying the geochemistry of oceanic volcanism.

(a) Abyssal peridotites

Abyssal peridotites, which are mantle samples recovered from the ocean ridges, represent the uppermost part of the depleted residue left after MORB generation. As such, these peridotites are highly depleted in many trace elements. However, this depletion event is very recent (typically less than 10 million years), so the isotope ratios of abyssal peridotites are identical to their values prior to MORB generation and represent the isotopic composition of upper-mantle peridotite beneath ocean

ridges (e.g. Roy-Barman & Allègre 1994; Snow & Reisberg 1995). The BSE value of $^{187}\text{Os}/^{188}\text{Os}$ is estimated at 0.127–0.129 from analysis of fertile peridotites and chondritic meteorites (Walker & Morgan 1989; Luck & Allègre 1992); the $^{187}\text{Os}/^{188}\text{Os}$ ratios measured in abyssal peridotites are all lower than this value and average 0.1246 (Snow & Reisberg 1995). These results indicate that the upper mantle has a depleted $^{187}\text{Os}/^{188}\text{Os}$ ratio due to long-term depletion of rhenium, a conclusion consistent with the depleted isotopic composition of strontium (Sr) and neodymium (Nd) in the upper mantle.

The upper mantle depletion in Sr and Nd isotopes is due to removal of Rb and Sm from the upper mantle. Although melts may have formed very deep and sunk into the lower mantle in a hotter, Archaean Earth, mass-balance calculations show that the mass of Rb and Sm removed from the upper mantle is similar to the mass of these elements in the continental crust (e.g. Hofmann 1988). For the Re–Os system, if the mean Re-depletion age of the upper mantle is 2 billion years, then the Re abundance of the upper mantle is estimated at 0.17 parts per billion (ppb), compared with 0.26 ppb for the BSE (Hauri & Hart 1997). If the mass of the depleted mantle is taken to be 50% of the mass of the total mantle, the mass of Re depleted from the mantle is estimated at 1.7×10^{17} g, compared with only 1×10^{16} g of Re estimated to reside in the continental crust (Esser 1991). Thus, unlike the Rb–Sr and Sm–Nd systems, the rhenium depletion of the upper mantle is not balanced by a complementary rhenium enrichment in the continental crust. An additional reservoir must exist to balance the upper-mantle depletion of rhenium (figure 3).

(b) *Mid-ocean-ridge basalts*

A vast majority of the Re–Os data on MORB shows $^{187}\text{Os}/^{188}\text{Os}$ ratios higher than abyssal peridotite ratios, leading to the suggestion that a rhenium-enriched mafic component contributes to MORB genesis but is not sampled by the seafloor dredging operations which recover abyssal peridotites (Roy-Barman & Allègre 1994; Schiano *et al.* 1997). However, two processes contribute together to complicate the MORB Os isotope data: sea-water addition and post-eruptive decay of ^{187}Re to ^{187}Os . The $^{187}\text{Os}/^{188}\text{Os}$ ratio of sea water is a factor of 10 higher than the mantle value, and precipitation of Fe- and Mn-oxyhydroxides on submarine lavas concentrates sea-water Os on the surfaces of seafloor rocks. Because the Os contents of MORB are so low, assimilation of small amounts of sea-water-derived Os by MORB magmas can greatly increase the magmatic $^{187}\text{Os}/^{188}\text{Os}$ ratio. In addition, the Re/Os ratios of MORB are so high that the age of eruption must be known very precisely in order to correct for the decay of ^{187}Re since eruption.

