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# Critical evaluation of Re–Os and Pt–Os isotopic evidence on the origin of intraplate volcanism

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## Abstract

Evaluation of Re–Os and Pt–Os isotope systematics indicates that the mantle plume model does not provide a unique explanation of the  $^{187}\text{Os}/^{188}\text{Os}$ – $^{186}\text{Os}/^{188}\text{Os}$  isotopic variation in intraplate volcanic rocks. The low Os contents of ocean floor basalt and sediment compositions results in the amount of recycled crust (up to 55%) required in a plume to explain the range in  $^{187}\text{Os}/^{188}\text{Os}$ , being unrealistically high unless non-equilibrium melting conditions are invoked. The low Pt content of MORB also limits the Pt/Os ratio of recycled crust, requiring plume models to resort to interaction with the outer core to explain supra-chondritic  $^{186}\text{Os}/^{188}\text{Os}$  ratios. Generation of the sources of intraplate volcanism by mixing of sediment into the mantle similarly requires high amounts (30–50%) of crustal materials. Non-equilibrium melting regimes can be avoided when the sources for intraplate volcanism are formed by metasomatic processes at shallow level in the mantle. Wet-spot compositions formed by fluid metasomatism at convergent margins could produce the range of  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  signatures in intraplate volcanism over 2 Gyrs if the fluid was derived principally from the slab sediment component and the Pt/Os and Re/Os ratios of the hydrous peridotite remained unmodified. However, the most feasible method of generating supra-chondritic  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  is from partitioning of platinum group elements into pyroxenites precipitated from Mg-rich melts. Isotopic compositions of  $^{186}\text{Os}/^{188}\text{Os} = 0.119850$ ,  $\gamma_{\text{Os}} = +10$  could be generated from depleted mantle compositions in 150 Myrs in an oceanic perisphere domain containing 60–70% pyroxenite veins, or in a continental mantle section containing as little as 15% pyroxenite over 2 Gyrs. Osmium isotope systematics therefore do not prove the mantle plume over alternative models, as illustrated for the Columbia River Basalt Group, where  $^{187}\text{Os}/^{188}\text{Os}$  ratios of up to 0.144 in the least crustally contaminated basalts can be explained with a source containing 15–35% Mesozoic pyroxenite.

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## 1. Introduction

Over the last three decades mantle geodynamics has developed to the stage where models for the origin of intraplate volcanism are dominated by concepts of hotspots and mantle plumes. The predominance of the plume model owes much to noble gas data which has generally been interpreted to mandate a primitive, lower mantle component in the source of such volcanism (e.g. Kurz et al., 1987; Kellogg and Wasserburg, 1990). However, the Re–Os and Pt–Os isotope systems, based on the  $\beta$ -decay of  $^{187}\text{Re}$  to  $^{187}\text{Os}$  and the  $\alpha$ -decay of  $^{190}\text{Pt}$  to  $^{186}\text{Os}$ , respectively, have played a major role in supporting established concepts regarding mantle plumes. In particular, suprachondritic  $^{187}\text{Os}/^{188}\text{Os}$  ratios in ocean island basalts ( $\gamma\text{Os}$  values up to +18 in samples not affected by sediment contamination; Hauri and Hart, 1993; Reisberg et al., 1993; Widom et al., 1999) have been taken to confirm the presence of recycled oceanic crust in the sources of intraplate volcanism (e.g. Shirey, 1994; Hauri and Hart, 1997; Marcantonio et al., 1995; Lassiter and Hauri, 1998). Likewise,  $^{186}\text{Os}/^{188}\text{Os}$  ratios of up to 0.119850 in Hawaiian picrites have been taken as evidence for interaction of plume sources with the outer core (Walker et al., 1995; Brandon et al., 1998, 1999a) thereby supporting an ultra-deep origin for this category of volcanism. Interpretations of the noble gas data are not unique however as has been addressed by Anderson (1998a,b, 2000). Important conflicts have also arisen with regard to the Os isotope systematics. Recent studies (e.g. Schiano et al., 1997) have demonstrated MORB to have an order of magnitude less Os than previously thought, and that platinum group elements (PGE) can be lost to fluids in the subduction zone environment (Brandon et al., 1996, 1999b; McInnes et al., 1999; Borg et al., 2000). The combination of these effects is to moderate the Os isotopic evolution of a plume-source, thereby requiring the percentages of recycled materials in bulk mixing calculations to be significantly greater than estimated from other geochemical evidence (Becker, 2000). To avoid this problem, Becker (2000) proposed that the mixing models were in error, and that Os isotope systematics could be governed by non-equilibrium melting processes. Such explanations would however appear inconsistent with the role for mantle peridotite indicated by the high MgO and Os contents of most intraplate volcanic rocks relative to recycled crustal components. The alternative approach is to consider that the bulk mixing calculations are valid and that it is the plume models that are flawed. The purpose of this paper is therefore to evaluate how the Os isotopic signatures could be generated by alternative processes at shallow levels in the mantle, thereby testing whether the plume model provides a unique explanation for the range of  $^{186}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  found in intraplate volcanic rocks.

## 2. Modelling: background

The plume model invokes vertical introduction of thermally anomalous source material for intraplate volcanism (Fig. 1a). Alternative models are based on the source material having a lower solidus temperature than the surrounding mantle peridotite, as in the “wet spot” concept of Bonatti (1990). In the perisphere model of Anderson (1995, 1996) (Fig. 1b), the sources are created in situ by mixing of sediment into the shallow mantle or by metasomatic processes, to form an enriched layer between the MORB-source mantle and the lithosphere. In the differential rotation model of Smith and Lewis (1999a), the source material is metasomatised continental

mantle or oceanic mantle accreted to, and aged as part of the continental mantle, which is later eroded and displaced laterally by mantle flow (Fig. 1c). Although the plume and alternative models differ greatly with regard to the ultimate depth of the source materials, all share a connection with processes at convergent margins, as it is in the subduction zone environment that important modifications are made to the composition of recycled material, sediment delaminated from the slab, and fluid/melt metasomatism of the mantle wedge takes place (Fig. 2). The starting

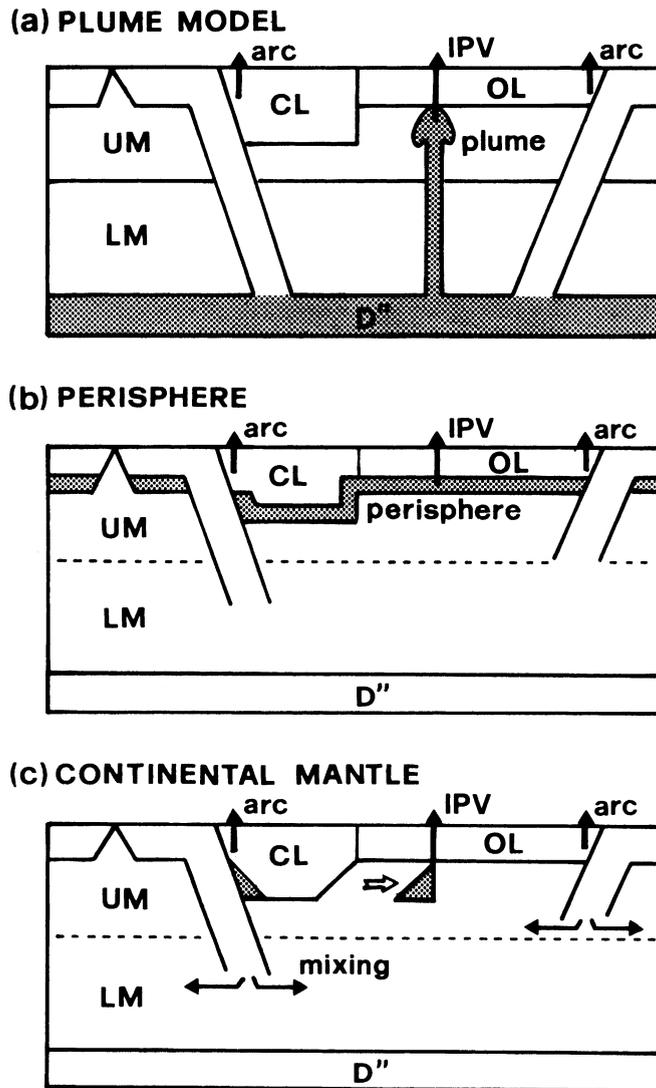


Fig. 1. Models for the origin of the source materials (shaded) of intraplate volcanism: (a) mantle plume model of Hofmann and White (1982), (b) perisphere model of Anderson (1995, 1996), (c) differential rotation model of Smith and Lewis (1999a,b). Models (b) and (c) both invoke formation of the sources of intraplate volcanism complementary to the generation of arc volcanism as illustrated in Fig. 2. Abbreviations: IPV, intraplate volcanism; CL, continental lithosphere; OL, oceanic lithosphere; LM, lower mantle; UM, upper mantle.

components to be considered in modelling such processes are the peridotite of the oceanic lithosphere and mantle wedge, and the basaltic layer of the oceanic crust and its overlying sedimentary veneer. Compositions for these components are summarised in Table 1.

