Os and U-Th isotope signatures of arc magmatism near Mount Mazama, Crater Lake, Oregon

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Abstract

Interaction of mantle melts with the continental crust can have significant effects on the composition of the resulting melts as well as on the crust itself, and tracing this interaction is key to our understanding of arc magmatism. Lava flows and pyroclastic deposits erupted from ~50 to 7.7 ka at Mt. Mazama (Crater Lake, Oregon) were analyzed for their Re/Os and U-Th isotopic compositions. Mafic lavas from monogenetic vents around Mt. Mazama that erupted during the buildup to its climactic eruption have lower $^{187}\text{Os}/^{188}\text{Os}$ ratios (0.1394 to 0.1956) and high ^{230}Th excess ($((^{230}\text{Th}/^{238}\text{U})_0$ of 1.18 to 1.302), whereas dacites and rhyodacites tend to have higher $^{187}\text{Os}/^{188}\text{Os}$ ratios (0.2292 to 0.2788) and significant ^{238}U excess ($((^{230}\text{Th}/^{238}\text{U})_0$ of 0.941 to

0.989). The less radiogenic Os isotope compositions of the mafic lavas can be modeled by assimilation of young (2.5 to 7 Ma), mafic lower crust that was modified during regional extension, whereas the more radiogenic Os isotope compositions of the dacites and rhyodacites can be attributed to assimilation of older (~10 to 16 Ma), mid to upper crust that acquired its composition during an earlier period of Cascade magmatism. Production of Th excesses in the lower crust requires very young garnet formation accompanying dehydration melting in the lower crust at less than a few 100 ka by heat from recent basaltic magma injection. The results from this study suggest that the combination of Os and Th isotopes may be used to provide insights into the timescales of evolution of the continental crust in arc settings, as well the influence of the crust on erupted magmas, and suggest a link between the age and composition of the lower and upper crust to regional tectonic extension and/or earlier Cascade magmatism.

Keywords: Mount Mazama, Crater Lake, Cascade arc, crustal assimilation, Os isotopes, U-Th isotopes

1. Introduction

Storage and differentiation of mafic magmas in the lower crust are processes that are central to models for crustal arc magmatism (e.g., Annen et al., 2006; Dufek and Bergantz, 2005; Hildreth and Moorbath, 1988; Raia and Spera, 1997), and can impart distinct geochemical signatures on arc magmas (e.g., Conrey et al., 2001; Hart et al., 2002; Hora et al., 2009). Tracing the interaction between mantle melts and crust at depth can be difficult in young, mafic arcs such as the Cascades, because the isotopic contrast between the mantle and crust may be too small to be reliably detected using common tracers such as O, Sr, Nd, Hf, and Pb isotopes (e.g., Bacon et al., 1997, 1994; Hildreth, 2007; Schmidt et al., 2008). The use of Re-Os isotopes, in concert with U-series isotopes, may provide an alternative means for identifying intracrustal melting,

assimilation, and homogenization processes in arcs underlain by young, mafic crust. These isotopic systems have been used individually in the Cascades to infer crustal interaction (Ankney et al., 2013; Hart et al., 2003, 2002; Schmidt et al., 2013), but only one previous study has combined them (Jicha et al., 2009b).

In the Re-Os system, rhenium behaves incompatibly during melting of the mantle and partitions into basaltic magmas injected into the crust, and the resultant high Re/Os ratios may produce highly radiogenic Os isotope compositions in young, mafic crust in only a few million years (Hart et al., 2003, 2002). New melts rising from the mantle that assimilate mafic crust will produce lavas with Re/Os isotope ratios that correspond to the age of the preceding intrusive event if the initial Os contents of the new melts are low enough to be dominated by crustal components (Hart et al., 2003).