These two effects together explain why MORB $^{187}\text{Os}/^{188}\text{Os}$ ratios are almost always higher than those of seafloor peridotites. Figure 4 shows an Re–Os isochron diagram for the existing MORB data, uncorrected for Re decay and grouped by ocean basin. The data for Pacific and Atlantic MORB give apparent Re–Os ages of *ca.* 557 000 years, while the data for Indian Ocean MORB give an apparent age of 1.37 million years. The older age for Indian Ocean MORB correlates with a slower mean-spreading rate compared with Atlantic and Pacific MORB. Because young (less than 3–5 million years old) MORB cannot be dated reliably, and because zero-age MORBs are erupted within a zone 500–1000 m wide on the ridge axis, the correlation of apparent Re–Os age with mean spreading rate is expected for osmium isotope

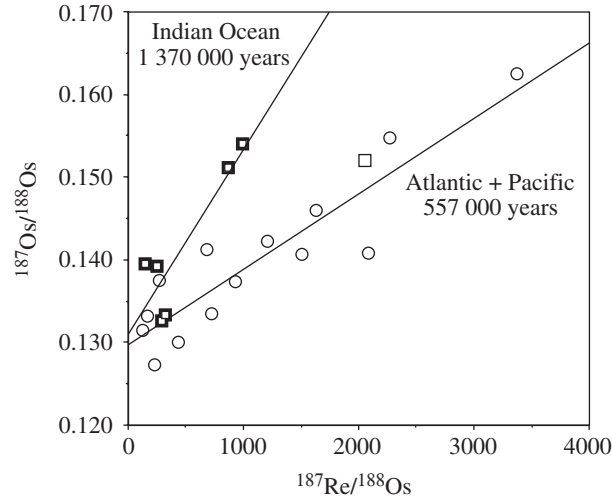


Figure 4. Re–Os isochron plot for MORBs divided into two groups, from the Indian Ocean and Atlantic–Pacific Oceans (Schiano *et al.* 1997). Because the ages of these MORBs are uncertain, they have not been corrected for ^{187}Re decay after eruption. The two groups of data show apparent ages that relate inversely to the average spreading rate, indicating that the MORB osmium isotope data are compromised by post-eruptive radiogenic ingrowth of ^{187}Os .

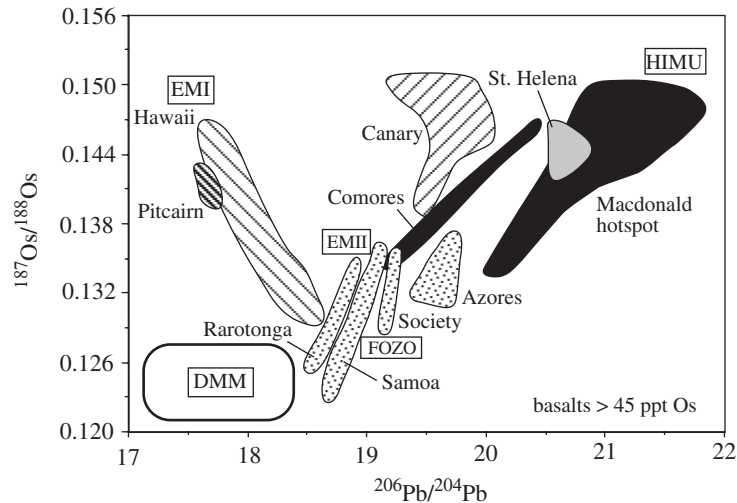


Figure 5. Osmium- and lead isotope data for oceanic basalts and peridotites. Field for the depleted MORB mantle (DMM) includes Os isotope data for abyssal peridotites and oceanic mantle xenoliths with Pb data from N-type MORB. Fields for oceanic island basalts enclose Os and Pb data on the same samples, restricted to samples with more than 45 ppb Os as a filter against sea-water contamination. Analogously to figure 2, there exists almost perfect separation in Os isotopes between oceanic hotspots and DMM.

data on high Re/Os MORB of uncertain age. In addition, the elevated $^{187}\text{Os}/^{188}\text{Os}$ ratios of the isochron intercepts indicate the possibility of widespread addition of sea-water Os to MORB. Analysis of magmatic sulphide in MORBs, which, because of their low Re/Os ratio, do not suffer post-eruptive Re decay, shows a positive cor-

