

# Genesis of primitive, arc-type basalt: Constraints from Re, Os, and Cl on the depth of melting and role of fluids

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## ABSTRACT

The general model for arc-type basalt genesis is that subducted plates reach a certain depth and release their fluids in a series of dehydration reactions. The fluid migrates into the overlying mantle wedge and initiates melting. High  $^{187}\text{Os}/^{188}\text{Os}$  ratios in some arc magmas have been attributed to this fluid. Although this interpretation follows logically from the general model for arc-type basalt genesis, it is not supported by experimental data or by Re, Os, or Cl data for arc-type basalt, eclogites, and peridotites. Our new data for basaltic rocks from the Mexican volcanic belt together with data from several other arcs lead us to propose that subduction fluids contain only minimal Re, Os, and Cl, and therefore that  $^{187}\text{Os}/^{188}\text{Os}$  is not increased significantly in the melts above 0.145. The observed low Re concentrations are best explained by initiation of arc-basalt melting in the garnet stability field. Retention of Re by garnet in the source will deplete arc-type basalts in Re relative to oceanic-island basalt and mid-ocean-ridge basalt. Radiogenic Os measured in many arc-type basalts is most likely due to crustal interaction rather than a subduction fluid with high and radiogenic Os concentrations.

**Keywords:** osmium, arc basalt, calc-alkaline, subduction, assimilation.

## INTRODUCTION

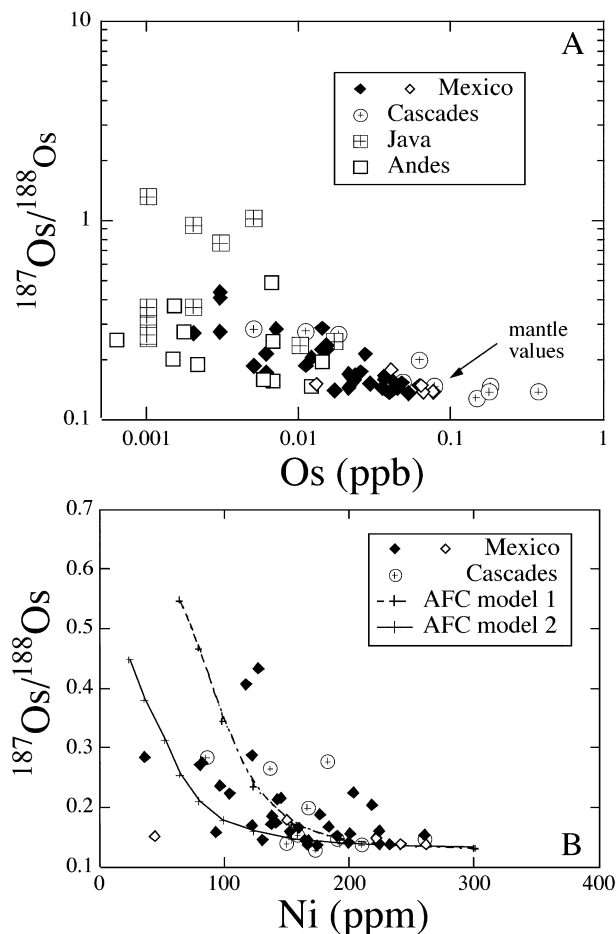
A standard model for arc-magma genesis is that oceanic crust is subducted to a depth of  $\sim 100$  km, where dehydration reactions occur. Fluids are released and migrate into the overlying mantle wedge. Melting due to fluid fluxing in the mantle wedge below the arc gives rise to primitive, arc-type basalt ("primitive" in this paper refers to a melt that is unmodified from its source region; in several diagrams, "primitive" includes melts with as little as 7 wt% MgO). This model has won acceptance among most petrologists and is the baseline upon which the worldwide diversity of arc magmas is interpreted (e.g., Arculus, 1994; Tatsumi et al., 1986). In this scenario, the same fluids are enriched in many incompatible elements, which are commonly associated with arc-type basalts and metasomatism—K, Rb, Ba, Sr, and the light rare earth elements. Radiogenic isotopes such as those of Sr, Nd, and Pb are also commonly associated with the fluids (Pearce and Peate, 1995), and some workers have interpreted Os isotope data in the same way.