U-Th isotopes have been used as tracers of many arc processes including slab dehydration, melting of the mantle, the slab, and subducted sediments, and assimilation of both the lower and upper crust (e.g., Ankney et al., 2013; Berlo et al., 2004; Jicha et al., 2009b; Reubi et al., 2014; Sigmarsson et al., 1998; Turner et al., 2000, 1997; Wende et al., 2015). Most arcs are dominated by ^{238}U -excesses ($(^{230}\text{Th}/^{238}\text{U})_0 < 1$), which are usually attributed to fluid-fluxing of the mantle wedge (e.g., Turner et al., 2003), whereas the Cascades are characterized by high ^{230}Th -excesses ($(^{230}\text{Th}/^{238}\text{U})_0 > 1$, Ankney et al., 2013). Excesses of ^{230}Th can be explained by various mantle and crustal processes. In the crust, generating Th-excesses is typically linked to the strong fractionation of U from Th by mineral phases such as garnet, Al-rich clinopyroxene, and zircon during partial melting or fractional crystallization (e.g., Blundy and Wood, 2003; Scheibner et al., 2008; Wood et al., 1999). The exceptionally high Th-excesses in the Cascades have been ascribed to assimilation of partial melts of crust that is garnet-bearing or where garnet

was produced in the residuum (e.g., Ankney et al., 2013; Jicha et al., 2009b; Wende et al., 2015). Preservation of these ^{230}Th -excesses also provides time constraints on the processes of crustal melting, as magmas would return to secular equilibrium after ~300 ka (Peate and Hawkesworth, 2005).

The combination of the Re-Os and U-Th isotope systems offers a potential tool to investigate and quantify fundamental processes occurring at depth in continental arcs. This may include the extent of interaction between arc magmas and mafic crustal substrate, and the effect of this interaction on not only the composition of the resulting magmas, but also the crust itself, which is essential for understanding the evolution of the crustal column in arc settings. In this study, we use Re/Os and U-Th isotopes in an attempt to enhance our understanding of the role of crustal assimilation in generating erupted compositions at Mt. Mazama, and provide constraints on the composition, age, and development of possible crustal contaminants.

2. Geologic background and prior isotopic evidence for crustal interaction

Crater Lake is located in the central part of the Cascade arc and at the western edge of the extensional Basin and Range province, which has produced a large number of mafic, monogenetic volcanoes, in addition to the large composite volcano characteristic of arc volcanism (Bacon and Lanphere, 2006) (Figure 1). The climactic eruption of Mt. Mazama at ~7.7 ka vented ~50 km³ of primarily rhyodacite magma as pyroclastic material and was accompanied by collapse of Crater Lake caldera (Bacon, 1983). Storage of magmas in the large, shallow magma chamber associated with the climactic eruption is expected to result in crustal assimilation (e.g., Bacon et al., 1989; Bacon and Lowenstern, 2005). On the other hand, mafic lavas erupted in the Mt. Mazama region likely would have experienced little to no residence time in the upper crust. These lavas therefore allow us to discern the range of parental magmas rising

from the mantle (e.g., Bacon et al., 1997; Bacon, 1990), and, where crustal interaction occurred, may also give insight into the composition of the lower crust. Previous isotope studies provide strong evidence for lower and upper crustal interaction in the petrogenesis of magmas erupted at Mt. Mazama and elsewhere in the Cascades (e.g., Ankney et al., 2013; Bacon et al., 1994; Bacon and Lowenstern, 2005; Jicha et al., 2009b; Schmidt et al., 2013; Wende et al., 2015). This interaction potentially provides an opportunity to evaluate the age and isotopic variability of the crust beneath Mt. Mazama, as well as variability in the composition of the crust along the Cascade arc through comparison with other studies.

3. Results

We report Os, U-Th, and Sr isotope data for lavas and pyroclastic volcanic rocks erupted during the buildup to and during the 7.7 ka caldera-forming eruption of Mt. Mazama (Crater Lake, Oregon) (Table A.1 in supplemental material). Details regarding sample selection and analytical methods are presented in Appendix A (supplemental material). Volcanic rocks from Mt. Mazama and the surrounding region have $^{187}\text{Os}/^{188}\text{Os}$ ratios that range from 0.1394 to 0.2794 ($\gamma_{\text{Os}} = +9$ to +119) as measured in magnetite and olivine separates, and are divisible into two distinct groups, one at lower and one at higher γ_{Os} , as seen in Figure 2. The low- γ_{Os} group extends from γ_{Os} of +9 to +53, and includes all of the mafic lavas erupted from monogenetic volcanoes, as well as a preclimactic (i.e., prior to the caldera-forming eruption) rhyodacite (Sharp Peak) and low-Sr scoria from the climactic eruption. The high- γ_{Os} group has γ_{Os} values that range from +76 to +119. The majority of samples erupted from the main Mt. Mazama volcanic complex are included in this group. Osmium isotope ratios measured in both olivine and magnetite separates in three lavas erupted from monogenetic volcanoes show that olivine has consistently lower $^{187}\text{Os}/^{188}\text{Os}$ ratios than magnetite. Magnetite separates are likely more