For simplicity, mantle wedge and lithosphere are assumed to have 3.3 ppb Os, 0.27 ppb Re, 6.54 ppb Pt similar to upper mantle abundances, and a depleted mantle isotopic composition of  $\gamma_{\text{Os}}(0\text{Ma}) = -3$ ,  $^{186}\text{Os}/^{188}\text{Os} = 0.119834$  corresponding to the median values for samples from oceanic peridotites in Brandon et al. (1998, 2000). Basaltic oceanic crust is assumed to have 1.0 ppb Re, 0.0075 ppb Os, and  $\gamma_{\text{Os}}(0\text{Ma}) = +11.9$ , corresponding to an average of MORB compositions reported by Schiano et al. (1997). Unfortunately, very little Pt data exists for basaltic crust, and a range of compositions is used in the calculations. MORB samples analysed by Oguri et al. (1999) from the Mid Atlantic Ridge gave an average of 0.09 ppb Pt, slightly higher Pt contents (0.4–1.2 ppb) were reported for gabbroic samples (McInnes et al., 1999; Blusztajn et al., 2000), while the highest Pt abundances (3 ppb average with values up to 15 ppb) have been reported for Early Proterozoic MORB-like basalts in the Chukotat Group of the Cape Smith fold belt (Barnes and Picard, 1993). Sediment compositions corresponding to the average upper continental crust of Saal et al. (1998) and the average of metalliferous sediments from the Troodos ophiolite reported by Ravizza et al. (2001), are used to represent continental-derived and oceanic sediment, respectively. In consideration of the likelihood of greater thicknesses of sediment on oceanic crust near continental margins compared to intra-oceanic environments, the basalt:sediment ratio is assumed to be 90:10 in calculations using the upper crustal composition and 95:5 in calculations using the metalliferous sediment composition.

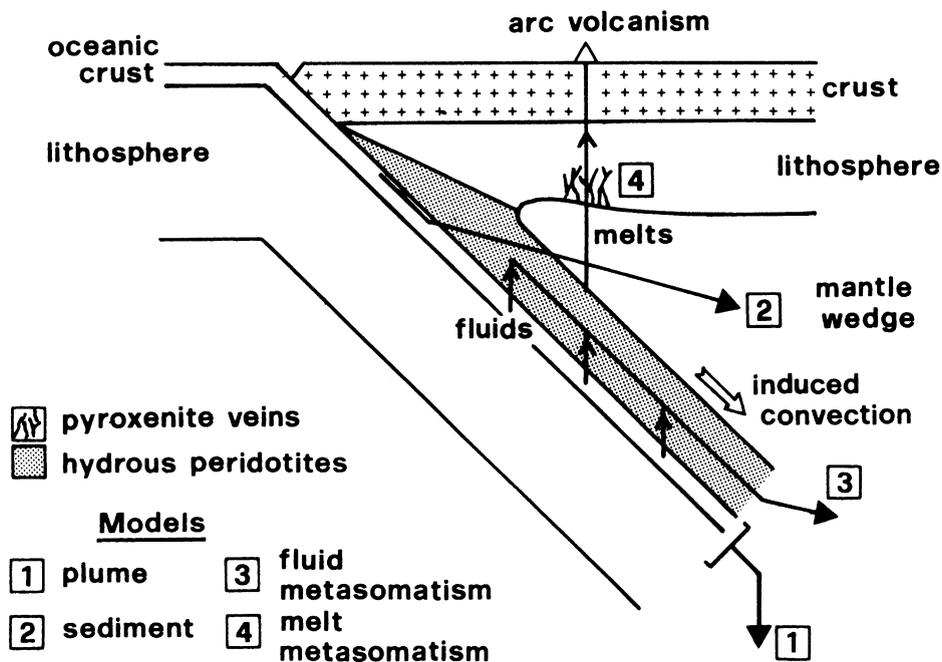


Fig. 2. Schematic depiction of a subduction zone illustrating formation of the sources of intraplate volcanism according to plume, sediment mixing, fluid metasomatism, and melt metasomatism models.

Crustal and mantle reservoirs are assumed to have evolved from a chondritic reservoir over 3 Ga as depicted in Fig. 3. Mixing calculations are performed for time periods of 2 Gyrs in plume and continental mantle-source models, and 150 Myrs in perisphere models where it is considered the lifetime of the domain would be comparable to that of the oceanic crust. Mixing models are required to produce realistic Os abundances in the source compositions (Fig. 4), along with the range of  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  variation found in intraplate volcanic rocks (Fig. 5). Partitioning of Os into the residue on melting constrains the source materials to possess higher Os contents than the most refractory compositions seen in intraplate volcanic rocks, such that the range of Re/Os, Pt/Os ratios suitable for evolution to radiogenic  $^{186}\text{Os}/^{188}\text{Os}$  and  $^{187}\text{Os}/^{188}\text{Os}$  is limited as illustrated by the shaded fields in Fig. 4.

### 3. Modelling

#### 3.1. Plume models

The most common variant of the plume model envisages that subducted oceanic crust is stored in a thermal boundary layer at the core-mantle boundary or base of the upper mantle for time periods of around 2 Gyrs (e.g. Hofmann and White, 1982; Becker, 2000). Interaction of plume sources with the outer core was discussed in detail by Brandon et al. (1998, 1999a) but is reconsidered here using a lower Os content for MORB and considering loss of elements to slab-derived fluids. Brandon et al. (1998, 1999a) also assumed the crustal components to mix with a plume-source mantle having a  $\gamma\text{Os}(0\text{Ma})$  value of +3, whereas in the model in Fig. 5a, the mantle

Table 1  
Present day compositions of components used in modelling

| Component              | Os<br>ppb           | Re<br>ppb         | Pt<br>ppb          | $\frac{\text{Pt}}{\text{Re}}$ | $\gamma\text{Os}$<br>(0Ma) | $\frac{^{186}\text{Os}}{^{188}\text{Os}}$ |
|------------------------|---------------------|-------------------|--------------------|-------------------------------|----------------------------|---|
| Depleted mantle        | 3.30 <sup>a</sup>   | 0.27 <sup>a</sup> | 6.54 <sup>a</sup>  | 24.2                          | −3.0 <sup>a</sup>          | 0.119834 <sup>a</sup>                     |
| Very depleted mantle   | 3.30 <sup>e</sup>   | 0.05 <sup>e</sup> | 2.00 <sup>e</sup>  | 40.0                          | −10.0 <sup>e</sup>         | 0.119834 <sup>e</sup>                     |
| MORB                   | 0.0075 <sup>b</sup> | 1.00 <sup>b</sup> | 0.09 <sup>c</sup>  | 0.09                          | −3.0 <sup>e</sup>          | 0.119834 <sup>e</sup>                     |
|                        |                     |                   | 3.00 <sup>d</sup>  | 3.00                          |                            |   |
| Upper crust            | 0.05 <sup>f</sup>   | 0.40 <sup>f</sup> | 2.50 <sup>a</sup>  | 6.25                          | +1409 <sup>f</sup>         | 0.120064 <sup>a</sup>                     |
| Metalliferous sediment | 0.24 <sup>g</sup>   | 0.14 <sup>g</sup> | 13.7 <sup>g</sup>  | 98.2                          | +336 <sup>g</sup>          | 0.119887 <sup>e</sup>                     |
| Clinopyroxenite        | 0.32 <sup>h</sup>   | 2.27 <sup>h</sup> | 84.4 <sup>h</sup>  | 37.2                          | +881 <sup>e</sup>          | 0.120598 <sup>e</sup>                     |
| Orthopyroxenite        | 1.06 <sup>h</sup>   | 4.18 <sup>h</sup> | 211.1 <sup>h</sup> | 50.5                          | +494 <sup>e</sup>          | 0.120417 <sup>e</sup>                     |

Where  $\gamma\text{Os} = [(\frac{^{187}\text{Os}}{^{188}\text{Os}})_{\text{sample}} / (\frac{^{187}\text{Os}}{^{188}\text{Os}})_{\text{SCHUR}} - 1] \times 100$ .