Os isotope measurements of some arc magmas have yielded  $^{187}\text{Os}/^{188}\text{Os}$  ratios as large as 1.5 (Fig. 1). Ratios of this magnitude have previously been attributed to high  $^{187}\text{Os}/^{188}\text{Os}$  fluid addition to a mantle-wedge peridotite with relatively low  $^{187}\text{Os}/^{188}\text{Os}$  values ( $\sim 0.13$ ). Such fluids would carry as much as 6000 ppt (parts per trillion) Os, which would be radiogenic in nature, having been derived from subducted oceanic crust (sediment, basaltic crust). The idea that fluids could be carriers of platinum-group elements, such as Os, was suggested by Boudreau et al. (1986). Subsequently, experimental work has determined that the only fluids to carry appreciable quantities of Os have a high oxygen fugacity ( $f_{\text{O}_2}$ ) and are rich in Cl. For example, 1M KCl fluids ( $\sim 3.5$  wt% Cl<sup>-</sup>) at 500 °C and NNO (Ni-NiO) buffers can carry as much as 3 ppb (parts per billion) Os (Xiong and Wood, 2000). Os increases to 130 ppb in a 1.5M KCl fluid and to 1705 ppb at a higher oxygen fugacity—that of the Re-ReO<sub>2</sub> buffer (Fig. 2). A

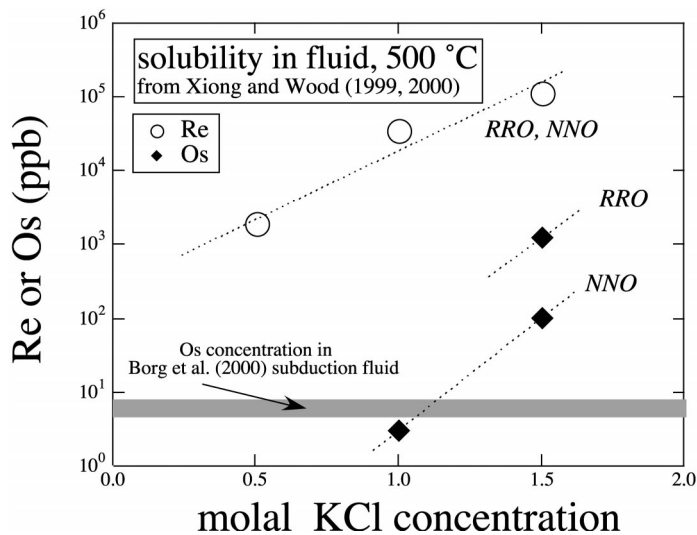
simple interpretation in terms of source contamination by a radiogenic Os-bearing fluid is problematic, as we demonstrate next.

## PROBLEMS WITH FLUID MOBILITY OF Re AND Os

Fluids that carry large amounts of Os (e.g., those of Xiong and Wood, 2000) are also capable of dissolving  $10^5$  times more Re. For



**Figure 1.** A: Os vs.  $^{187}\text{Os}/^{188}\text{Os}$  values measured in arc-type lavas (basalt, basaltic andesite, andesite, and dacite) from Mexico (solid symbols—Chesley et al., 2000, 2002; open symbols—Lassiter and Luhr, 2001), Cascades (Borg et al., 2000), Andes (Ruiz et al., 2000), and Java (Alves et al., 1999). Mantle value is from Shirey and Walker (1998). B: Ni vs.  $^{187}\text{Os}/^{188}\text{Os}$  values for same samples, together with assimilation and fractional crystallization (AFC) modeling that indicates small amounts of assimilation of lower crust can account for high  $^{187}\text{Os}/^{188}\text{Os}$  ( $>0.135$ ; see expanded discussion of this topic in Chesley et al., 2002). Lines represent different AFC trends for bulk  $D_{\text{Os}}$  of 10 (model 2) and 20 (model 1) and for bulk  $D_{\text{Ni}}$  of 5 for assimilation of lower crust by subduction-related melt (crosses represent 2% increments of lower crust). Values used for modeling: initial melt—250 ppt Os, 300 ppm Ni,  $^{187}\text{Os}/^{188}\text{Os} = 0.129$ ; lower crust—50 ppt Os, 100 ppm Ni, and  $^{187}\text{Os}/^{188}\text{Os} = 0.6$  (from Chesley et al., 2002); ratio of mass assimilated to mass fractionated is 0.6.



