

Preprint

Re-Os ISOTOPIC SYSTEMATICS OF PRIMITIVE LAVAS FROM THE
LASSEN REGION OF THE CASCADE ARC, CALIFORNIA

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Abstract

Rhenium-osmium isotopic systematics of primitive calc-alkaline lavas from the Lassen region appear to be controlled by mantle wedge processes. Lavas with a large proportion of slab components have relatively low Re and Os abundances, and have radiogenic Os and mid-ocean-ridge basalt-like Sr and Pb isotopic compositions. Lavas with a small proportion of slab components have higher Re and Os elemental abundances and display mantle-like Os, Sr, Nd, and Pb isotopic compositions. Assimilation with fractional crystallization can only generate the Re-Os systematics of the Lassen lavas from a common parent if the distribution coefficient for Re in sulfide is ~ 40 -1100 times higher than most published estimates and if most incompatible element abundances decrease during differentiation. High Re/Os ratios observed in mid-ocean-ridge basalts means that subducted oceanic crust may be a source of radiogenic Os in volcanic arcs. The slab beneath the southernmost Cascades is estimated to have $^{187}\text{Os}/^{188}\text{Os}$ ratios as high as 1.4. Mixing between a slab component and mantle wedge peridotite can generate the Os isotopic systematics of the Lassen lavas provided the slab component has a Sr/Os ratio of $\sim 7.5 \times 10^{-5}$ and Os abundances that are 100-600 times higher than mid-ocean-ridge basalts. If this model is correct, Os must be readily mobilized and concentrated in the slab component, perhaps as a result of high water and HCl fugacities in this subduction environment. Another possible mechanism to account for the correlation between the magnitude of the subduction geochemical signature and Os isotopic composition involves the possibility of increased stability of an Os bearing phase in mantle wedge peridotites as a result of fluxing with the slab component. Melting of such a source could yield low Os magmas that are more susceptible to crustal contamination, and hence have more radiogenic Os isotopic compositions, than magmas derived from sources with a smaller contribution from the slab. Thus, the addition of the slab

component to the mantle wedge appears to result in either the direct or indirect addition of radiogenic Os to arc magmas.

1. Introduction

The behaviors of Re and Os in the subduction cycle are poorly understood. Because of the high Re/Os ratios of basalts and oceanic sediments, subducted oceanic crust develops highly radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios over relatively short periods of time [e.g. 1]. Some peridotite xenoliths found in areas overlying modern subduction zones have $^{187}\text{Os}/^{188}\text{Os}$ ratios that are as much as 16% enriched in ^{187}Os compared with current estimates for the convecting upper mantle. These enrichments are consistent with interactions between mantle wedge peridotites and metasomatic agents that are likely, in part, derived from the subducting slab [2-5]. These results indicate that Os is mobile under some conditions of slab dehydration, and during fluid and melt transport in the mantle wedge. If Os-bearing slab-derived fluids induce partial melting in the mantle wedge to produce arc basalts, then these magmas may also potentially bring radiogenic Os from the slab to the surface. Thus, radiogenic Os in arc lavas may provide a sensitive indicator of wedge-slab interactions.

Assimilation of aged crust with high Re/Os and $^{187}\text{Os}/^{188}\text{Os}$ ratios by arc magmas en route to the surface, however, will also result in shifts to radiogenic Os compositions that mimic the effects of adding a slab component to the wedge source. Arc lavas are rarely undifferentiated and their geochemical and isotopic features frequently reflect magma mixing and/or interactions with the crust, rather than solely the compositions of their sources [e.g., 6]. For example, Alves et al. [7] recently attempted to identify slab-derived Os in arc lavas, but because of the evolved nature of the lavas they investigated it was not clear whether the highly

radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratios that they reported reflected addition of different proportions of a subducted component or crustal contamination.

In order to develop the Re-Os isotope system as a sensitive tracer of wedge-slab interactions, it is crucial to create a geochemical protocol that permits the deconvolution of metasomatic effects from those of crustal contamination. To do this, it is important to first compare and contrast the effects of slab metasomatism versus crustal assimilation for a system that has already been well characterized with respect to other isotope and trace element parameters. As a first step, here we examine the Re-Os isotopic systematics of a set of primitive basalts from the Lassen region of the southern Cascades in California. These primitive lavas have been well characterized for a comprehensive set of mineralogical and geochemical data. The lavas have Mg#s [molar $\text{Mg}/(\text{Mg}+\text{Fe})$] ranging from 68 to 75, consistent with their having undergone minimal differentiation and crustal assimilation since they were extracted from the mantle [8]. Consequently, the effects of crustal assimilation on their Os isotopic systematics may be considerably reduced compared to less primitive suites. Furthermore, previous work on this suite presented evidence that a slab component has contributed, in part, to observed compositional variations, and these basalts may be well suited for examining the effects of the variable addition of a slab component on Os isotopic compositions [9]. Nonetheless, despite the evidence for slab interaction and the lack of evidence for crustal contamination, the isotopic observations must still be considered within the framework of crustal contamination. This is because of the extreme sensitivity of low Os abundance melts, such as many of these arc lavas, to be significantly perturbed by crustal contamination that can not be easily detected via other isotope systems or trace elements [8, 10]. With these issues in mind, the data for the Lassen region lavas are used in this paper to assess: 1) the Os isotopic composition of potential mantle

components underlying the Lassen area, 2) the interaction between mantle-derived magmas and the northern California crust, and 3) the contribution of Os from the subducting slab.

2. Lassen primitive lavas

The focus of this study is young (mostly <0.5 Ma) primitive and compositionally diverse calc-alkaline (CA) basalt and magnesian andesite lavas from the Lassen region of the southernmost Cascade Range. These lavas are erupted from monogenetic cinder volcanoes and small shield volcanoes that overlie granitic basement of the northern Sierra Nevada batholith. The samples selected for this study are some of the most primitive that have been found in the Cascade arc. The phenocryst assemblages and compositions of the primitive lavas support the observation that they are little evolved since leaving their mantle sources and may approach primary compositions [8]. The lavas have low phenocryst contents (<5%) and simple mineral assemblages consisting primarily of forsteritic olivine (Fo_{85-90}). A few of the primitive magnesian andesites also contain clinopyroxene with high Mg#s [$100\text{Mg}/(\text{Mg}+\text{Fe}^{2+})$] around 90. Phenocrysts of plagioclase and magnetite are not present. Chromian spinel is often included in olivine and clinopyroxene or present in the groundmass. Fe-sulfides have also occasionally been observed in olivine phenocrysts.

Primitive CA lavas display a wide continuum of compositional diversity (Fig. 1). At one end of the spectrum are lavas with low contents of incompatible elements, high ratios of large ion lithophile element (LILE) to high field strength element (HFSE) abundances, and Sr and Nd isotopic compositions approaching those of mid-ocean ridge basalts (MORB; Appendix). The high abundance of Sr and high Sr/light rare earth element (LREE) and Sr/P compositions relative to primitive mantle led Borg et al. [9] to characterize this end member as having a high $(\text{Sr}/\text{P})_N$ value. Correlation of $(\text{Sr}/\text{P})_N$ with Ba/Ta (Fig. 2a), La/Ta, and U/Ta [9] indicates that

$(\text{Sr}/\text{P})_{\text{N}}$ is a measure of the arc geochemical signature in these lavas. The most extreme lavas in this group are primitive magnesian andesites, such as sample LC86-1009 (Fig. 1). The other end of the spectrum, represented by LC85-671 (Fig. 1), is characterized by magmas with higher abundances of incompatible elements, lower LILE/HFSE ratios, and Sr, Nd, and Pb isotopic ratios that are like those of some ocean island basalts (OIB). Lower relative enrichment of Sr over LREE and P led Borg et al. [9] to characterize this end member as having low $(\text{Sr}/\text{P})_{\text{N}}$. For plotting purposes, $(\text{Sr}/\text{P})_{\text{N}} = 3.3$ is used to distinguish low and high $(\text{Sr}/\text{P})_{\text{N}}$ samples.

Across-arc variation in the geochemistry of primitive lavas in the southernmost Cascade Range has been discussed previously [9, 11]. Low $(\text{Sr}/\text{P})_{\text{N}}$ basalts characterize the arc axis and backarc, and are sparsely present in the forearc, whereas high $(\text{Sr}/\text{P})_{\text{N}}$ basalts and magnesian andesites characterize the forearc, and are extremely rare in the arc axis and backarc. The petrogenesis of Lassen basalts has also been discussed [8, 9, 11]. Two conclusions derived from these studies provide the framework for a model in which to interpret the Os isotopic data..

First, Borg et al. [9] concluded that the origin of the geochemical variation of primitive CA magmas in the Lassen region could be explained by source mixing between a slab-derived fluid component, bearing an arc geochemical signature (high LILE/HFSE ratios) and MORB-like Sr, Nd and Pb isotopic compositions, and mantle wedge garnet-spinel peridotites with variable fertility and Sr, Nd and Pb isotopic compositions similar to the estimated sources of some types of OIB. Mixing models demonstrate that the fluid component required to reproduce the composition of the Lassen forearc lavas would have high Sr/P and unradiogenic Sr and Pb isotopic ratios and be compositionally similar to arc-derived fluids estimated for magmas of the Mariana trough [12]. Addition of slab-derived fluid to the mantle wedge results in the generation of high Sr/P melts characterized by large enrichments in Sr and Pb, strong depletions in Ta and Nb (Fig. 1), and Sr and Pb isotopic compositions that are similar to MORB. A

decrease in the subduction geochemical signature from forearc to back arc is inferred to reflect a decrease in the relative proportion of slab component as a result of dehydration of the slab. Low Cs/Rb ratios, Pb abundances, and unradiogenic Pb isotopic compositions of all of the Lassen lavas suggest that sediment plays, at most, a minor role.

Second, Clynne and Borg [8] and Clynne [11] showed that the simple phenocryst assemblages and Mg-rich phenocryst compositions observed in the Lassen lavas are consistent with minimal differentiation since leaving the mantle source. They also noted that assimilation fractional crystallization (AFC) models cannot reproduce the geochemical and isotopic variations observed in the Lassen lava suite using felsic to ultramafic crustal compositions. Clynne and Borg [8] further showed that systematic compositional differences between phenocrysts in low and high $(\text{Sr/P})_N$ lavas, and correlations between the compositions of spinels and the bulk compositions of Lassen lavas (Fig. 2b), reflect chemical variability and relative fertility of their mantle sources. They concluded that the relative source fertility decreased in the order low- $(\text{Sr/P})_N$ CA basalt - high- $(\text{Sr/P})_N$ CA basalt - high- $(\text{Sr/P})_N$ CA magnesian andesite. Thus, the relative fertility of the CA magma source decreases from the backarc to the forearc.