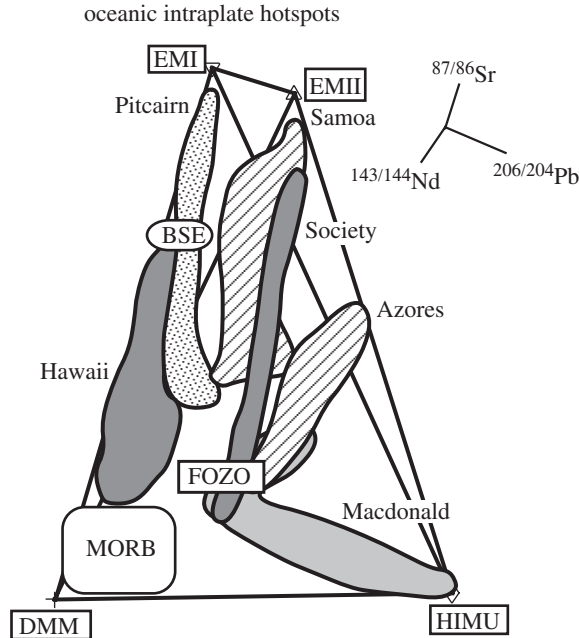


Figure 6. Two-dimensional projection of a three-dimensional plot of Sr, Nd and Pb isotopes for oceanic basalts, after Hart *et al.* (1992). Projected axes are shown in the upper right; mantle end-member components are from Zindler & Hart (1986) and Hauri *et al.* (1994). Data for oceanic hotspots do not show mixing arrays toward MORB or primitive mantle (bulk silicate Earth), but rather mix towards a depleted component distinct from MORB (FOZO). Hart *et al.* (1992) and van Keken *et al.* (2002) show that the FOZO component is the mantle component with high $^3\text{He}/^4\text{He}$ ratios.

relation between $^{187}\text{Os}/^{188}\text{Os}$ and stable boron isotope ratios that are indicative of sea water; the lowest of these $^{187}\text{Os}/^{188}\text{Os}$ ratios are free of sea-water contamination and overlap with abyssal peridotites (Roy-Barman *et al.* 1998). In short, MORB whole rocks and glasses contain contributions to their $^{187}\text{Os}/^{188}\text{Os}$ ratios from sea water and ^{187}Re decay that are unresolvable from the mantle signal. As a result, the $^{187}\text{Os}/^{188}\text{Os}$ ratio of the upper mantle beneath mid-ocean ridges is best preserved by abyssal peridotite and MORB magmatic sulphide that is free of sea-water Os.

(c) *Ocean-island basalts*

Like MORBs, nearly all basalts from oceanic hotspots have $^{187}\text{Os}/^{188}\text{Os}$ ratios higher than abyssal peridotites and the BSE (figure 5; see Hauri & Hart 1997). Unlike MORBs, many ocean-island basalts (OIBs) have sufficiently high Os abundances that they are not susceptible to sea-water contamination or post-eruptive Re decay, so their measured $^{187}\text{Os}/^{188}\text{Os}$ ratios correspond to those of their mantle sources. Also unlike MORBs, $^{187}\text{Os}/^{188}\text{Os}$ ratios in OIB from any single hotspot correlate with isotopic ratios of Sr, Nd and Pb, demonstrating that the Os isotopic composition of OIB reflects long-lived elevated Re/Os ratios in the mantle that are higher than in the BSE (see Hauri & Hart 1997; Shirey & Walker 1998 and references therein). Ancient subcontinental peridotites, which exhibit uniquely depleted Os isotope ratios, do not appear to be a recognizable component in oceanic hotspots.

Elevated $^{187}\text{Os}/^{188}\text{Os}$ ratios are nearly ubiquitous in basalts from oceanic hotspots, while abyssal peridotites are uniformly depleted in their $^{187}\text{Os}/^{188}\text{Os}$ ratios. The difference in $^{187}\text{Os}/^{188}\text{Os}$ ratios between OIBs and abyssal peridotites, both of which are derived from the convecting mantle, is strikingly similar to the difference in Os isotope ratios of peridotites and eclogites from the continental lithosphere. The range of $^{187}\text{Os}/^{188}\text{Os}$ ratios in the convecting mantle is smaller than that for the continental lithosphere, but this is undoubtedly the result of amplitude reduction due to convective solid-state mixing, and mixing of melts during magma genesis and transport. The Re–Os data for hotspot basalts suggests that their origin is closely tied to the presence of mafic components in the mantle, and the most plausible source of such components is ancient recycled oceanic crust. Subduction of silicic continental crust would also have the effect of introducing rhenium into the mantle but, because the rhenium content of continental crust and sediments is lower than that of basaltic crust, a relatively larger proportion of continental material would need to be present in the mantle (Hauri & Hart 1993). Such large amounts of continental material would then completely dominate the Sr- and Nd-isotope signatures of OIBs. Because most OIBs have distinctly non-continental Sr- and Nd-isotope ratios, the enriched components in hotspots must be dominated by mafic crust, most likely derived from ancient oceanic lithosphere.