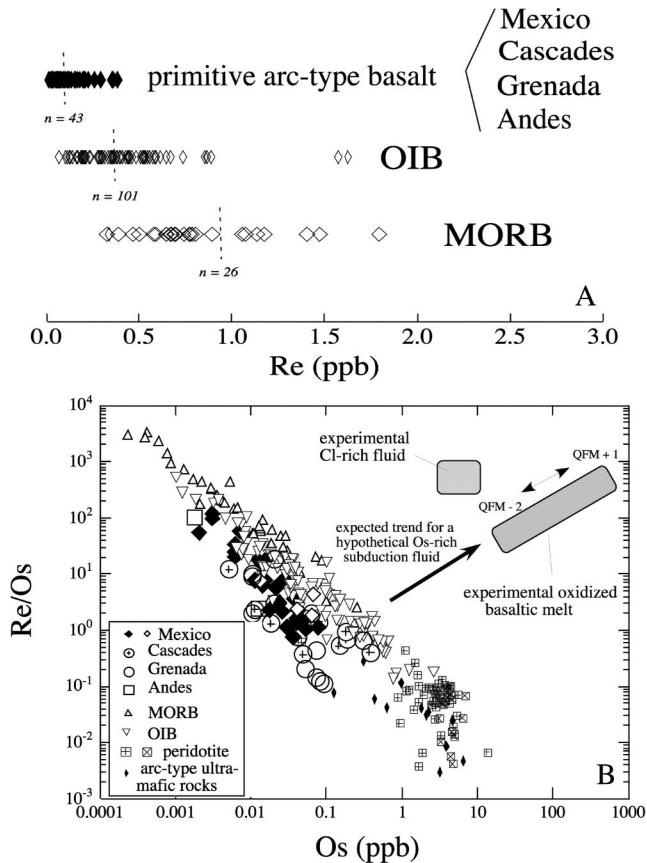
**Figure 2.** Summary of experimental data for Re and Os solubility in fluids taken from Xiong and Wood (1999, 2000), all at 500 °C. Data are shown for experiments carried out at Re-ReO<sub>2</sub> (RRO) and Ni-NiO (NNO) oxygen buffers. Also shown by shaded horizontal line is Os concentration in subduction fluid of Borg et al. (2000). Note that fluid carrying 0.7 ppb Os (as shown by Borg et al., 2000) would also carry 10 ppm Re.

example, 1M KCl fluids at 500 °C and an NNO buffer can carry 30 ppm Re (compared to 3 ppb Os; Xiong and Wood, 1999, 2000; Fig. 2), such that if Os can be carried by fluids (as suggested by Brandon et al., 1996), so can Re. There is, however, strong and diverse evidence that fluids are unlikely to be carriers of either Re or Os in subduction zones.

1. Arc-type basalts with primitive compositions contain very low Re concentrations, considerably lower than oceanic-island basalt and mid-ocean-ridge basalt (MORB) (Fig. 3). This result is the opposite expected of a Cl-rich fluid that should contain orders of magnitude more Re than Os, according to experimental work (Xiong and Wood, 1999, 2000). Even though the high-pressure fluids relevant to subduction zones will be more silicate rich (e.g., Bureau and Keppler, 1999), silicate melts dissolve even less Re and Os than Cl-rich fluids (e.g., Ertel et al., 2001; Borisov and Walker, 2000; Fig. 3B), making them unlikely carriers of large amounts of Re or Os. Low Re contents of arc-type basalts could also be attributed to the possible volatility of Re in fluid-saturated arc magmas (e.g., Bernard et al., 1990), but Os is also a volatile element (Finnegan et al., 1990), and arc-type basalts would also fall off the Ni-Os trend defined by Lassiter and Luhr (2001); such a displacement is not observed.