3. Analytical methods

Ten lavas have been analyzed for Re and Os abundances and $^{187}\text{Os}/^{188}\text{Os}$ ratios. These samples are among the most primitive lavas for which there are mineralogical, geochemical, and isotopic data and are representative of the spectrum of compositions present in the Lassen area. Sample chips were carefully selected to be free of hammer marks then crushed in a Al_2O_3 shatterbox. Two gram aliquots of whole-rock powder were spiked with ^{190}Os and ^{185}Re and were digested using aqua-regia in Carius tubes at 230°C following the methods of Shirey and Walker [13]. Osmium was extracted and purified using solvent extraction [14]. Rhenium was

purified using anion exchange chromatography [15]. Isotopic compositions were determined using negative thermal ionization mass spectrometry [16]. The total analytical blank during the course of the study for Os was 5.6 ± 0.8 pg (2σ , $n=4$) with $^{187}\text{Os}/^{188}\text{Os} = 0.155 \pm 0.005$ (2σ), and for Re was 2.3 ± 0.8 pg (2σ , $n=2$). Errors in corrected $^{187}\text{Os}/^{188}\text{Os}$ in Table 1 reflect uncertainty in mass spectrometry runs and in the blank. For samples LC88-1312, LC83-255, and LC86-1009, which have low Os abundances and $^{187}\text{Os}/^{188}\text{Os}$ ratios far removed from the blank composition, there were corrections as great as 13% in the $^{187}\text{Os}/^{188}\text{Os}$ ratio. Initial $^{187}\text{Os}/^{188}\text{Os}$ ratios were calculated using measured $^{187}\text{Re}/^{188}\text{Os}$ and either known ages (unpublished data) or age estimates of Guffanti et al. [17]. Low $^{187}\text{Re}/^{188}\text{Os}$ ratios, in combination with ages less than 1.5 Ma, result in age corrections that are within analytical uncertainty of the measured values.

4. Results

The Re and Os abundance and isotopic data are presented in Table 1 along with Sr, Nd, Pb, and O isotopic data [9, 18; unpublished data]. The relative variation of Re (900%) and Os (8200%) in the Lassen lavas is larger than for any other element (e.g. Rb = 550%) that has been analyzed (Table 1; Appendix). The Re abundances in all Lassen lavas are low (18-164 ppt) in comparison to Re abundances in average OIB (260 ± 120 ppt) [19], and MORB (856 ± 417 ppt) [20-22], as well as in comparison to high-alumina-olivine tholeiites (HAOT) from the northwestern USA (544 ± 387 ppt) [23, 24]. Rhenium abundances show weak positive correlations with abundances of highly compatible elements, such as Ni, and weak negative correlations with olivine Fo content and spinel Cr# (Fig. 3a-c). There are no clear correlations of Re with $(\text{Sr}/\text{P})_{\text{N}}$ (Fig. 2d), TiO_2 (Fig. 3d), or most incompatible elements (Appendix).

The Os abundances are also highly variable in these CA lavas (5-370 ppt), but within the range of Os abundances in average OIB (284 ± 186 ppt) [25], and MORB (0.2-3000 ppt) [20-

22], as well as in HAOT lavas from the northwestern USA (1-400 ppt) [23, 24]. With the exception of Ni (Fig. 3e), Os abundances do not clearly correlate with most other elements. There is also a positive correlation between Re and Os, and a weak negative correlation between Re/Os and Os (Fig. 3f-g). Although garnet is present in the source [9], and can control Re abundances [26], these correlations are more consistent with fractionation by a phase, such as sulfide, in which both Re and Os are compatible [27, 28].

The $^{187}\text{Os}/^{188}\text{Os}$ ratios of the CA lavas range from 0.1285 to 0.2828 (Table 1), and display a good negative correlation with Os abundance (Fig. 3h). The $^{187}\text{Os}/^{188}\text{Os}$ ratios also correlate positively with geochemical measures of the proportion of the slab component, such as $(\text{Sr}/\text{P})_{\text{N}}$ ratios (Fig. 2f). Borg et al. [9] have suggested that the slab component is also characterized by unradiogenic Sr and Pb isotopic composition. Negative correlation of $^{187}\text{Os}/^{188}\text{Os}$ with Sr and Pb isotopic compositions (Fig. 4) may therefore further suggest a relationship between Os isotopic composition and the presence of material from the subducting slab. Thus, in summary, CA lavas with the most radiogenic Os are characterized by strong enrichments in Sr and Pb, and strong depletions in Ta and Nb relative to other equally incompatible elements, and have MORB-like Sr and Pb isotopic compositions. These lavas are found almost exclusively in the forearc. The CA lavas with the least radiogenic Os have higher incompatible element abundances, relatively flat incompatible element patterns and OIB-like Sr, Nd, and Pb isotopic compositions. These lavas are found mostly in the arc axis and backarc.

5. Isotopic characteristics of Lassen magma sources

Of the lavas examined here, sample LC85-671 shows the least evidence for an arc geochemical signature. It has both low Ba/Ta and $(\text{Sr}/\text{P})_{\text{N}}$ ratios. Consequently, the isotopic composition of this rock may reflect that of the mantle source of the Lassen magmas more

closely than any of the other samples of this suite. Of note, however, the Sr, Nd and Pb isotopic compositions of this sample do not match those of the depleted MORB mantle (DMM) source. The $^{87}\text{Sr}/^{86}\text{Sr}$ ratio of this sample is well above DMM (0.70425 vs. 0.7025), $^{143}\text{Nd}/^{144}\text{Nd}$ is somewhat less than DMM (0.51278 vs. 0.51315), and $^{206}\text{Pb}/^{204}\text{Pb}$ is more radiogenic than DMM (18.97 vs. 18.75). Instead, these compositions are intermediate between the DMM and a mantle domain that in the past has been enriched in ancient recycled oceanic crust (Fig. 4), such as the EM II component of Zindler and Hart [29]. Thus, it was hypothesized by Borg et al. [9] that the ultimate source of the Lassen magmas was mantle that had been previously enriched in a recycled oceanic crustal component.

The $^{187}\text{Os}/^{188}\text{Os}$ of sample LC85-671 is 0.1285, and is the least radiogenic of this suite. Given that addition of either a slab component to the source of the Lassen magmas, or crustal contamination of the magmas would result in the addition of more radiogenic Os, this ratio likely represents a *maximum* value for the mantle source. Sample LC85-671 has an Os isotopic composition that is similar to that estimated for primitive upper mantle (PUM: ~ 0.129) [30], and the least radiogenic values determined for young MORB sulfides and glasses (0.125-0.130) [22, 31]. Consequently, the Os isotopic composition of this sample is indistinguishable from that of the present convecting upper mantle, including the DMM. We conclude that the Os isotopic composition of the mantle source of at least some of the Lassen magmas was similar to, or even possibly less radiogenic than, the modern DMM.

The observation that within this suite there is a generally positive correlation between arc geochemical signatures and measured $^{187}\text{Os}/^{188}\text{Os}$ ratios suggests that a component with radiogenic Os was preferentially added to samples with strong arc geochemical signatures. Such a correlation could result from the variable incorporation of a slab component carrying a radiogenic Os signal into wedge peridotites. Alternately, the increase in $^{187}\text{Os}/^{188}\text{Os}$ with

indicators of a slab component may reflect a correspondingly increased ability of slab-enriched magmas to assimilate crust. This could reflect a higher water content. In order to discriminate among these possibilities, mechanisms to generate the Re-Os isotopic systematics of the CA lavas, together with their other geochemical characteristics, are investigated below.

5.1 Crustal Assimilation

Variations in Re and Os abundances and Os isotopic composition observed in arc lavas can potentially be produced by AFC of continental crust. Previous studies of lavas that passed through continental crust, have concluded that positive correlations of $1/\text{Os}$ with $^{187}\text{Os}/^{188}\text{Os}$, as observed in this suite, are the result of AFC processes [7, 10, 32]. Although it has been argued on the basis of mineralogy, incompatible element abundances, and Sr and Pb isotopic ratios, that primitive CA lavas in the Lassen region are minimally differentiated [8, 9, 11], assimilation of small amounts of highly radiogenic Os from crustal rocks could potentially have controlled their Re-Os systematics, but had little effect on other geochemical and isotopic systematics. The models presented below attempt to reproduce the compositions of the samples with radiogenic Os from the sample with the least radiogenic Os.

The negative correlation between $^{187}\text{Os}/^{188}\text{Os}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ of the Lassen suite can be used to place strict constraints on AFC models by requiring that either: 1) the hypothetical assimilant had radiogenic Os, but unradiogenic (MORB-like) Sr isotopic composition, or 2) the amount of assimilation was relatively small so that Sr was unaffected by assimilation of crust with radiogenic Os and Sr, and the Sr variations were controlled by some other process. The second requirement is supported by the observation that the Lassen lavas have phenocrysts with high Mg#s and have high compatible-element abundances (Appendix and [8, 9]). As a result, the AFC models presented below are limited to no more than 10% fractionation. In order to model

the suite of lavas, we assume they are derived from a common source. The parent magma is assumed to have isotopic characteristics like LC85-671, but higher Re, Os, and Ni abundances of 250 ppt, 400 ppt, and 250 ppm, respectively. These Re, Os, and Ni abundances are only marginally higher than the highest measured values of the Lassen suite (Table 1). The models use various crustal compositions and partition coefficients (D) to assess the possible role of AFC (Fig. 3e-h). One crustal component used in the models is postulated to have the Re-Os composition of average of mafic lower crustal rocks estimated by Saal et al. [33]; Re = 250 ppt, Os = 50 ppt, and $^{187}\text{Os}/^{188}\text{Os} = 0.80$, and Ni of 100 ppm. A second composition used in the models is more typical of upper crustal rocks and is assumed to have 250 ppt Re, 10 ppt Os, Ni = 50 ppm, and a $^{187}\text{Os}/^{188}\text{Os}$ ratios ranging from 1 [34] to 4.