<sup>a</sup> Brandon et al. (1996, 1998, 2000).

<sup>b</sup> Schiano et al. (1997).

<sup>c</sup> Oguri et al. (1999).

<sup>d</sup> Barnes and Picard (1993).

<sup>e</sup> Estimated in this study.

<sup>f</sup> Saal et al. (1998).

<sup>g</sup> Ravizza et al. (2001).

<sup>h</sup> Edwards (1990).

component is represented by the oceanic lithosphere of the subducted slab. Loss of elements is assumed to take place only from the crustal layers, so the peridotite component undergoes little change in isotopic composition, evolving to present day  $\gamma_{Os} = -1.6$ ,  $^{186}Os/^{188}Os = 0.119834$  over 2 Gyrs. Despite losses of Re and Pt from the basaltic and sedimentary layers of the slab, the crustal components evolve to suprachondritic isotopic compositions, but the increase in  $^{186}Os/^{188}Os$  is much less than for  $^{187}Os/^{188}Os$  on account of the long half-life and low isotopic

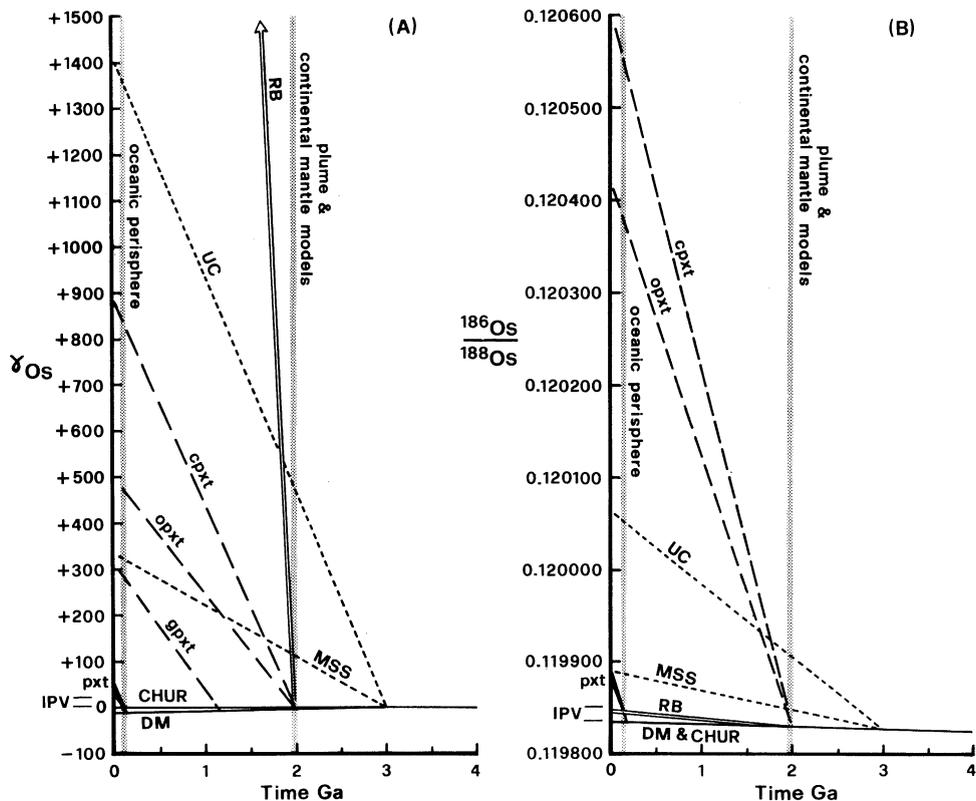


Fig. 3. Re–Os and Pt–Os isotopic evolution lines for components (CHUR: chondrite uniform reservoir, DM: depleted mantle, MSS: metalliferous sediment-source, UC: upper crust, RB: recycled basaltic crust) used in mixing calculations in this study, relative to present day isotopic compositions of intraplate volcanic rocks (IPV). Evolution lines were calculated using  $\lambda^{187}Re = 1.666 \times 10^{-11} \text{ y}^{-1}$  (Smoliar et al., 1996) and  $\lambda^{190}Pt = 1.542 \times 10^{-12} \text{ y}^{-1}$  (Walker et al., 1997), from Re, Pt and Os contents and isotopic compositions given in Table 1. The CHUR Re–Os evolution curve is from Walker et al. (1989), with  $^{187}Os/^{188}Os(0\text{Ma}) = 0.12757$ , and  $^{187}Re/^{188}Os = 0.3972$ . The ages of DM and UC reservoirs are assumed to be 3.0 Ga. The isotopic composition of metalliferous sediment is assumed to have been proportional to that of the continental crust through time, giving growth curves (MSS) representing an average for crustal components contributing to this type of sediment. Shaded vertical lines indicate timescales available for isotopic evolution in plume, continental mantle, and perisphere models. Opxt and cpxt are evolution lines for orthopyroxenite and clinopyroxenite compositions formed with DM isotopic compositions at 2 Ga and having comparable Re/Os and Pt/Os ratios to averages of compositions from the Bay of Islands ophiolite (Table 1). Fields labelled pxt show the ranges for similar pyroxenite compositions in an oceanic perisphere domain. The isotopic evolution of garnet pyroxenite DW236 (labelled gpxt) from Becker et al. (2000) is illustrated for comparison.