representative of the whole-rock Os isotope compositions of the crystallized magma, as olivine is often found in plagioclase + olivine $\pm$ augite microxenoliths in these units (Bacon, 2008). These microxenoliths likely are the result of assimilation of relatively shallow gabbroic rocks (Bacon, 2008).

The high- and low- γ_{Os} groups are also broadly distinguishable based on their whole-rock U-Th isotope compositions (Figure 3). The high- γ_{Os} group clusters around the equiline, and have only slight U- or Th-excesses ($<2\%$ ^{238}U - or ^{230}Th -excess) whereas the low- γ_{Os} group extends across a wide range of $(^{230}\text{Th}/^{238}\text{U})_0$ ratios from 0.941 to 1.306 (6.2% ^{238}U -excess to 30.6% ^{230}Th -excess). Several units analyzed for U-Th isotopes in this study were previously analyzed by Ankney et al. (2013). The data reported in this paper represent new samples collected from these units during fieldwork in 2010-2013 (sample numbers beginning “MBCL”) and 1998 (sample numbers beginning “98CH”). The trends in U-Th isotope compositions measured for this study are in agreement with those observed in Ankney et al. (2013). In several units for which multiple samples were analyzed, the U-Th isotope compositions vary slightly beyond analytical uncertainty. This suggests that there is some isotopic heterogeneity within these units. Notable examples include the basaltic andesite of Red Cone and the basalt of Castle Point. Strontium isotope compositions for both groups show no correlation with Os or U-Th isotope compositions and vary over similar ranges (low- γ_{Os} group $^{87}\text{Sr}/^{86}\text{Sr} = 0.70345\text{-}0.70376$; high- γ_{Os} group $^{87}\text{Sr}/^{86}\text{Sr} = 0.70353\text{-}0.70379$; Figure 2), in part reflecting variability in parental magmas at Mt. Mazama.

4. Discussion

4.1. Evidence for young, mafic lower crust and older, evolved upper crust

The Os isotope compositions measured for both the low- and high- γ_{Os} group are significantly more radiogenic than those measured for mantle xenoliths from Simcoe Volcanic Field (Brandon et al., 1999, 1996), as well as for MORBs and OIBs (e.g., Hauri and Hart, 1997, 1996; Schiano et al., 1997), suggesting that their compositions do not simply represent variability of their mantle sources. This also implies that both groups were affected by interaction with more radiogenic Os components. Radiogenic Os isotope compositions measured at Lassen Volcanic Center (Hart et al., 2002), Mt. Adams (Hart et al., 2003; Jicha et al., 2009b), and the North Sister and Little Brother volcanoes (Schmidt et al., 2013), all of which overlap with values measured for Mt. Mazama, are interpreted to reflect assimilation processes in the deep crust. A role for the assimilation of both lower and upper crust in the petrogenesis of magmas at Mt. Mazama is supported by large variations in U-Th isotope compositions and extensive modeling by Ankney et al. (2013). High Th-excesses measured in more primitive lavas erupted at monogenetic volcanoes are interpreted to reflect assimilation of partial melts generated through dehydration melting of mafic lower crust where garnet was produced in the residuum via the breakdown of amphibole and plagioclase (e.g., Wolf and Wyllie, 1993). Modeling suggests that rare earth element concentrations for mafic lavas erupted from monogenetic cones, and for low-Sr and high-Sr scoria erupted during the climactic eruption, are also permissive of mixing between partial melts of the mantle and lower crust (Ankney et al., 2013). Lower crustal assimilation and a role for garnet has also been proposed as a potential source for high Th-excesses measured in samples from Mt. Adams (Jicha et al., 2009b) and Mt. Shasta (Wende et al., 2015). Uranium excesses observed in preclimactic and climactic dacites and rhyodacites are thought to be the result of assimilation of an upper crustal component recently enriched in U via shallow hydrothermal circulation (~40-70 ka). Assimilation of shallow crust that has exchanged with