As per petrographic observations, the AFC models assume that olivine and sulfides are the only fractionating phases that affect Re-Os-Ni abundances. During fractional crystallization, Ni abundances are primarily controlled by olivine crystallization, whereas Re and Os abundances are dominated by sulfide crystallization. The Fe-sulfides that have been observed in Lassen lavas are included in olivines so that olivine fractionation can affect both Ni and Os abundances. Fractionation of clinopyroxene will have a small effect on the abundances of Re, Os, and Ni. Although magnetite may have high Re/Os ratios [24] and a relatively high affinity for Re ($D_{\text{magnetite}}^{\text{Re}} = 20\text{-}50$; [26]), it is not observed as a phenocryst in these lavas and, therefore, probably does not control Re-Os elemental abundances during differentiation.

In order to produce the observed variation in Ni and Os from a common parent magma, assuming that the ratio of assimilation to crystallization (Ma/Mc) is 0.6, bulk $D_{\text{Os}}/D_{\text{Ni}}$ must be ~ 4 (Fig. 3e). The bulk $D_{\text{Os}}/D_{\text{Ni}}$ ratio is strongly controlled by the relative modes of sulfide and olivine. Nevertheless, the $D_{\text{Os}}/D_{\text{Ni}}$ ratio required by the AFC models is similar to the ratio of 1-2 that is required to produce Os-Ni variations in oceanic and continental basalts [32]. and arc

lavas [35]. AFC models can also produce some of the $^{187}\text{Os}/^{188}\text{Os}$ -Os systematics of the CA lavas (Fig. 3h). Note that the AFC model involving lower crust best reproduces the Lassen data and that the upper crustal AFC model requires the assimilant to have a very radiogenic $^{187}\text{Os}/^{188}\text{Os}$ ratio of 4 (Fig. 3f). Also note that the compositions of many of the high $(\text{Sr}/\text{P})_{\text{N}}$ lavas fall off all of the model curves.

One potential problem with the AFC model for the Lassen lavas is that the Re-Os elemental systematics of the lavas are more difficult to reproduce than the Os-Ni or $^{187}\text{Os}/^{188}\text{Os}$ -Os systematics. In order to reproduce the Re-Os abundances observed in the Lassen lavas, the bulk $D_{\text{Os}}/D_{\text{Re}}$ ratio must be close to 1 (Fig 3f-g). Partition coefficients for Re and Os in sulfides are very poorly constrained. $D^{\text{sulfide}}_{\text{Os}}$ estimated for low pressure MORB melts by Roy-Barman et al. [31] is 48000 and is ~1000 times higher than their estimate of $D^{\text{sulfide}}_{\text{Re}}$ of 43, yielding a bulk $D_{\text{Os}}/D_{\text{Re}}$ ratio over 1100. Roy-Barman et al. [36] estimated $D^{\text{sulfide}}_{\text{Re}}$ to be 1200, which results in a bulk $D_{\text{Os}}/D_{\text{Re}}$ ratio of 40. Pearson et al. [27] have observed that Re/Os ratios in sulfides included in diamonds are similar to Re/Os ratios in host eclogites and peridotites. Thus, the Re and Os sulfide/melt partition coefficients could be roughly equal if the sulfide inclusions and host xenoliths crystallized contemporaneously, and the host rocks did not undergo metasomatism that mobilized Re and Os after isolation of sulfide inclusions in the diamonds. Even if the $D_{\text{Os}}/D_{\text{Re}}$ ratio determined for the sulfides included in diamonds reflects crystallization from a melt, the $D_{\text{Os}}/D_{\text{Re}}$ ratio determined for MORB is probably more applicable to crustal level AFC of the Lassen suite than $D_{\text{Os}}/D_{\text{Re}}$ ratio estimated for sulfide inclusions from such a high pressure mantle regime.

An increase in the bulk D_{Re} resulting from the presence of a phase such as magnetite in the fractionating assemblage is not expected because, as noted above, magnetite is not observed in the lavas, nor is there a correlation between Re and Ti observed (Fig. 3d). At present, no

other phase that is identified within the suite is known to favorably partition Re. Thus, AFC models can reproduce the Re-Os elemental systematics of the Lassen lavas only if the bulk D_{Os}/D_{Re} in the Lassen fractionating assemblage is 1, requiring the $D_{Re}^{sulfide}$ to be ~40-1100 times higher than the values published for MORB.

A second, more significant problem, with this AFC model is that it does not reproduce lithophile element abundances, incompatible element patterns, or the compositions of chromian spinels in the Lassen lavas. This stems from the fact that the parental magmas (the low $(Sr/P)_N$ lavas) have higher incompatible element abundances than the hypothetical differentiation products (the high $(Sr/P)_N$ lavas; Fig. 1). Strong relative enrichments of Sr and Pb, and depletions of Ta and Nb in the high $(Sr/P)_N$ lavas, as well as the presence of higher Cr# spinel in the high $(Sr/P)_N$ lavas are also inconsistent with derivation from the low $(Sr/P)_N$ lavas by AFC.

Finally, it should be noted that the high and low $(Sr/P)_N$ lavas are not observed in the same volcanic centers, and are in fact erupted from different locations within the arc. We conclude that the Re-Os systematics of the Lassen lavas are not the direct result of AFC processes, although some aspects of the Os isotopic characteristics of the suite can be successfully modeled. Instead, we must consider the possibility that the variations in the lavas reflect the compositions of their mantle source regions.

5.1.1 Oxygen isotopes

The oxygen isotopic compositions of many CA Lassen rocks are elevated ($\delta^{18}O = >6.5$ - 7.4‰) above typical mantle values ($\delta^{18}O \sim 5.5\text{‰}$) and have been difficult to explain given the minimally differentiated nature of this lava suite (Table 1). Elevated $\delta^{18}O$ values have been proposed to reflect contamination by mafic to ultramafic crustal rocks [18], as well as the composition of their mantle sources [9]. The great sensitivity of the Re-Os isotopic system to assimilation processes provides a test of these hypotheses.

The minimal amount of assimilation indicated by the Os isotopic systematics suggests that the heavy oxygen observed in some of the most primitive Lassen lavas is not derived from continental crust. Oxygen is the most abundant element in silicate melts and large amounts of assimilation (~30%) of crust with $\delta^{18}\text{O}$ of +12 are required to alter the $\delta^{18}\text{O}$ of mantle-derived magmas from 5.5‰ to 7.4‰. The presence of a mantle source with heavy oxygen is supported by the observation that sample LC85-671 has mantle-like Os, Sr, Nd, and Pb isotopic compositions and yet has the highest $\delta^{18}\text{O}$ in the suite (Table 1). Heavy O in the Lassen sub-arc mantle is consistent with recent studies that have suggested that the slab component may contain heavier O than typical mantle [5, 37]. High $\delta^{18}\text{O}$ values in the mantle wedge could therefore reflect the addition of slab-derived fluids, as suggested by McInnes et al [5] for the Papua-New Guinea arc. The lack of correlation of $\delta^{18}\text{O}$ values with $(\text{Sr}/\text{P})_{\text{N}}$ and Ba/Ta [9], however, indicate that the modern subduction component is not controlling the $\delta^{18}\text{O}$ values in the mantle wedge. Instead, the $\delta^{18}\text{O}$ values of the Lassen lavas may reflect the cumulative addition of slab-derived fluids from both past and present subduction regimes.

5.2 Slab-Derived Fluids

If the radiogenic Os observed in the Lassen lavas does not reflect crustal contamination, another source of radiogenic Os is required. Furthermore, if the radiogenic Os was derived from a slab, the requirement that the slab component have unradiogenic (approaching MORB-like) Sr and Pb isotopic compositions [9] constraints potential mechanisms for its generation. The following section presents mechanisms to generate a slab component with such an isotopic composition, and models to assess if mixing between this slab component and a sub-arc mantle component can produce the Os-Sr isotopic compositions observed in the Lassen lavas.

5.2.1 Mechanisms to generate the slab component

The behavior of Re and Os during prograde metamorphism and dehydration of the oceanic crust is poorly constrained and difficult to predict, so that the Os content and Os isotopic composition of slab-derived fluids are poorly known. A study of eclogites suggests that Re is significantly (>50%) removed from downgoing slabs during dehydration, whereas the removal of Os evidently occurs much less readily [38]. To some extent this may reflect the variable compatibility of Re and Os in minor and trace phases, such as sulfides, alloys, and oxides [27, 28, 35, 36]. On the other hand, metasomatized suprasubduction peridotites and gabbros in the Papua-New Guinea arc have Os isotopic compositions as high as 2.1 [5], indicating that the addition of a slab component may significantly increase the $^{187}\text{Os}/^{188}\text{Os}$ ratio of the mantle wedge. Thus, the slab component may have low abundance of radiogenic Os.

In order to explain correlated radiogenic Os-Nd isotopic systematics of mantle xenoliths from Simcoe volcanic field, Washington, Brandon et al. [2] evaluated the $^{187}\text{Os}/^{188}\text{Os}$ composition of the slab component. They assumed that the slab component contained radiogenic Os as a result of the presence of subducted sediment and isotopic ingrowth in the oceanic crust between the time of basalt crystallization and slab dehydration and/or melting beneath the arc. Using data available at the time, they calculated a $^{187}\text{Os}/^{188}\text{Os}$ composition of 0.22 for the modern oceanic crust beneath Simcoe assuming a $^{187}\text{Re}/^{188}\text{Os}$ ratio in the basalt of 240 and a subduction time of 25 Ma. The appropriate age for the Gorda slab beneath the Lassen area is about 17 Ma [17]. No Re or $^{187}\text{Re}/^{188}\text{Os}$ data for MORB from the Gorda or Juan de Fuca plate are available, but Schiano et al [22] reported data for zero age lavas from the East Pacific Rise (EPR) between 20°S and 20°N. The EPR lavas have an average $^{187}\text{Re}/^{188}\text{Os}$ of 4455 [22], and yield a calculated $^{187}\text{Os}/^{188}\text{Os}$ ratio of 1.4 at 17 Ma assuming an initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.125. It should be noted that basalts from the EPR contain higher Re (average 1120 ppt) than those

from the Mid-Atlantic Ridge (MAR; 830 ppt) or Indian Ridge (IR; 890 ppt). The $^{187}\text{Os}/^{188}\text{Os}$ calculated for the slab assuming $^{187}\text{Re}/^{188}\text{Os}$ ratio of average MAR and IR basalt [22] is ~ 1.0 . Although these calculations lead to much more radiogenic Os isotopic composition estimates for subducting slab than Brandon et al. [2], the difference is primarily because the EPR, MAR, and IR lavas have much lower Os concentrations than the Brandon et al. [2] model, not because of the marginally higher Re concentrations. Consequently, the quantity of ^{187}Os generated within the subducting slab would be approximately equivalent to that estimated for the slab beneath Simcoe volcanic field.