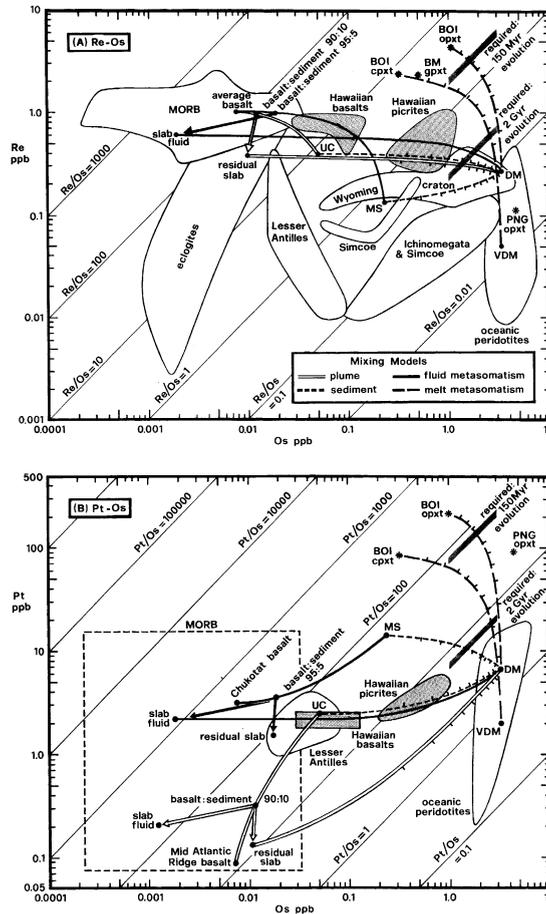


Fig. 4. Abundances of Re, Pt and Os in crustal and mantle rocks: MORB (Schiano et al., 1997), eclogites (Becker, 2000), Hawaiian basalts and picrites (Brandon et al., 1998; Bennett et al., 2000), Lesser Antilles andesites and picrites (Pearson and Woodland, 2000), oceanic abyssal peridotites (Roy-Barman and Allègre, 1994; Brandon et al., 2000; Pearson and Woodland, 2000; Tsuru et al., 2000), arc xenoliths (Simcoe and Ichinomegata localities: Brandon et al., 1996, 1999b) continental mantle (Wyoming province: Carlson and Irving, 1994). The Pt–Os range for Hawaiian basalts was constructed by combining the Os data of Brandon et al. (1999a) with the Pt abundances given in Oguri et al. (1999). Similarly, the Pt–Os range for MORB was constructed from the Os variation noted by Schiano et al. (1997) with ranges of Pt given by Barnes and Picard (1993) and Oguri et al. (1999), and is depicted by a dashed boundary to reflect the uncertainty arising from the limited available Pt data. The depleted mantle (DM) composition is used to represent mantle wedge and lithosphere in the mixing calculations. VDM is a more-depleted harzburgite or dunite composition. UC is the average upper crustal composition of Saal et al. (1998). MS is an average of metalliferous sediment compositions (excluding the anomalously Re-enriched sample UM84) from the Troodos ophiolite reported by Ravizza et al. (2001). Opxt, cpxt and gpxt are orthopyroxenite, clinopyroxenite, and garnet pyroxenite compositions from sections of oceanic lithosphere preserved in the Bay of Islands ophiolite (BOI; Edwards, 1990), Papua New Guinea (PNG; McInnes et al., 1999), and Bohemian Massif localities (BM; Becker et al., 2001). Also shown are mixing curves (tick marks indicate 10% increments) illustrating plume, sediment, fluid metasomatism and melt metasomatism models. Shading indicates Re/Os and Pt/Os ratios required for generation of the most radiogenic Os isotopic compositions observed in intraplate volcanic rocks ( $^{186}\text{Os}/^{188}\text{Os} = 0.119850$ ,  $\gamma_{\text{Os}} = +18$ ) over time periods of 150 Myr (oceanic perisphere model) and 2 Gyr (plume and continental mantle models) assuming the sources of such volcanism contained 1 to 3 ppb Os.

abundance of  $^{190}\text{Pt}$ , and the low Pt/Re ratio of MORB (Fig. 3). The mixing curves (Fig. 5a) are therefore characterised by low  $^{186}\text{Os}/^{188}\text{Os}$  over the range of  $^{187}\text{Os}/^{188}\text{Os}$  ratios found in OIB, similar to in the model of Brandon et al. (1998, 1999a). Furthermore, because of the low Os content of the basaltic component of the slab (Fig. 4), large amounts of recycled crust are necessary to generate the  $^{187}\text{Os}/^{188}\text{Os}$  range of ocean island basalts. The  $^{187}\text{Os}/^{188}\text{Os}$  ratios of Hawaiian picrites ( $\gamma\text{Os}$  up to +9) require 10–40% crustal component in a plume, while the  $\gamma\text{Os}$  values of

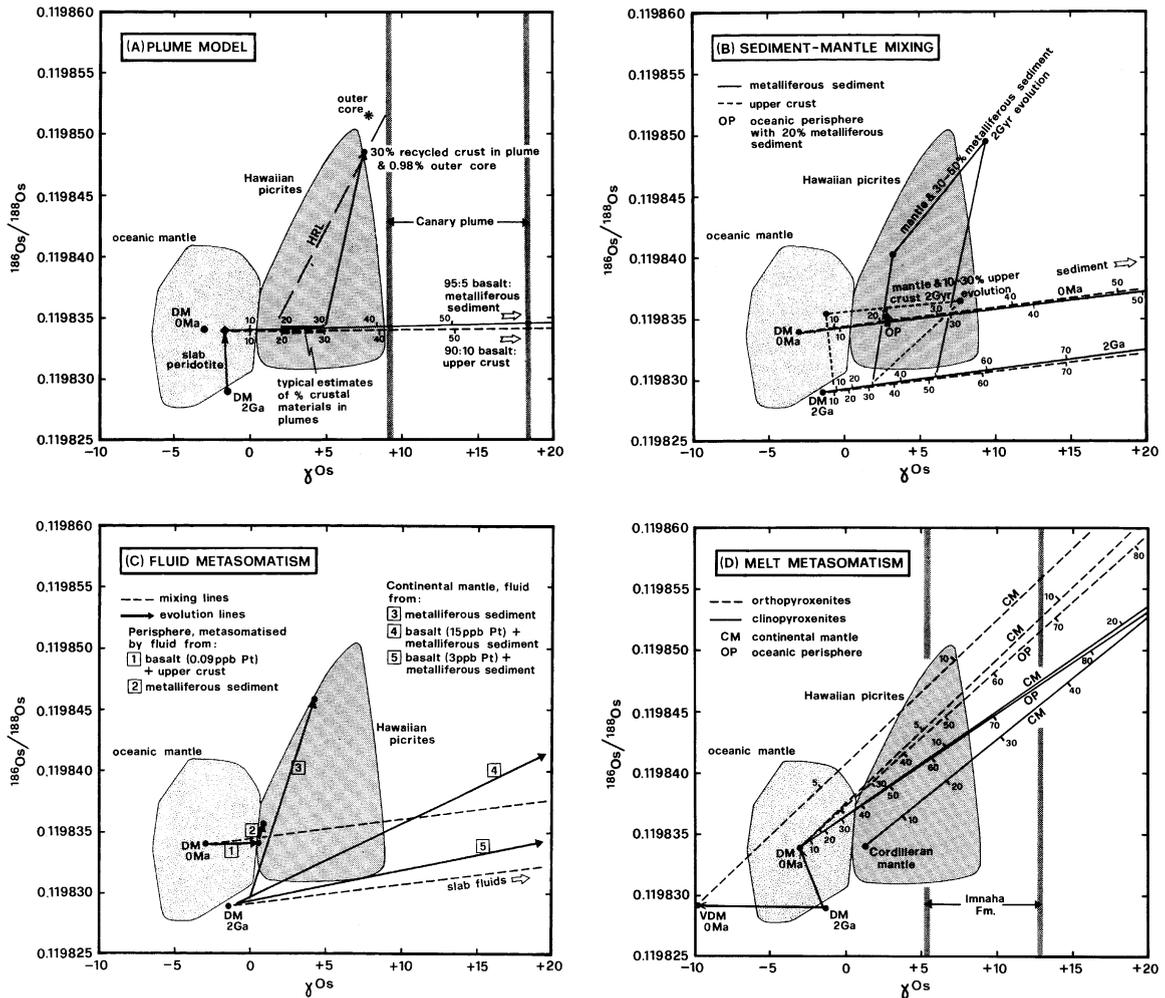


Fig. 5. Mixing models for the generation of  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  signatures in intraplate volcanic rocks: (A) plume model, (B) sediment mixing model, (C) fluid metasomatism, (D) pyroxenite model. Tick marks indicate increments of crustal or metasomatic components added to peridotite compositions. The field for oceanic peridotite, which is taken to define the depleted mantle (DM) composition, is from Brandon et al. (1998, 2000). The field for Hawaiian picrites is from Brandon et al. (1998, 1999a), while the ranges of  $^{187}\text{Os}/^{188}\text{Os}$  in the Canary plume and Imnaha formation of the Columbia River Basalt Group are from Widom et al. (1999) and Chesley and Ruiz (1998), respectively. HRL is the Hawaiian reference line of Brandon et al. (1998). Composition VDM (very depleted mantle) was calculated assuming isotopic evolution from DM with element abundances in Table 1.

ocean island basalts would require 40–55% crustal component (Fig. 5a). Although the percentages are not as high as the 80–90% recycled crust estimated by Becker (2000), they are nonetheless almost double the estimates of 20–30% made from other geochemical evidence.