hydrothermal fluids is supported by relatively low- $\delta^{18}\text{O}$ values measured for preclimactic and climactic eruptive products (Bacon et al., 1989, 1994), and the presence of partially melted, low- $\delta^{18}\text{O}$ granitoid blocks in deposits of the climactic eruption, as well as rare occurrences in preclimactic eruption products (Bacon et al., 1989). The granitoid blocks and associated antecrysts are thought to represent wall rock that was assimilated by the growing climactic magma chamber (Bacon et al., 1989, 2000; Bacon and Lowenstern, 2005).

The high Th-excesses measured for basalt to basaltic andesite lavas erupted from monogenetic cones in this study are consistent with those measured in Ankney et al. (2013), although we point out that a more recent study by Reubi et al. (2014) suggests that large Th-excesses in arc magmas can also be traced to melting of sediments. We do not, however, observe any correlation between Th-excesses and high Th/La and Th/Nb or low Sm/La in Mt. Mazama samples, which are used by Reubi et al. (2014) as indicators of interaction with sediment melts. For these reasons, we choose to focus our discussion on evaluating crustal components involved in generating both the measured Os and U-Th isotope compositions, particularly with regard to determining the age of possible crustal contaminants.

As a result of the compatible nature of Os during partial melting of the mantle, Os has low concentrations in mantle-derived melts especially at extents of melting less than 15-20%. Furthermore, fractionation of mafic minerals quickly lowers Os contents during differentiation of mantle-derived melts. Differentiating magmas in the deep crust with such low Os contents will therefore tend to acquire the Os isotope composition of crustal assimilants (e.g., Asmerom and Walker, 1998; Chesley et al., 2002; Lassiter and Luhr, 2001).

Vertical stratification of the continental crust has been previously documented based on *P*-wave velocities and compositions of deep crustal xenoliths (Rudnick and Fountain, 1995).

This stratification is thought to result from crustal differentiation where mantle-derived melts that pool at the base of the crust create a mafic lower crust and more evolved upper crust (e.g., Annen et al., 2006; Bachmann et al., 2007; Raia and Spera, 1997). Importantly, the development of compositional stratification is a primary result of the processes by which continental crust forms and evolves. This process is incremental in nature, and thus can produce crust that is variable not only in composition, but also in age and Os isotopic composition (e.g., Hart et al., 2002; Schmidt et al., 2013). Given that U-Th isotope compositions at Mt. Mazama may be produced by interaction with distinct crustal domains (Ankney et al., 2013), we propose that the differences in Os isotope compositions between the low- and high- γ_{Os} groups at Mt. Mazama may reflect melting and assimilation of different crustal contaminants at varying depths in the crust.

The low- γ_{Os} group is dominated by high Th excess lavas, but also includes the rhyodacite of Sharp Peak and low-Sr scoria samples, which have U-excesses of 0.6% and 6.2% respectively. The radiogenic Os isotope compositions of the low- γ_{Os} group relative to the mantle are consistent with interaction with a crustal component. We suggest this is probably a partial melt of a mafic lower crust, because the basalt to basaltic andesite lavas that comprise most of the low- γ_{Os} samples likely experienced little to no residence time in the upper crust. For those samples in Th-excess, modeling by Ankney et al. (2013) argues strongly for a role for garnet to produce the high Th-excesses. The Os and U-Th isotope composition of the low-Sr scoria, on the other hand, reflects either the absence of the influence of garnet on the petrogenesis of the low-Sr parent or masking of the effect of garnet by assimilation of U-enriched material. The U-Th isotope composition of the rhyodacite of Sharp Peak is likely due to mixing between low-Sr (U-excess) and high-Sr (Th-excess) parents (Ankney et al., 2013). For both the rhyodacite of Sharp

Peak and low-Sr scoria, as well as the high- γ_{Os} samples discussed below, U-enrichment is probably associated with more recent processes relative to those that generated the Os isotope compositions of the two crustal components, as crust older than a few 100 ka would not retain ^{238}U -excesses.