Subducted sediment may also be a source of radiogenic Os in the slab component. Brandon et al. [2] modeled the slab component as a mixture of 90-95% of 25 Ma oceanic crust ($^{187}\text{Os}/^{188}\text{Os}$ of 0.22) and 5-10% sediment ($^{187}\text{Os}/^{188}\text{Os}$ of 1.02) to estimate a value of 0.3 for the Os isotopic composition of the slab component. Although a slab component with a large contribution from sediment could produce the radiogenic Os required in the source of the high $(\text{Sr}/\text{P})_{\text{N}}$ magmas, it is not consistent with previous estimates of $<0.1\%$ based on Cs/Rb and Pb isotopic ratios [9]. If the slab component was derived from a mixture of 95% average Juan de Fuca MORB [39, 40] and 5% Pacific sediment [41]), it would have an isotopic composition that is more radiogenic than the MORB-like Pb values required to produce the Pb isotopic compositions of the high $(\text{Sr}/\text{P})_{\text{N}}$ magmas ($^{206}\text{Pb}/^{204}\text{Pb}$ of 18.7, $^{207}\text{Pb}/^{204}\text{Pb}$ of 15.6, and $^{208}\text{Pb}/^{204}\text{Pb}$ of 38.7). Consequently, subduction of sediment does not appear to significantly contribute to the Os budget of the slab component in the Lassen region and is ignored in our calculations.

5.2.2 Mixing Models

Models reproducing the Sr-Os isotopic systematics of the Lassen lavas by mixing sub-arc mantle with hypothetical slab-derived fluids are presented in Figure 5. The Sr and Os

isotopic composition of the non-subduction enriched sub-arc mantle is assumed to be the same as the Lassen sample with the smallest slab geochemical signature (LC85-671). The high $(\text{Sr}/\text{P})_{\text{N}}$ lavas are derived from relatively depleted peridotites and the low $(\text{Sr}/\text{P})_{\text{N}}$ lavas are derived from relatively fertile peridotites [8, 9]. As a result, the Sr and Os abundances of the peridotite component are varied in the models from relatively depleted to relatively enriched compositions. The Sr abundances of depleted (MORB-source-like) and fertile (OIB-source-like) mantle were calculated by Borg et al. [9] from average Juan de Fuca N-MORB and Hawaiian tholeiite, assuming 5% partial melting of olivine-two-pyroxene peridotites and are 6 and 30 ppm, respectively. The Os abundances of the peridotites are represented by the Os compositions of mantle xenoliths from Simcoe volcano, and range from 300-1400 ppt [2]. Low Os abundances in the high $(\text{Sr}/\text{P})_{\text{N}}$ lavas suggest that these lavas are derived from a source with a relatively low Os concentration. Coincidentally, both of the depleted and fertile mantle compositions have Sr/Os ratios of $\sim 2 \times 10^4$.

The slab component is assumed to have $^{87}\text{Sr}/^{86}\text{Sr}$ of 0.7029 [9, 12] and $^{187}\text{Os}/^{188}\text{Os}$ of 1.0 (see above). Stolper and Newman [12] estimated that slab-derived H_2O -rich fluids from the Mariana arc have about 4500 ppm Sr, and Borg et al. [9] were able to successfully model the composition of subduction enriched mantle sources in the Lassen region using this concentration. Osmium abundances in the slab components are not known, but can be constrained in the models assuming that the Sr and Os geochemical and isotopic systematics discussed above are approximately correct. An additional constraint on the models is the relatively small contribution expected from the slab component. Borg et al. [9] previously modeled the slab component to represent less than 1% of the mantle source region. In the mixing models presented below this component is limited to less than 5%.

The mixing models are able to reproduce the Os-Sr isotopic data using the range of source compositions discussed above (Fig. 5) provided the slab component is enriched in Os over the slab. In order to reproduce the Sr-Os data with the mixing models the slab component must have a Sr/Os ratio of $\sim 7.5 \times 10^5$. This ratio is required regardless of whether the peridotite component is assumed to have the depleted or fertile composition. If the slab component is assumed to have a higher Sr/Os ratio, then the curve is too concave to reproduce the data, whereas if the slab component is assumed to have a lower Sr/Os ratio, then the curve is not sufficiently concave. The Sr/Os ratio of the modeled slab component is approximately 20 times higher than the Sr/Os ratio measured in average Pacific MORB [22, 39, 42], requiring Sr to be concentrated over Os in the slab component by a factor of 20.

The abundance of Os in the slab component can also be constrained by the models. If the slab component has 4500 ppm Sr, as estimated by Borg et al [9] and Stolper and Newman [12], then a very high Os abundance of 6000 ppt is required. Conversely, if a maximum of 5% slab component in the source region is assumed, then the Os abundance in the slab component can be as low as 1300 ppt. Thus, Os abundances in the slab component required by the models must be much higher than in average MORB (~ 10 ppt; [22]). Although a high concentration of Os in the slab component is consistent with the suggestion of Brandon et al. [2] that Os in the subduction environment is highly volatile and mobile as a result of high water and HCl fugacities in slab-derived fluids/melts, it requires Os to behave incompatibly in the slab during dehydration and/or melting. $D^{\text{solid/liquid}}_{\text{Os}}$ calculated for this fluid assuming MORB with Os = 10 ppt [22] range from 0.001 to 0.008 and are slightly elevated above similar partition coefficients calculated by Stolper and Newman [12] for other metals such as Cu (0.0024) and Zn (0.0020). Osmium must therefore behave slightly more compatibly during slab dehydration than Cu and Zn.

Analysis of Re and Os in eclogites, interpreted to be obducted oceanic crust, do not show evidence for major Os mobility during subduction [38]. The relatively high concentrations of Os required to be in the slab component may therefore preclude it from directly affecting Os isotopic compositions of these lavas. Below, an alternate model involving a slab component for the production of the Os isotopic variability in the Lassen CA lavas is presented.

5.3 Combined AFC and slab fluid-peridotite mixing model

Any petrogenetic model for the Lassen CA lavas must account for the fact that the lavas display: 1) large variations in Re and Os abundances that correlate with inferred source fertility, 2) inverse correlations of Os abundances and Os isotope compositions with geochemical indices of the proportion of slab component, and 3) inverse correlations between the relative source fertility and the proportion of slab component. AFC can only explain the Re-Os systematics of the Lassen lavas from a common parent if $D_{\text{Re}}^{\text{sulfide}}$ is ~40-1100 times higher than current estimates from MORB sulfides, and most LILE, HFSE, and REE behave compatibly during differentiation. Addition of a slab component with radiogenic Os can only account for the variations in Os isotopic compositions if Os behaves incompatibly during dehydration and/or melting of the slab, and Os abundances in the slab component are 100-600 times higher than typical MORB. As a result, neither of these models are satisfactory.

As noted above, variations in the abundance of Os in the Lassen CA lavas are probably not produced directly by AFC. Instead, the abundance of Os in the Lassen lavas correlates with the relative fertility of the source regions inferred on the basis of mineralogy and the magnitude of their subduction geochemical signature inferred from $(\text{Sr}/\text{P})_{\text{N}}$ ratios. This suggests that the Os abundances observed in the lavas reflect processes occurring in the mantle wedge. One possible mechanism that could account for the correlation between Os abundance and the magnitude of

the subduction signature is if fluids derived from the slab increased the stability of an Os-bearing phase, such as a sulfide, in the mantle wedge. Schiano et al [43] have identified sulfide inclusions in metasomatic minerals in xenoliths from the Luzon volcanic arc that they interpret to have formed by crystallization of a water + sulfur-rich melt derived from the subducting slab. Thus, the addition of the subduction component may indeed stabilize sulfides in the mantle wedge beneath the Lassen region. Melting of such a sulfide-rich source would result in magmas with lower Os abundances than magmas derived from a source with a smaller slab component and lower abundances of sulfides.

If this scenario is correct, the effects of crustal assimilation on the Os isotopic composition of the various Lassen magmas would be different from batch to batch because of the variable Os abundances. For a given amount of assimilation, the high $(\text{Sr}/\text{P})_N$ magmas with low Os abundances would be expected to have more radiogenic Os than the low $(\text{Sr}/\text{P})_N$ magmas with higher Os abundances. This model can account for the correlations of Os elemental and isotopic compositions with geochemical indices of the proportion of slab component in the source region. AFC models demonstrate that only ~1% assimilation of a material with the composition of lower crust [33; discussed above] by a magma with 5 ppt Os is required to increase $^{187}\text{Os}/^{188}\text{Os}$ from 0.128 to 0.283. Such a small amount of assimilation would not significantly affect the composition of phenocrysts or LILE, HFSE, and REE abundances of the lavas [9, 11].

The combination of geochemical zoning and variations in the relative fertility of mantle source regions across the arc suggest a mechanism for the origin of Lassen CA lavas that is a result of incremental melting and extraction of magma from the convecting mantle wedge as it moves across and beneath the arc. In the backarc, relatively fertile mantle melts under the influence of a relatively small proportion of slab component. These magmas have high Os

abundances and retain their mantle-like Os isotopic compositions despite small amounts of AFC. Beneath the arc axis, mantle depleted by removal of melt in the backarc melts under the influence of a larger proportion of slab component. Finally, in the forearc an even larger proportion of slab component is required to melt the now refractory mantle. These melts have lower Os abundances and consequently more radiogenic Os as a result of AFC than the arc axis or backarc magmas. This mechanism can explain the geochemical zoning of the arc and the relative fertility of the magma sources. Thus, the arc magmas are derived through the superimposed effects of progressive depletion of the mantle peridotite source from east to west and progressive increase of the proportion of the slab component from east to west. The AFC process only affects the Re-Os systematics of the magmas in proportion to their Os abundances.