Non-equilibrium melting regimes might potentially reduce the amounts of recycled crust required in plume models as discussed by Becker (2000), but isotopic compositions would still lie along the same mixing curves in Fig. 5a. Plume models must therefore explain the  $^{186}\text{Os}/^{188}\text{Os}$  ratios of up to 0.119850 found in Hawaiian picrites by interaction with the outer core (Brandon et al., 1998, 1999a). Outer core forming at 4.3 Ga has been estimated by Brandon et al. (1999a) to have  $\gamma\text{Os} = +7.95$ ,  $^{186}\text{Os}/^{188}\text{Os} = 0.1198515$ , and an Os content of 1112 ppb. Addition of 0.98% of such material would increase the  $^{186}\text{Os}/^{188}\text{Os}$  ratio of a plume containing 30% recycled crust to 0.119848, in addition to raising its  $\gamma\text{Os}$  value by approximately 2 units (Fig. 5a). However, the model can not produce compositions more radiogenic than the highest outer core estimate of  $\gamma\text{Os} = +10$ , such that non-equilibrium melting regimes would still be required to generate  $\gamma\text{Os}$  of +9 to +18 found in other intraplate volcanic rocks such as from the Canary islands (Fig. 5a). Unfortunately, non-equilibrium melting models also encounter problems, as the partial melting of an eclogite to yield a siliceous melt which then reacts with peridotite to shield later melts from equilibration with mantle compositions as envisaged by Becker (2000), would be unlikely to yield the high MgO, Ni and Cr contents which characterise some intraplate volcanic rocks with radiogenic  $^{187}\text{Os}/^{188}\text{Os}$ . Other possibilities for reducing the percentages of recycled materials by invoking subduction of unaltered basaltic crust which had lost a lesser percentage of PGE to the slab fluid (Becker et al., 2000), encounter difficulties with regard to Pb isotope systematics as the recycled material would be unlikely to possess the required U/Pb ratios to evolve to HIMU isotope compositions (Becker, 2000).

### 3.2. *Mixing of sediment into the mantle*

Formation of the sources for intraplate volcanism as a result of mixing the sediment layer of the oceanic crust into the mantle at convergent margins has been invoked in a number of studies (e.g. Tu et al., 1991; Molzahn et al., 1996) and is an important feature of the perisphere model on account of the potential of sediment to impart ancient isotopic signatures directly onto the mantle during a relatively young event. However, in bulk mixing calculations the mechanism suffers similar difficulties to the plume model in that the low Os contents of crustal materials would require up to 50% sediment to produce the highest  $^{187}\text{Os}/^{188}\text{Os}$  ratios found in intraplate volcanic rocks (Fig. 5b). The mixing lines in  $^{186}\text{Os}/^{188}\text{Os}$ – $\gamma\text{Os}$  space likewise have flat trajectories and can not directly reproduce the high  $^{186}\text{Os}/^{188}\text{Os}$  found in picritic compositions. The effects of ageing a sediment-contaminated domain differ depending on sediment type (Fig. 5b), although neither of the sediment compositions considered here could generate radiogenic  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  compositions in the lifetime of an oceanic perisphere domain. A mantle domain contaminated with 30% of a sediment composition corresponding to average crust would evolve to  $\gamma\text{Os} = +8$ , but only  $^{186}\text{Os}/^{188}\text{Os} = 0.119836$  over 2 Gyrs, whereas the high Pt, low Re contents of metalliferous sediment would allow compositions of up to  $\gamma\text{Os} = +9$ ,  $^{186}\text{Os}/^{188}\text{Os} = 0.119850$  to be attained. However, the amounts of sediment required (up to 50%) in the source remain unrealistically high (Fig. 5b), as potential advantages from a longer evolution period are offset by the convergence of crustal and mantle isotopic evolution lines with age.

### 3.3. Fluid metasomatism

Geochemical similarities between intraplate basalts and compositions found toward the back-arc region in several arcs, raises the possibility of residual assemblages from arc volcanism at deeper levels in the mantle wedge becoming potential wetspot sources for intraplate volcanism (Smith and Lewis, 1999b). Metasomatism of the mantle wedge at convergent margins can be divided into at least two stages (e.g. Tatsumi and Eggins, 1995; Brandon et al., 1999b) (Fig. 2). In the first stage, fluids or melts released from the subducting slab react with the base of the mantle wedge to form a zone of hydrous peridotites above the slab. In the second stage, hydrous peridotite assemblages melt as they are dragged to greater depth by induced convection from the slab, releasing melts to metasomatise the overlying mantle wedge and lithosphere. Results from eclogites indicate that the crustal layers of the slab may lose up to 99% of their Re, with the average loss being approximately 60% (Becker, 2000). Although Os contents of eclogites overlap those of MORB (Fig. 4), some mobility is indicated by increases in  $^{187}\text{Os}/^{188}\text{Os}$  of mantle wedge xenoliths (Brandon et al., 1996, 1999b). Enrichments in PGE in metasomatised harzburgites from Papua New Guinea suggest the mobility of Pt may be similar to that of Re (McInnes et al., 1999), hence for modelling purposes it is assumed that the crustal part of the slab loses 60% of its Pt and Re, and 10% of its Os. Modern altered oceanic crust has  $^{187}\text{Os}/^{188}\text{Os}$  overlapping the range for intraplate volcanic rocks (Schiano et al., 1997), but as only the sediment component of the slab will have high  $^{186}\text{Os}/^{188}\text{Os}$ , fluid-mantle mixing lines are flat as in the plume and sediment mixing models (Fig. 5c). Although Re/Os and Pt/Os would be increased in the metasomatised peridotite, the long half life of  $^{190}\text{Pt}$  precludes evolution to high  $^{186}\text{Os}/^{188}\text{Os}$  over the lifetime of an oceanic perisphere domain. Increases in the Pt/Os ratio would be sufficient for metasomatised peridotite to evolve to  $^{186}\text{Os}/^{188}\text{Os} = 0.119850$  over 2 Gyrs, but only if the basaltic component of the slab had Pt within the higher range for MORB (Figs. 4 and 5c). The corresponding enrichment in Re would however produce  $\gamma\text{Os}$  values of +30 to +35 causing ancient metasomatised compositions to lie to the right of the Hawaiian picrite field. Isotopic evolution parallel to the Hawaiian reference line could be produced if a slab comprised unaltered basaltic crust which did not contribute to the PGE budget, overlain by metalliferous sediment which imparted high Pt/Re to the fluid (Fig. 5c). The isotopic evolution of the hydrous peridotite also depends on modifications to the Re/Os and Pt/Os ratios on partitioning of the elements into the melt phase during the mineralogical transformations amphibole-phlogopite-K richterite. However, assemblages formed at the end of a subduction regime might escape modification to their Pt/Os and Re/Os ratios and would be those more likely to involve subduction of young unaltered oceanic crust. A fluid derived predominantly from the sediment layer under such circumstances might therefore produce a zone of metasomatised peridotite which could evolve to radiogenic  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  signatures along a suture zone in a long-lived reservoir such as the continental mantle.