Recycled oceanic crust, identified by its high $^{187}\text{Os}/^{188}\text{Os}$ ratio and stored in the deep mantle in the sources of oceanic hotspots, is likely to represent the reservoir of rhenium-enriched material that balances the depletion of rhenium in the upper mantle. As outlined in § 3*a*, if this material had a composition similar to average MORB (1 ppb Re), then the amount needed to balance the upper-mantle rhenium depletion amounts to 5–10% of the mass of the mantle. Using the estimate of $2.56 \times 10^{17} \text{ g yr}^{-1}$ for the global hotspot flux (Sleep 1990), we can estimate that this reservoir is cycled through hotspots on a time-scale of 800–1600 million years.

The preservation of a reservoir of recycled oceanic crust has important implications for geochemical mass-balance estimates. With a composition similar to MORB, such a reservoir would sequester 35–80% of the Earth's budget of Sr and Nd. Together with the continental crust, the existence of a deep-mantle reservoir of stored oceanic crust would require the depletion of nearly the entire mantle, making the preservation of a primitive, undifferentiated mantle component difficult.

(d) Osmium isotopes and mantle components

The chemical heterogeneity of the Earth's mantle as expressed in the isotopic variability of Sr, Nd and Pb in oceanic basalts has been well documented (see Hart 1988). This variability has been described by a small number of chemical 'end members' which define the extremes in the isotopic data for oceanic basalts. Using the terminology of Zindler & Hart (1986) and Hart *et al.* (1992), five mantle end members have been suggested. Two of these end members have Sr- and Nd-isotope signatures of depletion (DMM, depleted MORB mantle; FOZO, depleted mantle with high $^3\text{He}/^4\text{He}$), while the remaining three end members have isotopic signatures of enrichment (EM1 and EM2, enriched in Rb/Sr and Nd/Sm; HIMU, enriched in (U+Th)/Pb). Isotopic compositions intermediate to these end members can be explained by mixing, and several mixing relationships have been delineated (figure 6; see also Hart 1988; Hart *et al.* 1992; Hauri *et al.* 1994).

The distinction between ‘depleted’ (DMM, FOZO) and ‘enriched’ (EM1, EM2, HIMU) mantle end members is emphasized in the $^{187}\text{Os}/^{188}\text{Os}$ data for abyssal peridotites and OIBs (Os data for MORBs are not included in this comparison; see § 3 *b*). The depleted DMM and FOZO components both have depleted $^{187}\text{Os}/^{188}\text{Os}$ ratios, while the enriched end members, EM1, EM2 and HIMU, have elevated $^{187}\text{Os}/^{188}\text{Os}$. Keeping in mind the distinct Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios displayed by peridotites and mafic rocks from the mantle, the Os isotope signatures of the mantle end members strongly suggest that the depleted components (DMM, FOZO) are composed of peridotite, while the enriched components (EM1, EM2, FOZO) contain a significant fraction (greater than 10%) of mafic material, most likely recycled oceanic crust. Oxygen isotope data on many of these end members support this possibility (Eiler *et al.* 1997). The variability of Sr, Nd and Pb isotopes among the enriched hotspot components can be explained by the presence or absence of a minor sedimentary component associated with recycled oceanic crust.