6. Conclusions

The Os elemental and isotopic systematics of the Lassen CA lavas correlate with geochemical indices of the proportion of the slab component and mineralogical indices of source fertility. The lavas with the most radiogenic Os have the largest slab geochemical signatures (strong enrichments in Sr and Pb and strong depletions in Ta and Nb relative to other equally incompatible elements and have MORB-like Sr and Pb isotopic compositions) and are derived from the most depleted sources. The lavas with the least radiogenic Os have the smallest slab geochemical signatures (flat incompatible element patterns and have OIB-like Sr, Nd, and Pb isotopic compositions) and are derived from the most fertile sources.

Assimilation-fractional-crystallization models demonstrate that the variation in Re-Os elemental and isotopic systematics are unlikely to reflect differentiation in the crust from a common parent magma unless $D_{\text{Re}}^{\text{sulfide}}$ is ~40-1100 times higher than current estimates and LILE, HFSE, and REE behave compatibly during differentiation. Another possibility is that Re-

Os elemental and isotopic systematics reflect the mixing between hydrous fluids/melts derived from the slab and mantle source regions. Calculations based on Re/Os ratios of MORB and the age of the slab beneath the Lassen region indicate that subducted oceanic crust may have $^{187}\text{Os}/^{188}\text{Os}$ ratios as high as 1-1.4 and yet retain MORB-like Sr, Nd, and Pb isotopic compositions. Mixing models, however, require that Os is enriched 100-600 times in the slab component in comparison to MORB basalts. Such large enrichments in Os in the slab component may preclude this model for the production of the Lassen magmas unless the mobility of Os in the subduction environment is greater than in other mantle source regions. An alternative possibility accounting for correlations between Os isotopic compositions and geochemical indices of the proportion of slab component is that the slab-derived fluids increase the stability of an Os bearing phase, such as a sulfide, during mantle melting. This could result in low Os magmas that are relatively easily contaminated by crustal rocks during AFC. Thus, magmas derived from sources strongly enriched in slab components could have more radiogenic Os isotopic compositions than lavas derived from weakly enriched sources. In either scenario, the addition of the slab component to the mantle wedge appears to directly or indirectly result in addition of radiogenic Os to arc magmas.

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References

- [1] R.J. Walker, L.M. Echeverria, S.B. Shirey, M.F. Horan, Re-Os isotopic constraints on the origin of volcanic rocks, Gorgona Island, Columbia; Os isotopic evidence for ancient heterogeneities in the mantle, *Contrib. Mineral. Petrol.* 107 (1991) 150-162.
- [2] A.D. Brandon, R.A. Creaser, S.B. Shirey, R.W. Carlson, Osmium recycling in subduction zones, *Science* 272 (1996) 861-864.
- [3] I.J. Parkinson, C.J. Hawkesworth, A.S. Cohen. Ancient mantle in a modern arc: Osmium isotopes in the Izu-Bonin-Mariana forearc peridotites, *Science* 281 (1998) 2011-2013.
- [4] A.D. Brandon, H. Becker, R.W. Carlson, and S.B. Shirey, Isotopic constraints on time scales and mechanisms of slab material transport in the mantle wedge: Evidence from the Simcoe mantle xenoliths, Washington, USA, *Chem. Geol.* 160 (1999) 387-408.
- [5] B.I.A. McInnes, J.S. McBride, N.J. Evans, D.D. Lambert, A.S. Andrew, Osmium isotope constraints on ore metal recycling in subduction zones, *Science* 286 (1999), 512-516.
- [6] T.L. Grove, D.C. Gerlach, T.W. Sando, Origin of calc-alkaline series lavas of Medicine Lake Volcano by fractionation, assimilation, and mixing, *Contrib. Mineral. Petrol.* 80 (1982) 160-182.
- [7] S. Alves. P. Schiano, C.J. Allègre, Rhenium-osmium isotopic investigation of Java subduction zone lavas, *Earth Planet. Sci. Lett.* 168 (1999) 65-77.
- [8] M.A. Clynne, L.E. Borg, Olivine and chromian spinel in primitive calc-alkaline and tholeiitic lavas from the southernmost Cascade Range, California: A reflection of relative fertility of the source, *Can. Mineral.* 35 (1997) 453-472.
- [9] L.E. Borg, M.A. Clynne, T.D. Bullen, The variable role of slab-derived fluids in the generation of a suite of primitive calc-alkaline lavas from the southernmost Cascades, California, *Can. Mineral.* 35 (1997) 425-452.

- [10] Y. Asmerom, R.J. Walker, Pb and Os isotopic constraints on the composition and rheology of the lower crust, *Geology* 26 (1998) 359-362.
- [11] M.A. Clynne, Geologic studies of the Lassen volcanic center, Cascade Range, California, Ph.D. Dissertation, University of California, Santa Cruz, (1993) pp. 404.
- [12] E. Stolper, S. Newman, The role of water in the petrogenesis of Mariana trough magmas, *Earth Planet. Sci. Lett.* 121 (1994) 293-325.
- [13] S.B. Shirey, R.J. Walker, Carius tube digestions for low-blank rhenium-osmium analysis, *Anal. Chem.* 67 (1995) 2136-2141.
- [14] A.S. Cohen, F.G. Waters, Separation of Osmium for geologic materials by solvent extraction for analysis by TIMSW, *Anal. Chem. Acta.* 332 (1996) 269-275.
- [15] J.W. Morgan, R.J. Walker, Isotopic determinations of rhenium and osmium in meteorites by using fusion, distillation, and ion-exchange separations, *Anal. Chim. Acta* 222 (1989) 291-300.
- [16] R.A. Creaser, D.A. Papanastasio, G.J. Wasserburg, Negative thermal ion mass spectrometry of osmium, rhenium, and iridium, *Geochim. Cosmochim. Acta* 55 (1991) 397-401.
- [17] M. Guffanti, M.A. Clynne, J.G. Smith, L.J.P. Muffler, T.D. Bullen, Late Cenozoic volcanism, subduction, and extension in the Lassen region of California, southern Cascade Range, *J. Geophys. Res.* 95 (1990) 19453-19464.
- [18] C.R. Bacon, P.E. Bruggman, R.L. Christiansen, M.A. Clynne, J.M. Donnelly-Nolan, W. Hildreth, Primitive magmas at five Cascade volcanic fields: melts from hot, heterogeneous sub-arc mantle, *Can. Mineral.* 35 (1997) 397-423.
- [19] E.H. Hauri, S.R. Hart, Rhenium abundances and systematics in oceanic basalts. *Chem. Geol.* 139 (1997) 185-204.

- [20] J. Hertogen, M.-J. Janssens, H. Palme, Trace elements in ocean ridge basalt glasses: implications for fractionations during mantle evolution and petrogenesis, *Geochim. Cosmochim. Acta* 44 (1980) 2125-2143.
- [21] M. Roy-Barman, C.J. Allegre, $^{187}\text{Os}/^{188}\text{Os}$ ratios of mid-ocean ridge basalts: tracing crust recycling in the mantle, *Geochim. Cosmochim. Acta* 58 (1994) 5043-5054.
- [22] P. Schiano, J.-L. Birck, C.J. Allegre, Osmium-strontium-neodymium-lead isotopic covariations in mid-ocean ridge basalt glasses and the heterogeneity of the upper mantle, *Earth Planet. Sci. Lett.* 150 (1997) 363-379.
- [23] W.K. Hart, R.W. Carlson, S.B. Shirey, Radiogenic Os in primitive basalts from the northwestern U.S.A.: Implications for petrogenesis, *Earth Planet. Sci. Lett.* 150 (1997) 103-116.
- [24] J.T. Chesley, J. Ruiz, Crust-mantle interaction in large igneous provinces: Implications from the Re-Os isotope systematics of the Columbia River flood basalts *Earth Planet. Sci. Lett.* 154 (1998) 1-11.
- [25] E.H. Hauri, S.R. Hart, Re-Os isotope systematics of HIMU and EM II ocean island basalts from the South Pacific. *Earth Planet. Sci. Lett.* 114 (1993) 353-371.
- [26] K. Righter, J.T. Chesely, D. Geist, J. Ruiz, Behavior of Re during magma fractionation: an example from Volcán Alcedo, Galápagos, *J. Petrol.* 39 (1998) 785-795.
- [27] D.G. Pearson, S.B. Shirey, J.W. Harris, R.W. Carlson, Sulfide inclusions in diamonds from the Koffiefontein kimberlite, S. Africa: constraints on diamond age and mantle Re-Os systematics, *Earth Planet. Sci. Lett.* 160 (1998) 311-326.
- [28] S.B. Shirey, R.J. Walker, The Re-Os isotope system in cosmochemistry and high-temperature geochemistry, *Ann. Rev. Earth Planet. Sci.* 26 (1998) 423-500.

- [29] A. Zindler, S.R. Hart Chemical geodynamics, *Annu. Rev. Earth Planet. Sci. Lett.* 52 (1986) 493-571.
- [30] T. Meisel, R.J. Walker, J.W. Morgan, The osmium isotopic composition of the Earth's primitive upper mantle, *Nature* 383 (1996) 517-520.
- [31] M. Roy-Barman, G.J. Wasserburg, D.A. Papanastassiou, M. Chaussidon, Osmium isotopic compositions and Re-Os concentrations in sulfide globules from basalt glasses, *Earth Planet. Sci. Lett.* 154 (1998) 331-347.
- [32] J.C. Lassitier, J.F. Luhr, Osmium isotope and abundance variations in Mexican arc lavas: Constraints on partitioning of osmium in arc and non-arc settings, Ninth Annual V. M. Goldschmidt Conf. LPI contrib. # 971 (1999) CD ROM #7282.
- [33] A.E. Saal, R.L. Rudnick, G.E. Ravizza, S.R. Hart, Re-Os isotope evidence for the composition, formation and age of the lower continental crust, *Nature* 393 (1998) 58-61.
- [34] B.K. Esser, K.K. Turekian, The osmium isotopic composition of the continental crust, *Geochim. Cosmochim. Acta* 57 (1993) 3093-3104.
- [35] S.R. Hart, G.E. Ravizza, Os partitioning between phases in lherzolite and basalt, In *Earth Processes: Reading the Isotopic Code*, Geophysical Monograph 95 (1996) 123-134.
- [36] M. Roy-Barman, G.J. Wasserburg, D.A. Papanastassiou, Osmium isotopic composition of sulfides from basaltic glasses, *ICOG & U.S. Geological Survey Circular* 1107 (1994) pp. 272.
- [37] J.M. Eiler, B. McInnes, J.W. Valley, C.M. Graham, E.M. Stolper, Oxygen isotope evidence for slab-derived fluids in the sub-arc mantle, *Nature* 393 (1998) 777-781.
- [38] H. Becker, Re-Os fractionation in eclogites and blueschists and the implications for recycling of oceanic crust into the mantle, *Earth Planet. Sci. Lett.* (in preparation).