### 3.4. Melt metasomatism and pyroxenites

The shallow mantle may also be metasomatised by melts generated from the breakdown of hydrous peridotites or derived directly from the slab at convergent margins, and may also serve as a host for melt fractions from the asthenosphere during episodes of continental rifting (Smith and Lewis, 1999b). In mixing calculations, the effect of introducing melt compositions into the mantle

would be similar to mixing of basalt and peridotite in plume models. Several harzburgite and lherzolite xenoliths from the Simcoe, Ichinomegata and Bohemian Massif localities which may represent the products of melt metasomatism have suprachondritic  $^{187}\text{Os}/^{188}\text{Os}$  (Brandon et al., 1996, 1999b; McInnes et al., 1999; Becker et al., 2001), but the low Pt contents of most melts would make it unlikely that such assemblages could have sufficiently high Pt/Os to evolve to suprachondritic  $^{186}\text{Os}/^{188}\text{Os}$ . The fractional crystallisation products of melts, however, present a more favourable scenario. Ortho- and clino-pyroxenites found in mantle xenolith suites and ophiolite sections have been interpreted as products of the precipitation sequence olivine-orthopyroxene-clinopyroxene from Mg-rich melts such as boninites (Edwards, 1990). During such processes, Os may be removed from the melt in sulphides trapped within chromite and Pt removed as arsenides and incorporated into pyroxenes, whereas a relatively large fraction of Re may remain in the melt (Edwards, 1990; Peck and Keays, 1990). Pyroxenites from a range of localities including the fore-arc region of Papua New Guinea (McInnes et al., 1999), the Bohemian Massif (Becker et al., 2001) and Bay of Islands (Edwards, 1990) ophiolites thus have higher Pt contents but similar Re contents to volcanic rocks (Fig. 4). Consequently, the mixing lines between pyroxenite and mantle in Fig. 4b are much steeper than in the plume, sediment mixing and fluid metasomatism models, enabling metasomatised compositions to evolve to high  $^{186}\text{Os}/^{188}\text{Os}$ , but moderate  $^{187}\text{Os}/^{188}\text{Os}$ , over a comparatively short time scale (Fig. 3). Using average pyroxenite compositions from the Bay of Islands ophiolite (Table 1) as an example on account of the larger data set for this locality, it is calculated that pyroxenites could evolve from depleted mantle isotopic compositions to  $\gamma\text{Os}$  values between +31 and +65 and  $^{186}\text{Os}/^{188}\text{Os}$  ratios of 0.119878 to 0.119891 in 150 Myrs (Fig. 3). Mixing curves between such material and mantle peridotite would replicate the Os isotopic composition of Hawaiian picrites with 55 to 65% pyroxenite (Fig. 5d). Over a 2 Gyr period,  $^{186}\text{Os}/^{188}\text{Os}$  ratios of 0.120410 to 0.120600, and  $\gamma\text{Os}$  values of +500 to +885 could be attained (Fig. 3), reducing the amounts of pyroxenite required to less than 15% of the source in the continental mantle model (Fig. 5d). Pyroxenite would also satisfy requirements for high Os in the source, although a potential drawback is that the mixing models could produce higher Pt in the source than in the melt (Fig. 4b). However, the problem is easily resolved by invoking pyroxenite veining of a more depleted, dunite or harzburgite composition with low Pt and Re contents (VDM composition; Figs. 4 and 5d, Table 1). A dunite or harzburgite host would also be consistent with major element evidence (Francis, 1995) for equilibration of intraplate melts with refractory peridotite compositions. Further advantages of the model are that the high U/Pb and Th/Pb ratios of clinopyroxene (Meijer et al., 1990) would account for coupled radiogenic Os–HIMU Pb isotope signatures noted in intraplate basalts, whereas the low melting point of pyroxenites (Hirschmann and Stolper, 1996) would allow melting without the large thermal anomalies involved in the plume model.

### 3.5. *A pyroxenite-veined source for the Columbia River Basalt Group*

With the presently available data, the pyroxenite model offers the most viable alternative to the plume model. An example for which both types of sources have been proposed is the Columbia River Basalt Group (CRBG). Pyroxenites in the lithospheric section beneath the Columbia River province could have been produced by injection of melts during northward translation of accreted terranes along the North American continental margin during the Late Mesozoic

(Smith, 1992), or be cumulates from Early Mesozoic arc volcanism preserved when oceanic lithosphere was accreted to cratonic mantle to the east. Criticism of the pyroxenite model by Chesley and Ruiz (1998) focused on the He and Os isotopic composition ( $^3\text{He}/^4\text{He}$  ( $R/R_a$ ) = 11.0–12.2,  $^{187}\text{Os}/^{188}\text{Os}$  = 0.134–0.158; Dodson et al., 1997; Chesley and Ruiz, 1998) of samples from the Imnaha formation which contains most the primitive compositions in the CRBG. High  $^3\text{He}/^4\text{He}$  ratios may however reflect a depletion in  $^4\text{He}$  (Anderson, 1998a,b) particularly when volcanism is characterised by low He abundances as in the case of the CRBG where He contents ( $1 \times 10^{-9}$ – $3 \times 10^{-9}$  cc/g; Dodson et al., 1997) are up to an order of magnitude less than for typical ocean island basalts (e.g. Hawaiian basalts,  $2 \times 10^{-9}$ – $5 \times 10^{-8}$  cc/g; Kurz et al., 1987). The  $^3\text{He}/^4\text{He}$  ratios are also not statistically different from the depleted mantle average (Anderson, 2000), hence the He data does not mandate a lower mantle component. The range in  $^{187}\text{Os}/^{188}\text{Os}$  of the Imnaha basalts was argued by Chesley and Ruiz (1998) to require large amounts (30–60%) of unrealistically old ( $\sim 2.5$  Ga) pyroxenite in the source. However, the highest  $^{187}\text{Os}/^{188}\text{Os}$  ratio is found in the sample with lowest Os content, indicative of crustal contamination. The range of  $^{187}\text{Os}/^{188}\text{Os}$  for uncontaminated samples is therefore more likely from 0.134 to 0.144. Moreover, the mixing lines are controlled not by the composition of the pyroxenite which was the only composition varied by Chesley and Ruiz (1998), but by the  $^{187}\text{Os}/^{188}\text{Os}$  ratio and Os content of the host peridotite (Fig. 6). The  $^{187}\text{Os}/^{188}\text{Os}$  ratio of 0.110 assumed for the peridotite by Chesley and Ruiz (1998) is similar to values for depleted compositions from ancient cratonic mantle roots. Xenoliths representing continental mantle beneath equivalent crustal units farther north in the Cordillera (Carignan et al., 1996; Peslier et al., 2000) indicate a  $^{187}\text{Os}/^{188}\text{Os}$  ratio of 0.129 would be more appropriate. Lherzolites, harzburgites and dunites analysed by Carlson and Irving (1994) also suggest that regions of the cratonic mantle of the Wyoming province adjacent to the accreted terranes have  $^{187}\text{Os}/^{188}\text{Os}$  ratios up to 0.220. The concentration of 3.5 ppb Os used in the mixing

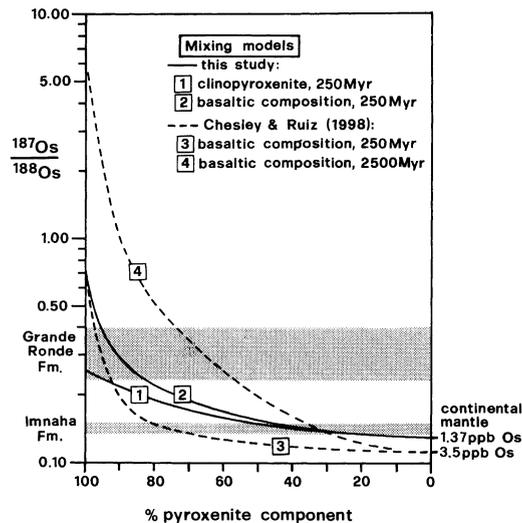


Fig. 6. Mixing model illustrating the amounts of pyroxenite required in the source of the Columbia River Basalt Group. Dashed lines show mixing curves between continental mantle ( $^{187}\text{Os}/^{188}\text{Os}$  = 0.110, 3.5 ppb Os) and pyroxenite components according to Chesley and Ruiz (1998). Solid lines illustrate mixing of the pyroxenite components with average Cordilleran mantle xenolith compositions ( $^{187}\text{Os}/^{188}\text{Os}$  = 0.129, 1.37 ppb Os) substituted for the continental mantle.