2. Undegassed melt inclusions in olivine from primitive calc-alkalic basalt contain only 0.07–0.16 wt% Cl<sup>-</sup> (e.g., Sisson and Bronto, 1998; Roggensack et al., 1997; Harris and Anderson, 1984), far below the values of 2–3 wt% Cl<sup>-</sup> expected of a basaltic melt saturated with a Cl-rich or hypersaline fluid (Webster et al., 1999). Although the low Cl<sup>-</sup> contents of the melt-inclusion glasses could be attributed to other processes such as pressure-dependent solubility or fluid undersaturation during melt ascent, a satisfactory explanation for this trait does not yet exist, and thus the presence of a low-Cl primary fluid should be considered.

3. Evidence from Mexican arc-type basalt (Chesley et al., 2000, 2002; Lassiter and Luhr, 2001) indicates that primitive magmas from clearly metasomatized source regions have low <sup>187</sup>Os/<sup>188</sup>Os ratios (~0.135) and cannot have been derived from a mantle source that has interacted with a fluid containing high concentrations of radiogenic Os (e.g., 6000 ppt according to Borg et al. [2000] or 700 ppt according to Parkinson [2000]). Such fluids may contain small amounts of Cl,



**Figure 3.** A: Histogram of Re contents of mid-ocean-ridge and oceanic-island basalt (MORB, OIB) (same data sources as cited by Righter and Hauri, 1998), and arc-type basalts with MgO > 7 wt% (Cascades: Borg et al., 2000; Grenada: Woodland et al., 2002; Andes: Ruiz et al., 2000; Mexico: calc-alkalic basalt from Lassiter and Luhr, 2001—open symbols and from this study and Chesley et al., 2002—solid symbols). Vertical dashed lines are average Os concentrations of MORB (0.922 ppb;  $n = 26$ ) and OIB (0.377 ppb;  $n = 101$ ), and arc-type basalt (0.117 ppb;  $n = 43$  for MgO > 7 wt%). B: Re/Os ratios vs. Os concentrations of arc-type basalt (same references as in A), MORB and OIB (references cited in Righter and Hauri, 1998), xenolith and massif peridotites (data from Pattou et al., 1996; Burnham et al., 1998; Reisberg et al., 1991), and arc-type ultramafic rocks (data from McInnes et al., 1999; Brandon et al., 1996). Also shown are fields for experimental fluids (Xiong and Wood, 1999, 2000) and melts (Ertel et al., 2001; Borisov and Walker, 2000), showing that if fluid or melt was involved with arc-type basalt genesis, Re/Os should be much higher than MORB or OIB (at given Os content), but this is not the case (field labeled QFM + 1 and QFM - 2 refers to range of Os and Re/Os ratios for experimental melts produced at oxygen fugacities of one log  $f_{O_2}$  unit above and two below quartz-fayalite-magnetite oxygen buffer). Involvement of Os-rich subduction fluid such as that proposed by Borg et al. (2000) and Brandon et al. (1996) would push arc-type basalt values to right of OIB array, as indicated by arrow, but this effect is not observed.

but are not necessarily Cl rich. Such fluids will not boost the <sup>187</sup>Os/<sup>188</sup>Os ratios to very high values (>0.3), as argued by Borg et al. (2000) and Alves et al. (1999); subduction fluids will be capable of elevating Os ratios to values only slightly higher than the convecting mantle ( $\leq 0.14$ ).

4. Metasomatized mantle xenoliths have no higher concentrations of Re or Pd than unmetasomatized xenoliths (e.g., Wilson et al., 1996).

5. Because Re contents of some eclogites are lower than MORB values, Becker (2000) argued that Re is lost to the fluid during subduction. There are many eclogites, however, that contain large amounts

of Re comparable to concentrations in MORB (e.g., Pearson et al., 1995). In addition, eclogites contain just as much Os as do MORBs, indicating that none is lost during subduction (Becker, 2000; Pearson et al., 1995; Ruiz et al., 1999).