- [39] E. Hegner, M. Tatsumoto, Pb, Sr, and Nd isotopes in basalts and sulfides from the Juan de Fuca Ridge, *J. Geophys. Res.* 92 (1987) 11380-11, 386.
- [40] W.M. White, A.W. Hofmann, H. Puchelt, Isotope geochemistry of Pacific mid-ocean ridge basalt, *J. Geophys. Res.* 92 (1987) 4881-4893.
- [41] D. Ben Othman, W.M. White, J. Patchett, The geochemistry of marine sediments, island arc magma genesis, and crust mantle recycling, *Earth Planet. Sci. Lett.* 94 (1989) 1-24.
- [42] D.S. Stakes, J.M. Franklin, Petrology of igneous rocks at middle valley, Juna de Fuca Ridge, In Mottl, M.J., Davis, E.E., Fisher, A.T., Slack, J.F. (Eds.), *Proc. ODP Sci. Results*, 134: College Station, TX.
- [43] P. Sciano, R. Clocchiatti, N. Shimizu, R.C. Maury, K.P. Jochum, A.W. Hofmann, Hydrous, silica-rich melts in the sub-arc mantle and their relationship with erupted lavas, *Nature* 377 (1995) 595-600.
- [44] S.-S. Sun, W.F. McDonough Chemical and isotopic systematics of ocean basalts: implications for mantle composition and processes, in: A.D. Saunders & M.J. Norry (Eds), *Magmatism in the Ocean Basins*, Blackwell Scientific Publ., London, U.K., 1989, pp. 313-345
- [45] L.E. Borg, The origin and evolution of magmas from the Lassen Region of the southernmost cascades, Ph.D. Dissertation, University of Texas, Austin, (1995) pp. 228.

TABLE 1. Isotopic Data for Primitive Lassen Lavas

Sample	Re	% Re Blk	Os	% Os Blk	$^{187}\text{Re}/^{188}\text{Os}$	$^{187}\text{Os}/^{188}\text{Os}$ measured	$^{187}\text{Os}/^{188}\text{Os}$ corrected	$^{87}\text{Sr}/^{86}\text{Sr}$	$^{143}\text{Nd}/^{144}\text{Nd}$	$^{206}\text{Pb}/^{204}\text{Pb}$	$^{207}\text{Pb}/^{204}\text{Pb}$	$^{208}\text{Pb}/^{204}\text{Pb}$	$\delta^{18}\text{O}$ (‰)
LB91 -105 ^a	109	0.11	76.9	3.4	6.88	0.14645 ±27	0.14616 ±57	0.70416	0.512771	18.988	15.635	38.690	+6.1
LC85 -671 ^a	75.8	0.08	144	1.9	2.53	0.12894 ±18	0.12845 ±38	0.70425	0.512780	18.965	15.630	38.637	+7.4
LC86 -905 ^a	149	0.15	370	0.8	1.94	0.13808 ±19	0.13795 ±26	0.70393	0.512813	18.972	15.607	38.612	+5.9
LB92 -170 ^a	123	0.12	180	1.4	3.31	0.14638 ±10	0.14626 ±21	0.70343	0.512918	18.809	15.590	38.419	+6.5
LC86 -1005 ^b	164	0.16	176	1.5	4.49	0.13738 ±30	0.13712 ±43	0.70383	0.512898	18.863	15.608	38.506	+5.6
LC86 -829 ^{a,c}	17.8	0.02	48.4	5.4	1.77	0.15317 ±24	0.15309 ±58	0.70401	0.512799	18.975	15.613	38.567	+6.7
LC88 -1312 ^b	54.1	0.05	4.53	36.7	58.6	0.23528 ±50	0.2829 ±150	0.70317	0.512970	18.814	15.579	38.388	+6.9
LC83 -255 ^{b,c}	22.9	0.02	17.7	13.7	6.34	0.24974 ±47	0.2651 ±41	0.70308	0.512901	18.844	15.585	38.406	+6.9
LC88 -1308 ^a	120	0.12	61.3	4.4	9.53	0.19674 ±30	0.19867 ±33	0.70321	0.512961	18.757	15.547	38.272	+7.2
LC86 -1009 ^a	26.0	0.03	11.1	19.5	11.22	0.25314 ±54	0.2773 ±103	0.70305	0.512869	18.674	15.535	38.217	+6.9

a. Sr, Nd, Pb, and O isotopic data from [9]; b. Sr, Nd, Pb, and O isotopic data from [18], c. Pb or O isotopic data previously unpublished. Uncertainties are 2 sigma and are in last digits reported. Concentration of Re and Os in parts per trillion. %Re Blk and %Os Blk refer to contribution of from blank to Re and Os abundances. $^{187}\text{Os}/^{188}\text{Os}$ corrected for blank contribution using $^{187}\text{Os}/^{188}\text{Os}$ of blank = 0.155.

APPENDIX. Major and Trace Element Data For Primitive Lassen Lavas

sample	LB91 -105 ^a	LC85 -671 ^a	LC82 -905 ^a	LB92 -170 ^a	LC86 -1005 ^b	LC86 -829 ^a	LC88 -1312 ^b	LC83 -255 ^a	LC88 -1308 ^{a,c}	LC86 -1009 ^a
(Sr/P) _N	1.49	1.67	1.69	3.27	3.79	3.89	5.37	5.47	5.96	6.52
SiO ₂	52.09	51.35	50.37	50.53	51.30	51.50	50.80	54.49	51.46	58.17
TiO ₂	0.92	1.19	0.99	0.64	0.52	0.71	0.73	0.85	0.60	0.52
Al ₂ O ₃	16.83	17.02	17.73	16.78	15.70	17.24	16.60	17.07	16.82	16.00
FeO*	7.61	8.45	8.43	7.99	8.37	7.33	7.83	6.31	7.38	5.62
MnO	0.14	0.15	0.16	0.15	0.14	0.13	0.15	0.10	0.16	0.10
MgO	8.91	8.05	8.43	10.52	11.10	9.20	9.97	7.73	9.09	7.57
CaO	8.85	9.14	9.79	9.89	10.70	10.42	11.00	8.98	11.25	7.72
Na ₂ O	3.07	3.14	3.02	3.67	2.45	2.57	2.48	3.47	2.59	3.25
K ₂ O	1.11	1.02	0.65	0.51	0.32	0.61	0.30	0.63	0.41	0.80
P ₂ O ₅	0.31	0.30	0.25	0.13	0.08	0.12	0.10	0.23	0.08	0.12
Mg#	72.3	68.0	69.0	74.6	71.5	73.7	70.1	73.2	73.3	75.0
Rb	18.0	16.8	7.3	8.7	3.3	6.7	4.7	12.9	6.2	9.7
Ba	323	371	285	158	112	187	108	293	121	181
Zr	134	130	116	64	59	75	80	139	69	100
Sr	452	487	408	416	294	452	520	1220	462	758
Y	21	22	23	16	14	15	19	15	22	17
Nb	14	10	10		1.5	2	2.2	3	5	3
Ni	190	172	149	260	209	158	85	136	166	182
Cr	370	317	340	581	628	401	501	249	444	242
Co	35	36.7	41	42	43.7	39	38.5	32	38	30
Cs	0.60	0.47	0.37	0.22	0.107	0.43	0.226	0.29	0.35	0.47
Hf	2.7	2.7	2.43	1.6	1.14	1.65	1.72	2.66	1.35	1.83
Ta	0.5	0.63	0.51	0.25		0.25	0.162	0.33	0.14	0.13
Th	1.6	1.93	1.74	1.0	0.61	1.1	0.68	1.96	0.55	1.14
U	0.5	0.31	0.58	0.27	0.41	0.25		0.54		0.8
Pb			4.3		1.40		1.40	4.3	1.5	3.4
La	13.9	13.9	12.37	6.4	3.69	7.0	6.99	18.6	3.95	7.53
Ce	30	29	27.47	12	8.96	15	16.44	37.8	9.51	16.04
Nd	15	16.1	15.41	8.0	6.09	8.6	9.48	21	6.39	9.32
Sm	3.2	3.94	3.46	2.18	1.69	2.47	2.26	3.77	1.77	2.12
Eu	1.05	1.21	1.09	0.73	0.61	0.80	0.83	1.09	0.675	0.73
Gd			3.55		1.98		2.58	3.20	2.21	2.01
Tb	0.60	0.63		0.38		0.44		0.42		
Dy					2.22		3.20		2.78	1.85
Er					1.45		2.21		1.89	1.06
Yb	1.84	3.07	2.32	1.40	1.44	1.60	2.20	1.30	1.93	0.98
Lu	0.24	0.30	0.34	0.21		0.22		0.22	0.307	0.16
Olivine Fo	88.2	86.8	87.2	88.9	85.1	89.5	89.8	87.7	88.9	90.1
Spinel Cr#	46.1	42.6	33.7	49.8	51.8	44.1	42.8	65.4	46.3	70.9

Mineralogical data from [8, 45]. a. major and trace element data from [9]; b. major and trace element data from [18], c. supplemental trace element data from [11]. Mg# calculated using $\text{Fe}_2\text{O}_3 = 0.2 \times \text{Total Fe analyzed as Fe}_2\text{O}_3$. $\text{Mg\#} = 100(\text{Mg}/(\text{Mg} + \text{Fe}^{+2}))$ atomic.

Figure Captions

Figure 1. Incompatible element spider diagram illustrating differences between a representative low $(\text{Sr}/\text{P})_{\text{N}}$ calc-alkaline lava (LC85-671) and a high $(\text{Sr}/\text{P})_{\text{N}}$ calc-alkaline lava (LC86-1009). Normalized to primitive mantle values of Sun and McDonough [44]. Note the relatively high incompatible element abundances and relatively smooth pattern of the low $(\text{Sr}/\text{P})_{\text{N}}$ lava and the strong enrichments in Sr and Pb and depletions in Ta and Nb of the high $(\text{Sr}/\text{P})_{\text{N}}$ lava. These differences are attributed primarily to variable contributions of a slab component to variably incompatible-element-depleted peridotites of the mantle wedge [8, 9].