calculations by Chesley and Ruiz (1998) is also suspect as xenoliths from the Wyoming province and beneath the accreted terranes have average Os contents of 1.33 and 1.37 ppb Os, respectively (Carlson and Irving, 1994; Carignan et al., 1996; Peslier et al., 2000). Substituting a peridotite composition of  $^{187}\text{Os}/^{188}\text{Os} = 0.129$  and 1.37 ppb Os into the mixing calculation of Chesley and Ruiz (1998) produces the range of  $^{187}\text{Os}/^{188}\text{Os}$  for uncontaminated Imnaha basalts with as little as 20% of a basaltic pyroxenite composition (Fig. 6). Alternatively, a cumulate clinopyroxenite would evolve to a lower  $^{187}\text{Os}/^{188}\text{Os}$  ratio of 0.260, but as the Os content of pyroxenite cumulates is higher than for basaltic compositions (Fig. 4), the percentage of pyroxenite required (15–35%; Fig. 6) is still much lower than the estimates of Chesley and Ruiz (1998). Differences in pyroxenite composition would be expected to be reflected in Pt–Os systematics, with a source veined with a basaltic composition retaining depleted mantle-like  $^{186}\text{Os}/^{188}\text{Os}$ , whereas a cumulate-veined source is predicted to evolve to  $^{186}\text{Os}/^{188}\text{Os}$  ratios of up to 0.119843 (Fig. 5d). Hence, high  $^3\text{He}/^4\text{He}$  and  $^{187}\text{Os}/^{188}\text{Os}$  ratios, nor high  $^{186}\text{Os}/^{188}\text{Os}$  ratios should they be found, do not prove a plume origin over pyroxenite sources for the CRBG.

#### 4. Summary and conclusions

Alternatives to the plume model for the generation of the source materials of intraplate volcanism are mixing sediment into the mantle, formation of hydrous peridotite wetspot sources by fluid metasomatism, and melt metasomatism of the shallow mantle. Plume and sediment-mixing models share a common problem in that the low Os contents of basalt and sediment compositions results in unrealistically large amounts of crustal materials being required to explain the range of  $^{187}\text{Os}/^{188}\text{Os}$  ratios unless non-equilibrium melting is invoked. The sediment mixing model could explain elevated  $^{186}\text{Os}/^{188}\text{Os}$  ratios, but only with an ancient source contaminated with oceanic metalliferous sediment. The generation of radiogenic  $^{186}\text{Os}/^{188}\text{Os}$  compositions in the plume model is hindered by the low Pt content of the recycled basalt component, such that elevated  $^{186}\text{Os}/^{188}\text{Os}$  ratios can only be explained by interaction of plume sources with the outer core.

Requirements for non-equilibrium melting are avoided if the sources of intraplate volcanism are generated by metasomatic processes. The transfer of PGE to the mantle wedge by slab-derived fluids should impart sufficiently high Pt/Os ratios for hydrous peridotites to evolve to radiogenic  $^{186}\text{Os}/^{188}\text{Os}$ . However, unless the fluids were derived largely from a metalliferous sediment layer, the corresponding enrichment in Re would lead to higher  $^{187}\text{Os}/^{188}\text{Os}$  than seen in most intraplate volcanic rocks. In contrast, melt metasomatism can generate high Pt/Os but moderate Re/Os from the concentration of PGE into pyroxenites precipitated from Mg-rich melts. Isolation of pyroxenites in a long-lived reservoir such as the continental mantle would allow generation of the coupled  $^{186}\text{Os}/^{188}\text{Os}$ – $^{187}\text{Os}/^{188}\text{Os}$  signatures seen in intraplate volcanic rocks with as little as 15% vein material. Erosion or delamination of veined continental mantle into the asthenosphere could therefore produce a suitable source for intraplate volcanism without any requirement for deep recycling processes. Isotopic evolution of pyroxenites in a more transient domain such as an oceanic perisphere layer would also be feasible despite requiring larger amounts of pyroxenite. Os isotope systematics do not therefore prove the mantle plume model over alternatives involving the generation of source materials for intraplate volcanism at shallow levels in the mantle.

## References

- Anderson, D.L., 2000. The statistics and distribution of helium in the mantle. *International Geology Review* 42, 289–311.
- Anderson, D.L., 1998a. Helium paradoxes. *Proceedings of the National Academy of Sciences USA* 95, 4822–4827.
- Anderson, D.L., 1998b. A model to explain the various paradoxes associated with mantle noble gas geochemistry. *Proceedings of the National Academy of Sciences USA* 95, 9087–9092.
- Anderson, D.L., 1996. Enriched asthenosphere and depleted plumes. *International Geology Review* 38, 1–21.
- Anderson, D.L., 1995. Lithosphere, asthenosphere, and perisphere. *Reviews of Geophysics* 33, 125–149.
- Barnes, S.-J., Picard, C.P., 1993. The behaviour of platinum-group elements during partial melting, crystal fractionation, and sulphide segregation: an example from the Cape Smith fold belt, northern Quebec. *Geochimica Cosmochimica Acta* 57, 79–87.
- Becker, H., 2000. Re–Os fractionation in eclogites and blueschists and the implications for recycling of oceanic crust into the mantle. *Earth and Planetary Science Letters* 177, 287–300.
- Becker, H., Shirey, S.B., Carlson, R.W., 2001. Effects of melt percolation on the Re–Os systematics of peridotites from a Paleozoic convergent plate margin. *Earth and Planetary Science Letters* 188, 107–121.
- Becker, H., Jochum, K.P., Carlson, R.W., 2000. Trace element fractionation during dehydration of eclogites from high-pressure terranes and the implications for element fluxes in subduction zones. *Chemical Geology* 163, 65–99.
- Bennett, V.C., Norman, M.D., Garcia, M.O., 2000. Rhenium and platinum group element abundances correlated with mantle source components in Hawaiian picrites: sulphides in the plume. *Earth and Planetary Science Letters* 183, 513–526.
- Blusztajn, J., Hart, S.R., Ravizza, G., Dick, H.J.B., 2000. Platinum-group elements and Os isotope characteristics of the lower oceanic crust. *Chemical Geology* 168, 113–122.
- Bonatti, E., 1990. Not so hot ‘hot-spots’ in the oceanic mantle. *Science* 250, 107–111.
- Borg, L.E., Brandon, A.D., Clyne, M.A., Walker, R.J., 2000. Re–Os isotopic systematics of primitive lavas from the Lassen region of the Cascade arc, California. *Earth and Planetary Science Letters* 177, 301–317.
- Brandon, A.D., Snow, J.E., Walker, R.J., Morgan, J.W., Mock, T.D., 2000.  $^{190}\text{Pt}$ – $^{186}\text{Os}$  and  $^{187}\text{Re}$ – $^{187}\text{Os}$  systematics of abyssal peridotites. *Earth and Planetary Science Letters* 177, 319–335.
- Brandon, A.D., Norman, M.D., Walker, R.J., Morgan, J.W., 1999a.  $^{186}\text{Os}$ – $^{187}\text{Os}$  systematics of Hawaiian picrites. *Earth and Planetary Science Letters* 174, 25–42.
- Brandon, A.D., Becker, H., Carlson, R.W., Shirey, S.B., 1999b. Isotopic constraints on time scales and mechanisms of slab material transport in the mantle wedge: evidence from the Simcoe mantle xenoliths, Washington, USA. *Chemical Geology* 160, 387–407.
- Brandon, A.D., Walker, R.J., Morgan, J.W., Norman, M.D., Prichard, H.M., 1998. Coupled  $^{186}\text{Os}$  and  $^{187}\text{Os}$  evidence for core-mantle interaction. *Science* 280, 1570–1573.
- Brandon, A.D., Creaser, R.A., Shirey, S.B., Carlson, R.W., 1996. Osmium recycling in subduction zones. *Science* 272, 861–864.
- Carlson, R.W., Irving, A.J., 1994. Depletion and enrichment history of subcontinental lithospheric mantle: an Os, Sr, Nd and Pb isotopic study of ultramafic xenoliths from the northwestern Wyoming craton. *Earth and Planetary Science Letters* 126, 457–472.
- Carignan, J., Ludden, J., Francis, D., 1996. On the recent enrichment of subcontinental lithosphere: a detailed U–Pb study of spinel lherzolite xenoliths, Yukon, Canada. *Geochimica et Cosmochimica Acta* 60, 4241–4252.
- Chesley, J.T., Ruiz, J., 1998. Crust-mantle interaction in large igneous provinces: implications from the Re–Os isotope systematics of the Columbia River flood basalts. *Earth and Planetary Science Letters* 154, 1–11.
- Dodson, A., Kennedy, B.M., DePaolo, D.J., 1997. Helium and neon isotopes in the Imnaha basalt, Columbia River Basalt Group: evidence for a Yellowstone plume source. *Earth and Planetary Science Letters* 150, 443–451.
- Edwards, S.J., 1990. Harzburgites and refractory melts in the Lewis Hills massif, Bay of Islands ophiolite complex: the base-metals and precious-metals story. *Canadian Mineralogist* 28, 537–552.
- Francis, D., 1995. The implications of picritic lavas for the mantle sources of terrestrial volcanism. *Lithos* 34, 89–106.
- Hauri, E.H., Hart, S.R., 1993. Re–Os isotope systematics of HIMU and EMII oceanic island basalts from the South Pacific Ocean. *Earth and Planetary Science Letters* 114, 353–371.