6. Peridotite samples high in radiogenic Os ( $^{187}\text{Os}/^{188}\text{Os} > 0.137$ ) are extremely rare, as might be expected in an Os-rich fluid-fluxed subduction environment. Only one sample from the Aleutians has been reported (Widom et al., 2001).

7. The subducted slab will have very high concentrations of Re (0.5–1 ppb), but low concentrations of Os (1 ppt). Thus it would be very difficult to concentrate Os in the fluid without Re.

#### ALTERNATIVE HYPOTHESIS: GARNET RETENTION AND CRUSTAL INTERACTION

Re, Os, and trace element analyses of basaltic rocks from four different regions of the Mexican volcanic belt (Tables 1 and 2)<sup>1</sup>, together with previously acquired data from the Cascades, Andes, and Grenada arcs, suggest that the Re, Os, Cl, and Os isotope values of primitive, arc-type basalts can best be explained by invoking a two-stage process of fluid-fluxed melting within the garnet stability field of the asthenospheric wedge, followed by combined fractional crystallization and assimilation of lower crustal material, causing an elevated  $^{187}\text{Os}/^{188}\text{Os}$  signature (as high as 0.41; Chesley et al., 2002).

The requirement of melting in the garnet stability field is based on the low Re, Yb, Y, and high Zr/Y in primitive, arc-type basalts documented in this study and a number of subduction zones (Cascades—Baker et al., 1994; Andes—Hildreth and Moorbath, 1988; Mexico—Luhr, 1997; Fig. 4). A few of the primitive basalts from the Cascades and Mexico do not require garnet to be a residual phase in the source (e.g., those with Zr/Y < 5 ppm and Yb > 2 ppm; Fig. 4). There are good petrologic arguments for the origin of some Cascades arc-type basalts by shallow melting of spinel peridotite (e.g., Bartels et al., 1991), but it is clear from the data and modeling of this study that polybaric melting models may be required to explain all geochemical data. For these latter liquids, residual sulfide is still required. Sulfur may be present as sulfate (not sulfide) under the oxidized conditions of some arc magmas (e.g., Carmichael, 1991). However, the primitive, arc-type basalts in this study equilibrated close to the Ni-NiO (NNO) oxygen buffer (e.g., Hasenaka and Carmichael, 1987; Lange and Carmichael, 1990; Wallace and Carmichael, 1999), where sulfide is still stable under magmatic conditions (Wallace and Carmichael, 1992). Samples TMV-16 and KR-102 have sulfide inclusions trapped within olivine phenocrysts, and the Re and Os contents of the basalts in this study are fully consistent with the presence of residual sulfide in the source region (see Chesley et al., 2002).

Assimilation of lower crust is based on a combination of Os isotope and Ni and MgO constraints (Fig. 1 and Chesley et al., 2002). The radiogenic Os values in Mexican basalt can be explained by assimilation of moderate amounts of lower crustal granulite (to 25%), together with fractionation of olivine, spinel, augite, and plagioclase. Similarly, the Cascades arc-type basalt samples of Borg et al. (2000) that have the highest  $^{187}\text{Os}/^{188}\text{Os}$  are also the most evolved (as low as 7 wt% MgO), an observation that is easily explained by assimilation of a small amount of lower crust with high  $^{187}\text{Os}/^{188}\text{Os}$ , rather than by source modification by a subduction fluid. In a suite of basalts from Medicine Lake volcano (Cascades), Donnelly-Nolan et al. (1991) showed that only basalts with MgO > 10.5 wt% have escaped assimilating lower crustal materials and remained primitive.

<sup>1</sup>GSA Data Repository item 2002065, Tables 1 and 2, Sample analyses and information, is available from Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, editing@geosociety.org, or at www.geosociety.org/pubs/ft2002.htm.