Figure 2. Plots illustrating covariation of selected mineralogical, geochemical, and isotopic compositions with $(\text{Sr}/\text{P})_{\text{N}}$. Filled circles are lavas with $(\text{Sr}/\text{P})_{\text{N}} > 3.3$ and open squares are lavas with $(\text{Sr}/\text{P})_{\text{N}} < 3.3$. Positive correlation of $(\text{Sr}/\text{P})_{\text{N}}$ with LILE/HFSE ratios, such as Ba/Ta, suggests that $(\text{Sr}/\text{P})_{\text{N}}$ is representative of the subduction geochemical signature [9]. Correlation between $(\text{Sr}/\text{P})_{\text{N}}$ and spinel Cr# suggests that the source region also becomes less fertile (fewer easily fusible components) as the relative proportion of slab components in the source increases [8]. Inverse correlation between $(\text{Sr}/\text{P})_{\text{N}}$ and $^{87}\text{Sr}/^{86}\text{Sr}$ indicates the slab component contributes unradiogenic Sr to the mantle wedge. Note that lavas derived from sources inferred to have large subduction geochemical signatures have low Os abundances and radiogenic Os isotopic compositions.

Figure 3. Plots illustrating covariation of selected mineralogical, geochemical, and isotopic compositions with Re (a-d) and Os (e-h) abundances. Symbols same as Fig. 2. AFC models are included on Os plots. Tick marks are at $F = 1\%$ intervals where F represents fraction of magma remaining. Note log scale for Ni, Re, and Os abundances. The parent magma is assumed to have $\text{Re} = 250$ ppt, $\text{Os} = 400$ ppt, and $\text{Ni} = 250$ ppm and the same isotopic composition as

sample LC85-671. Bulk distribution coefficients are calculated assuming that the modal sulfide/olivine ratio in the fractionating assemblage is 0.0004, $D_{Os}^{sulfide}$ is 48000 [30], and $D_{Re}^{sulfide}$ and $D_{Os}^{olivine}$ are both 0. $D_{Re}^{olivine}$ and $D_{Os}^{olivine}$ near 0 are warranted on the basis of measured $D_{Re}^{olivine}$ of 0.01 [34] and the likelihood of similar partitioning of Re and Os in olivine. $D_{Ni}^{olivine}$ and $D_{Re}^{sulfide}$ are varied in the models. The numbers besides the various curves on figure e represent $D_{Ni}^{olivine}$, whereas the numbers beside the curves on figures f-g represent $D_{Re}^{sulfide}$. For Ni, Re, and Re/Os models (Figs. e-g), the assimilant is assumed to have Re = 250 ppt, Os = 10 ppt, and Ni = 100 ppm. The Re-Os-Ni systematics can only be reproduced if $D_{Ni}^{olivine}$ is ~5 (Fig. e) and significantly lower than the values of 10-25 estimated by Clyne and Borg [8]. $D_{Re}^{sulfide}$ must be ~48000 (Fig. f-g) and significantly above the values of 43-1200 estimated by Roy-Barman et al. [30, 36]. Numbers beside curves in figure h identify mixing models with different assimilant compositions. The assimilant modeled in curves 1 and 2 has upper crustal characteristics: Os = 10 ppt and $^{187}Os/^{188}Os = 4$ and Os = 10 ppt and $^{187}Os/^{188}Os = 1$, respectively. Curve 3 the assimilant has lower crustal characteristics: Os = 50 ppt and $^{187}Os/^{188}Os = 0.8$ [32]. Note that the assimilant with an upper crustal Os abundance must have very radiogenic Os to reproduce the compositions of the Lassen lavas.

Figure 4. Plots of $^{87}Sr/^{86}Sr$, $^{143}Nd/^{144}Nd$, and $^{206}Pb/^{204}Pb$ versus $^{187}Os/^{188}Os$. Hypothetical mantle source compositions are also plotted on figures (diamonds) for reference (Os isotopic compositions from [27]). Symbols same as Fig. 2. Note that as $^{187}Os/^{188}Os$ increases $^{87}Sr/^{86}Sr$ and $^{206}Pb/^{204}Pb$ decrease and $^{143}Nd/^{144}Nd$ increases. Lassen lava LC85-671 lies on a mixing line between ~80% depleted MORB source (DMM; Sr = 120 ppm, Nd = 5 ppm, Pb = 0.5 ppm, Os = 50 ppt) and ~20% EM II source (Sr = 350 ppm, Nd = 20 ppm, Pb = 2 ppm, Os = 100 ppt) indicating that it has an isotopic composition that is consistent with derivation from a potential mantle source. Tick marks on mixing line represent 20% intervals.

Figure 5. Plot of $^{87}\text{Sr}/^{86}\text{Sr}$ versus $^{187}\text{Os}/^{188}\text{Os}$. Curve illustrates the results of mixing mantle peridotites with a slab component. Symbols same as Fig. 2. The Sr/Os ratios calculated for both depleted and fertile mantle is $\sim 2 \times 10^4$ (see text). The slab component must have a Sr/Os ratio of 7.5×10^5 to reproduce the Lassen isotopic data. All mixing curves have identical shapes because Sr/Os ratios in the depleted and fertile peridotite component are the same. The numbers below the curve represent % slab component assuming a depleted mantle composition with Sr = 6 ppm, Os = 300 ppt; $^{187}\text{Os}/^{188}\text{Os} = 0.128$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70425$ and a slab component with Sr = 4500 ppm, Os = 6000 ppt; $^{87}\text{Sr}/^{86}\text{Sr} = 0.7029$; $^{187}\text{Os}/^{188}\text{Os} = 1$ (model 1). Numbers above the curve represent % slab component assuming a fertile mantle composition with Sr = 30 ppm, Os = 1400 ppt; $^{187}\text{Os}/^{188}\text{Os} = 0.128$; $^{87}\text{Sr}/^{86}\text{Sr} = 0.70425$ and a slab component with Sr = 4500 ppm, Os = 6000 ppt; $^{87}\text{Sr}/^{86}\text{Sr} = 0.7029$; $^{187}\text{Os}/^{188}\text{Os} = 1$ (model 2). The results of mixing depleted mantle with a slab component with Sr = 975 ppm, Os = 1300 ppt; $^{87}\text{Sr}/^{86}\text{Sr} = 0.7029$; $^{187}\text{Os}/^{188}\text{Os} = 1$ are the same as model 2. This model represents the lowest Sr and Os abundances permissible in the slab component assuming that the source region contains less than 5% slab component. Note that all of the mixing models require a slab component that is strongly enriched in Os over oceanic crust, and therefore for Os to behave incompatibly during dehydration/melting of the slab.