When the OIB data are examined as individual hotspots, most hotspots are demonstrated to be isotopically variable. The data for such hotspots are consistent with two-component mixing, with FOZO (not DMM) as one component and an enriched component as the other. Indeed, all of the enriched hotspot components have elevated $^{187}\text{Os}/^{188}\text{Os}$, suggesting that recycled oceanic crust is a major component of most hotspots. In addition, the presence of FOZO as a depleted component in hotspots worldwide suggests that it is a volumetrically important reservoir. The data are important in demonstrating that a primitive, undifferentiated reservoir such as the BSE is not an identifiable component in any of the mixing relationships. It is unlikely that such a reservoir exists in the mantle (van Keken *et al.* 2002).

(e) Core–mantle exchange

Due to their siderophile chemistry, *ca.* 99% of the Earth’s budget of rhenium and osmium resides in the core, with the result that the Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios of the bulk core are very similar to those of the bulk Earth and carbonaceous chondrites. Solidification of the inner core could, however, change the Re/Os ratio of the liquid outer core and thus its $^{187}\text{Os}/^{188}\text{Os}$ ratio. A small addition of metal from the outer core to the mantle could strongly influence the $^{187}\text{Os}/^{188}\text{Os}$ ratio of the resulting mixture and any basalt derived therefrom. This possibility has been discussed by Walker *et al.* (1995) and Brandon *et al.* (1999).

Does the Earth’s core contribute to the Os isotopic heterogeneity of the mantle? The bulk of the evidence suggests not. The model proposed by Brandon *et al.* (1999) requires a very specific set of circumstances, including formation of the inner core very early in Earth’s history, a very specific sense of siderophile-element fractionation during formation of the inner core, isotopic disequilibrium between the inner and outer core persisting for the age of the Earth, and a specified flux of Os from the core to the mantle. Solid-metal–liquid-metal fractionations and the direction and magnitude of core–mantle Os fluxes at core pressures have not been determined and are difficult even to estimate, and cogent arguments exist concerning the young age of the Earth’s inner core (e.g. Labrosse *et al.* 2001). Measured oxygen fugacities of peridotites and mantle-derived basalts are too high to permit the stabilization of iron metal in the mantle. While the possibility of core–mantle exchange awaits further tests, the Re–Os isotopic heterogeneity of the Earth’s mantle is easily explained

by observable phenomena that are the result of the plate-tectonic cycle, and this conclusion is consistent with a wide variety of complementary geochemical evidence.

4. Conclusion

The rhenium–osmium isotope system possesses a unique relationship with the partial-melting process, unlike any other radiogenic isotope pair. The formation and segregation of melt from the mantle results in distinct Re/Os ratios for residual peridotites and mantle-derived magmas that do not overlap. With time, the Re/Os fractionations characteristic of partial melting result in low $^{187}\text{Os}/^{188}\text{Os}$ ratios for peridotites and high $^{187}\text{Os}/^{188}\text{Os}$ ratios for mafic rocks, with almost no overlap between these two rock types. The opposite and complementary $^{187}\text{Os}/^{188}\text{Os}$ ratios of peridotites and mafic rocks are best observed in mantle-derived samples from the subcontinental lithosphere. The lithologic variability of the subcontinental mantle, and its relationship to Re/Os fractionation and $^{187}\text{Os}/^{188}\text{Os}$ ratios, is likely to provide a good analogy to the lithologic variation of the convecting mantle. The co-existence of mantle peridotite and pyroxene-rich mafic components in the convecting mantle is strongly suggested by the differences in $^{187}\text{Os}/^{188}\text{Os}$ ratios between seafloor peridotites and hotspot basalts, and the relationships between $^{187}\text{Os}/^{188}\text{Os}$ and other isotopes (Sr, Nd, Pb, O) suggest that most of the mafic components in the convecting mantle originate from ancient subducted oceanic crust. A significant fraction (5–10%) of the convecting mantle must consist of recycled oceanic crust in order to balance the upper mantle rhenium depletion recorded by the low $^{187}\text{Os}/^{188}\text{Os}$ ratios of abyssal peridotites. The presence of such a reservoir has important implications for isotopic and trace-element mass-balance estimates, and suggests that the entire mantle has been depleted to form continental and oceanic crust. These inferences are consistent with the absence of an identifiable primitive mantle component in oceanic basalts, and the widespread observation of depleted mantle components at both mid-ocean ridges and hotspots.

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