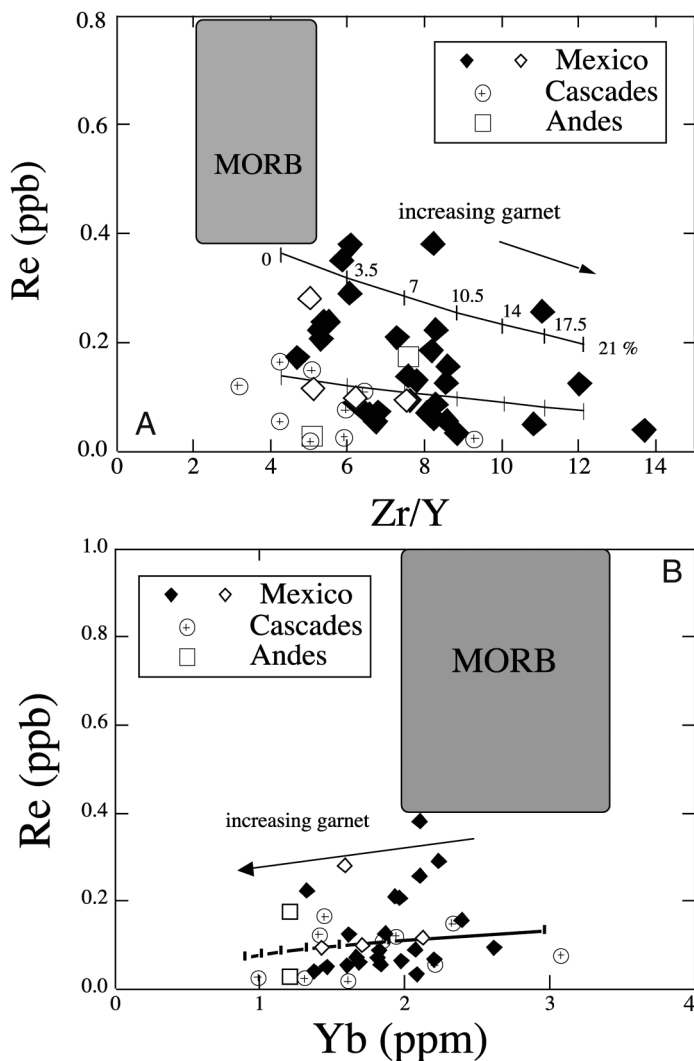


Figure 4. Re vs. Zr/Y and Re vs. Yb for primitive (>7 wt% MgO), arc-type basalts from Mexico, Cascades, and Andes (same references as for Fig. 3). Mid-ocean-ridge basalt (MORB) fields are from data sources cited by Righter and Hauri (1998). Re-Zr/Y and Re-Yb characteristics can be modeled by equilibrium melting of mantle with residual sulfide (sulf) (fixed at 0.088%) and garnet (gt) (0%–21%—heavy lines with tick marks at 3.5% intervals). Two lines represent calculations carried out for mantle with 0.15 or 0.40 ppb Re (these represent lower and upper boundaries of Re contents in fertile mantle; see Shirey and Walker, 1998) and for fixed percentage of melting,  $f$ , equal to 0.05 as estimated by Wallace and Carmichael (1999) for primitive Mexican basalt;  $X_{\text{ol}}$  (olivine) = 55%,  $X_{\text{opx}}$  (orthopyroxene) = 25%,  $X_{\text{cpx}}$  (clinopyroxene) = 20%, and  $X_{\text{gt}} = 21\%$  to 0, at expense of orthopyroxene. Partition coefficient data for Re, Y, Yb, and Zr are from Righter and Hauri (1998) and references therein.

#### CONCLUSIONS

Interpretation of Re, Os, and Os isotope data for arc-type basalt in terms of a general model for fluxing of the mantle wedge below the arc by high  $^{187}\text{Os}/^{188}\text{Os}$  and other radiogenic isotopes is problematic for several reasons. An alternative explanation for the low Re and Cl contents and low  $^{187}\text{Os}/^{188}\text{Os}$  ratios of primitive, arc-type basalts is that they are derived from melting in the garnet stability field, by fluxing with a relatively Cl- and Os-poor fluid. The radiogenic nature of many arc magmas can instead be attributed to assimilation of lower crustal material during magmatic differentiation.

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