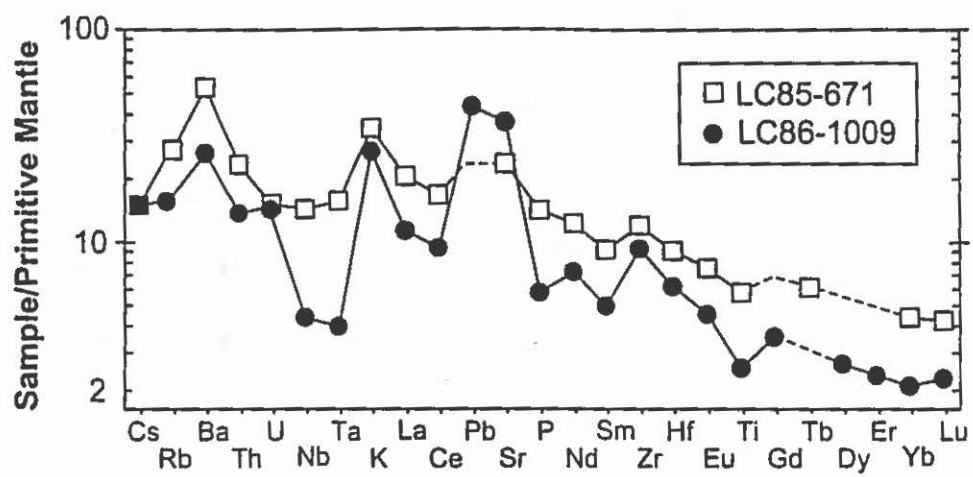


Figure 1

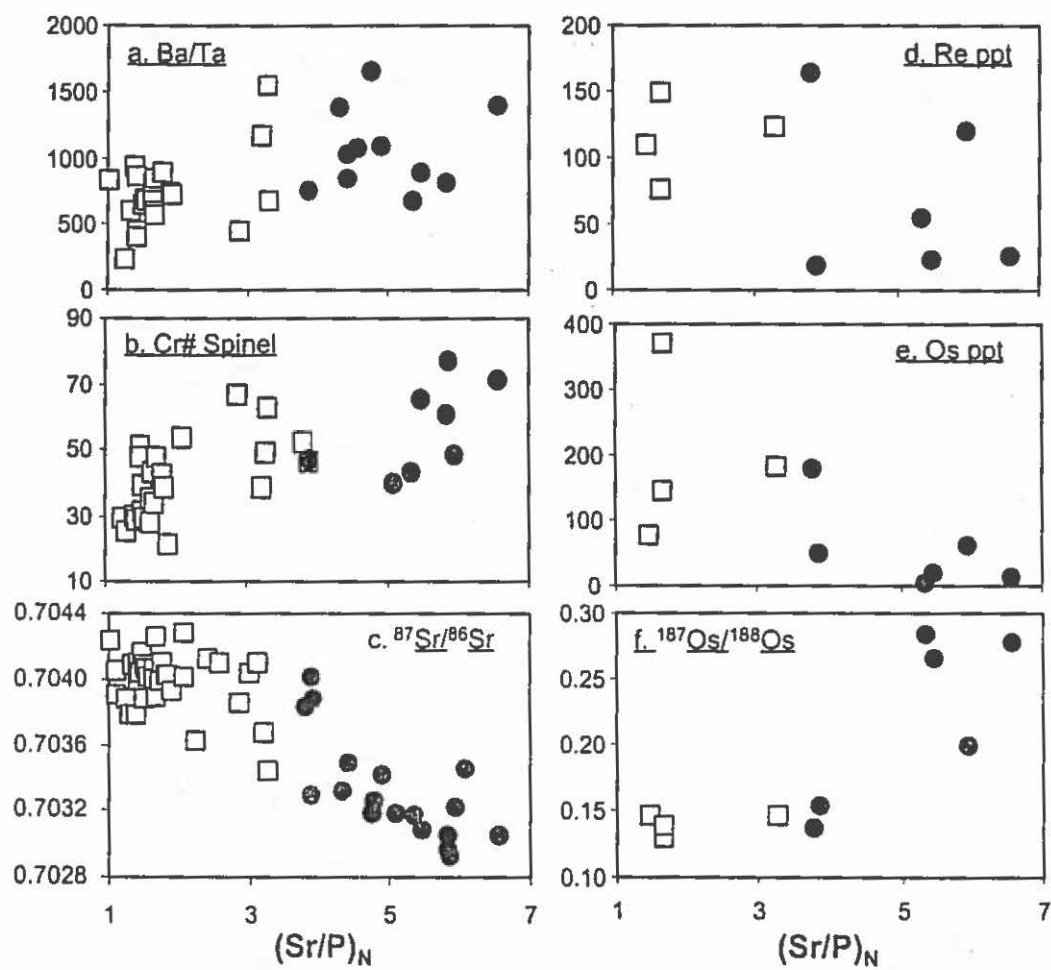


Fig. 2

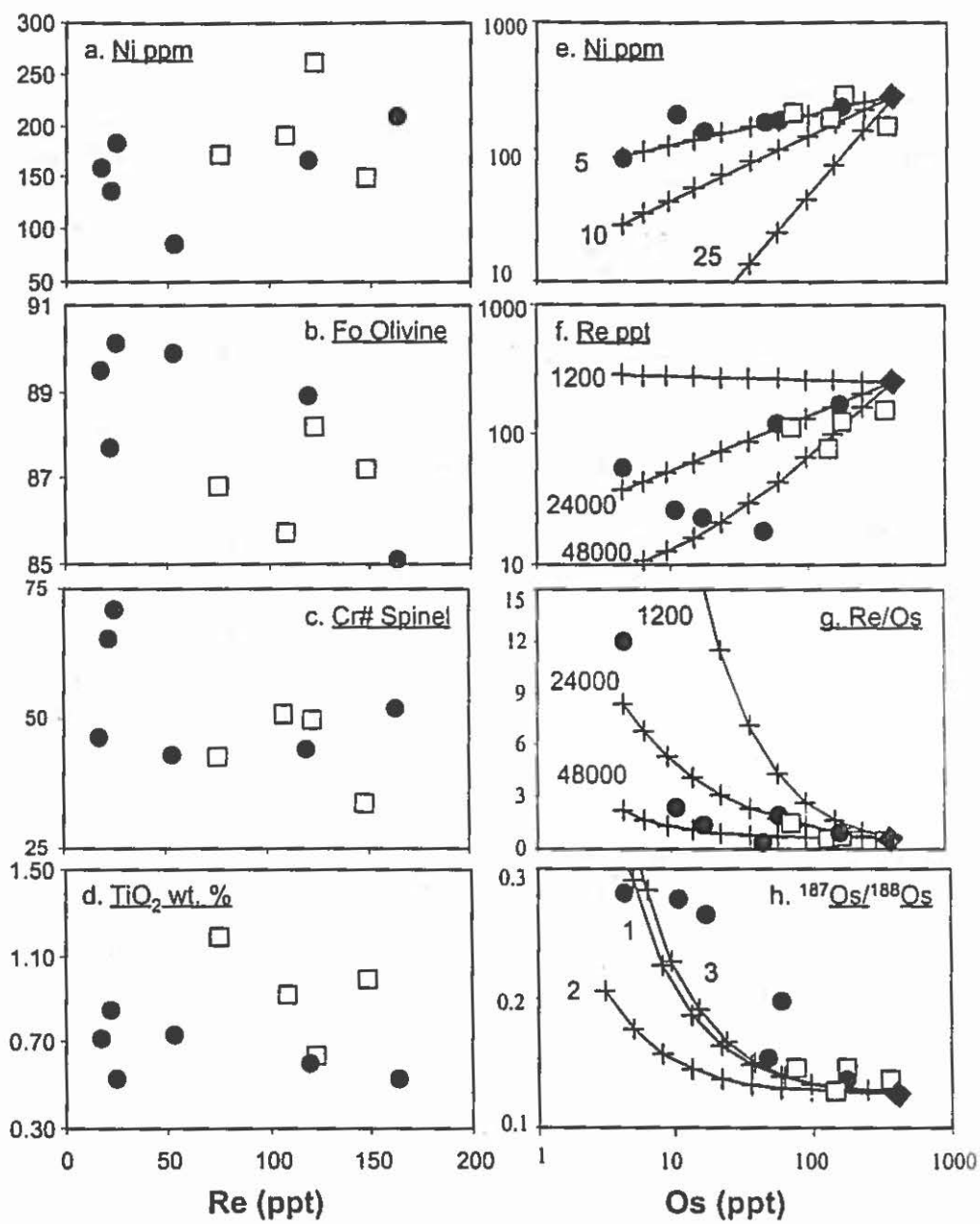


Fig. 3

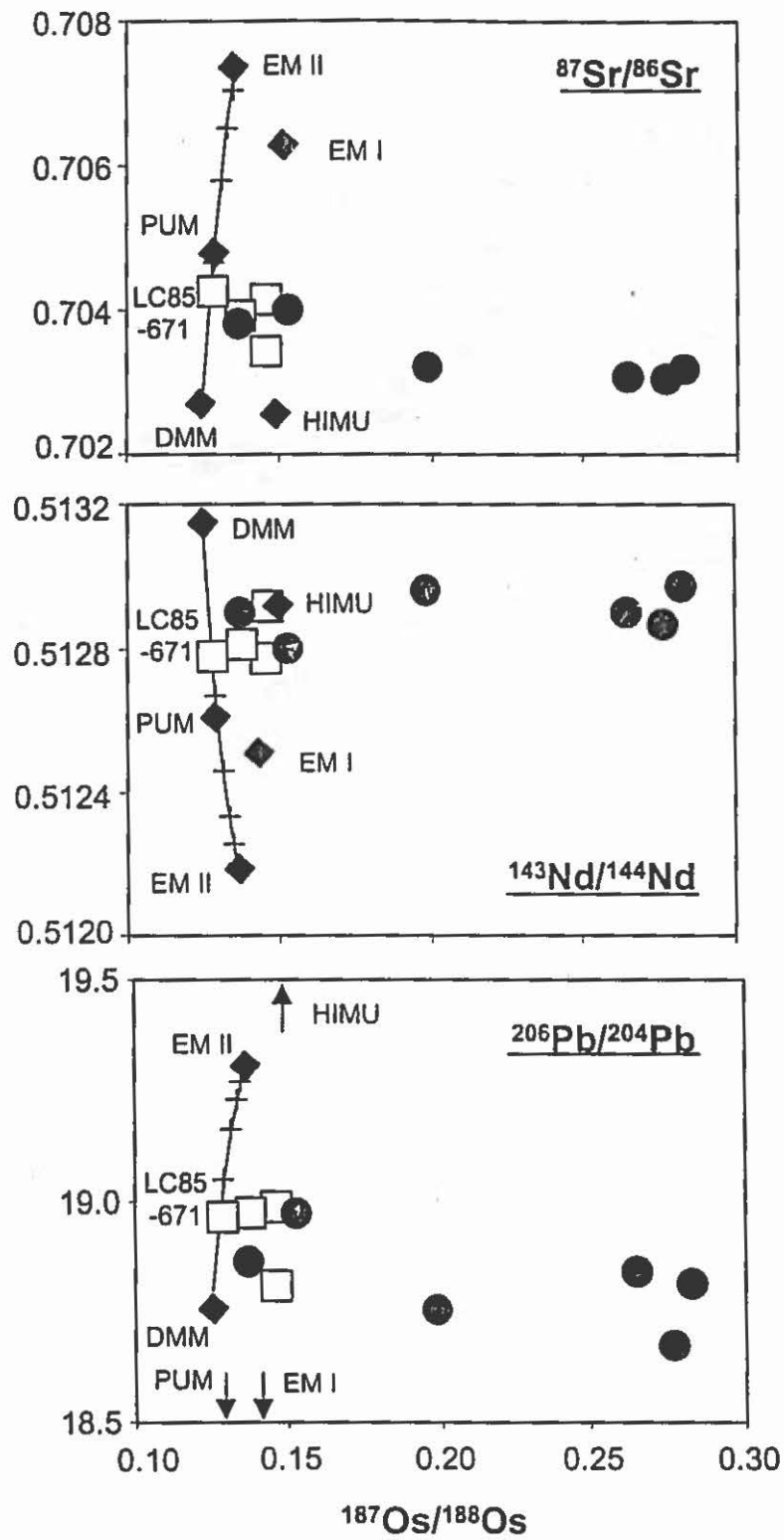


Fig. 4

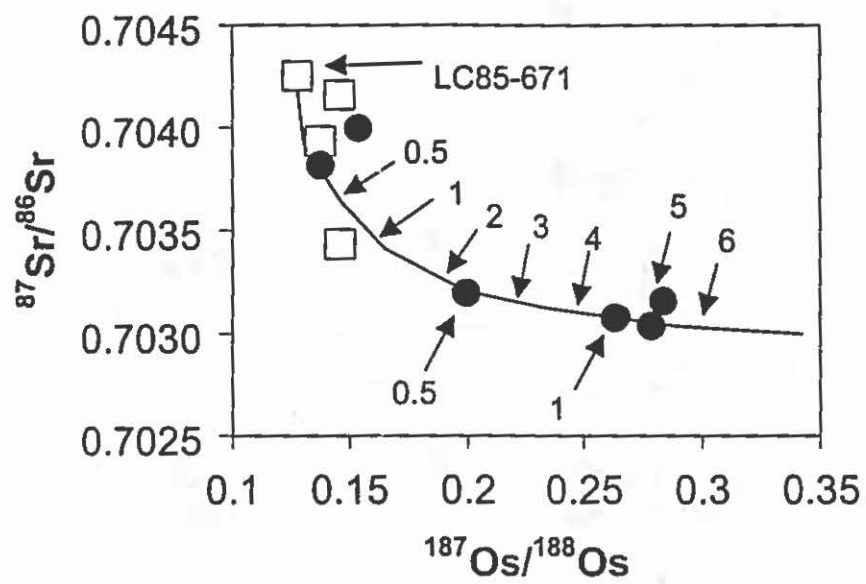


Fig. 5