- Hauri, E.H., Hart, S.R., 1997. Rhenium abundances and systematics in oceanic basalts. *Chemical Geology* 139, 185–204.
- Hirschmann, M.M., Stolper, E.M., 1996. A possible role for garnet pyroxenite in the origin of the “garnet signature” in MORB. *Contributions to Mineralogy and Petrology* 124, 185–208.
- Hofmann, A.W., White, W.M., 1982. Mantle plumes from ancient oceanic crust. *Earth and Planetary Science Letters* 57, 421–436.
- Kellogg, L.H., Wasserburg, G.J., 1990. The role of plumes in mantle helium fluxes. *Earth and Planetary Science Letters* 99, 276–289.
- Kurz, M.D., Garcia, M.O., Frey, F.A., O’Brien, P.A., 1987. Temporal helium isotopic variations within Hawaiian volcanoes: basalts from Mauna Loa and Haleakala. *Geochimica et Cosmochimica Acta* 51, 2905–2914.
- Lassiter, I., Hauri, E.H., 1998. Os-isotope variations in Hawaiian lavas; evidence for recycling of oceanic lithosphere in the Hawaiian plume. *Earth and Planetary Science Letters* 164, 483–496.
- Marcantonio, F., Zindler, A., Elliott, T., Staudigel, H., 1995. Os isotope systematics of La Palma, Canary Islands: evidence for recycled crust in the mantle source of HIMU ocean islands. *Earth and Planetary Science Letters* 133, 397–410.
- McInnes, B.I.A., McBride, J.S., Evans, N.J., Lambert, D.D., Andrew, A., 1999. Osmium isotope constraints on ore metal recycling in subduction zones. *Science* 286, 512–516.
- Meijer, A., Kwon, T.T., Tilton, G.R., 1990. U-Th-Pb partitioning behaviour during partial melting in the upper mantle: implications for the origin of the high mu components and the “Pb paradox”. *Journal of Geophysical Research* 95, 433–448.
- Molzahn, M., Reisberg, L., Wörner, G., 1996. Os, Sr, Nd, Pb, O isotope and trace element data from the Ferrar flood basalts, Antarctica: evidence for an enriched subcontinental lithospheric source. *Earth and Planetary Science Letters* 144, 529–546.
- Oguri, K., Shimoda, G., Tatsumi, Y., 1999. Quantitative determination of gold and the platinum-group elements in geological samples using improved NiS fire-assay and tellurium coprecipitation with inductively coupled plasma-mass spectrometry (ICP-MS). *Chemical Geology* 157, 189–197.
- Pearson, D.G., Woodland, S.J., 2000. Solvent extraction/anion exchange separation and determination of PGE’s (Os, Ir, Pt, Pd, Ru) and Re–Os isotopes in geological samples by isotope dilution ICP-MS. *Chemical Geology* 165, 87–107.
- Peck, D.C., Keays, R.R., 1990. Insights into the behaviour of precious metals in primitive, S-undersaturated magmas: evidence from the Heazlewood River complex, Tasmania. *Canadian Mineralogist* 28, 553–577.
- Peslier, A.H., Reisberg, L., Ludden, J.N., Francis, D., 2000. Os isotopic systematics in mantle xenoliths; age constraints on the Canadian Cordillera lithosphere. *Chemical Geology* 166, 85–101.
- Ravizza, G., Blusztajn, J., Pritchard, H.M., 2001. Re–Os systematics and platinum-group element distribution in metalliferous sediments from the Troodos ophiolite. *Earth and Planetary Science Letters* 188, 369–381.
- Reisberg, L., Zindler, A., Marcantonio, F., White, W.M., Wyman, D., Weaver, B., 1993. Os isotope systematics in ocean island basalts. *Earth and Planetary Science Letters* 120, 149–167.
- Roy-Barman, M., Allègre, C.J., 1994.  $^{187}\text{Os}/^{186}\text{Os}$  ratios of mid-ocean ridge basalts and abyssal peridotites. *Geochimica et Cosmochimica Acta* 58, 5043–5054.
- Saal, A.E., Rudnick, R.L., Ravizza, G.E., Hart, S.R., 1998. Re–Os isotope evidence for the composition, formation and age of the lower continental crust. *Nature* 393, 58–61.
- Schiano, P., Birck, J.L., Allègre, C.J., 1997. Osmium-strontium-neodymium-lead isotopic covariations in mid-ocean ridge basalt glasses and the heterogeneity of the upper mantle. *Earth and Planetary Science Letters* 150, 363–379.
- Shirey, S., 1994. Evolution of the Earth’s mantle: perspective from the Re–Os isotopic system. *Mineralogical Magazine* 58A, 833–834.
- Smith, A.D., 1992. Back-arc convection model for Columbia River basalt genesis. *Tectonophysics* 207, 269–285.
- Smith, A.D., Lewis, C., 1999a. Differential rotation of lithosphere and mantle and the driving forces of plate tectonics. *Journal of Geodynamics* 28, 97–116.
- Smith, A.D., Lewis, C., 1999b. The planet beyond the plume hypothesis. *Earth Science Reviews* 48, 135–182.
- Smoliar, M.I., Walker, R.J., Morgan, J.W., 1996. Re–Os ages of Group IIA, IIIA, IVA and IVB iron meteorites. *Science* 271, 1099–1102.

- Tatsumi, Y., Eggins, S., 1995. *Subduction Zone Magmatism*. Blackwell Scientific Publications, Massachusetts, 211p.
- Tsuru, A., Walker, R.J., Kontinen, A., Peltonen, P., Hanski, E., 2000. Re–Os isotopic systematics of the 1: 95 Ga Jormua ophiolite complex, northeastern Finland. *Chemical Geology* 164, 123–141.
- Tu, K., Flower, M.F.J., Carlson, R.W., Zhang, M., Xie, G.-H., 1991. Sr, Nd and Pb isotopic compositions of Hainan basalts (south China): implications for a subcontinental lithosphere Dupal source. *Geology* 19, 567–569.
- Walker, R.J., Morgan, J.W., Bearg, E., Smoliar, M.I., Czamanske, G.K., Horan, M.F., 1997. Applications of the  $^{190}\text{Pt}$ – $^{186}\text{Os}$  isotope system to geochemistry and cosmochemistry. *Geochimica et Cosmochimica Acta* 61, 4799–4808.
- Walker, R.J., Morgan, J.W., Horan, M.F., 1995. Osmium-187 enrichment in some plumes: evidence for core-mantle interaction? *Science* 269, 819–822.
- Walker, R.J., Carlson, R.W., Shirey, S.B., Boyd, F.R., 1989. Os, Sr, Nd, and Pb isotope systematics of southern African peridotite xenoliths: implications for the chemical evolution of the subcontinental mantle. *Geochimica et Cosmochimica Acta* 53, 1583–1595.
- Widom, E., Hoernle, K.A., Shirey, S.B., Schmincke, H.-U., 1999. Os isotope systematics in the Canary Islands and Madeira: lithospheric contamination and mantle plume signatures. *Journal of Petrology* 40, 279–296.