The high- γ_{Os} group contains samples with more evolved compositions and/or those from units associated with the central Mt. Mazama edifice. We propose that their Os isotope compositions may reflect assimilation of an older (relative to the low- γ_{Os} group), mid to upper crust as a consequence of residence in the silicic upper crustal magma chamber beneath Mt. Mazama. The rhyodacite of Sharp Peak, despite being a relatively evolved composition, is not associated with the high- γ_{Os} group. We note that it was emplaced as a series of domes located several kilometers from the main Mt. Mazama edifice and was evidently fed by a lateral dike system from the climactic magma chamber ~10 kyr before the climactic eruption (Bacon, 2008; Bacon et al., 1994). This may mean that the magma had a different pathway through the uppermost crust relative to other rhyodacites, and implies that the rhyodacite of Sharp Peak experienced less upper crustal assimilation.

4.1.1. Determining the age of the lower and upper crust beneath Mt. Mazama

The relative differences in the Os isotope compositions of the low- and high- γ_{Os} groups are interpreted to reflect possible variability not only in the composition, but also the age of the sub-arc crust, where lower, less radiogenic γ_{Os} values presumably correspond to younger crust. Potential ages for these crustal contaminants may be modeled using the mass- and concentration-weighted crystal fractionation model from Hart et al. (2002) (Appendix B in supplemental material). This model predicts that significantly radiogenic Os isotope compositions can develop in mafic crust in only a few million years due to its very high Re/Os, which is in stark contrast to

the much lower Re/Os ratios and less radiogenic Os isotope composition of the mantle. The typically high Re/Os ratios of mafic magmas are further augmented by even modest amounts of fractional crystallization, which will also produce high Re/Os ratios. Because K_d values for Re and Os are best constrained for basalt to basaltic andesite compositions, we used values determined by the 0-60% crystallization interval in the model to estimate ages for the high- and low- γ_{Os} arrays measured at Mt. Mazama (Figure 4).

The radiogenic Os growth model of Hart et al. (2002) suggests that Os isotope compositions for the low- γ_{Os} group (magnetite analyses) are consistent with ages of ~7 to 2.5 Ma for the crustal component (Figure 4; see Appendix 2 for calculation details). These model ages overlap with a spatial shift in volcanism from 7 to 4 Ma in the Crater Lake region (du Bray and John, 2011; Priest, 1990), possibly related to the inception of Basin and Range extension (Priest et al., 2013). Basin and Range extension is associated with more voluminous mafic volcanism in this portion of the Cascade arc, as well as eruption of a higher proportion of HAOT magmas relative to calc-alkaline basalts (Priest et al., 2013; Schmidt et al., 2008). We propose that a more abundant mafic input into the lower crust occurred during extension, which would have added a component that had a less radiogenic Os isotope composition and shifted the bulk lower crust towards more mantle-like Os compositions.

Regional geology suggests that the lower crust beneath Crater Lake is comprised of Klamath-type basement rocks, which include Neoproterozoic to Mesozoic ophiolite sequences (Riddihough et al., 1986; Snoke and Barnes, 2006), and it is therefore probable that interaction with these rocks occurred for melts rising from the mantle. The ultramafic portions of ophiolites (e.g., Guillot et al., 2000) are associated with low Re/Os ratios, which would produce very low γ_{Os} values of <0 (calculated for >150 M.y. of radiogenic decay). The basaltic portions, on the

other hand, would be associated with higher, MORB-like Re/Os ratios (e.g., Shirey and Walker, 1998) and produce $^{187}\text{Os}/^{188}\text{Os}$ ratios that are very high γ_{Os} values ($\geq \sim 200$). We do not observe these extreme Os isotope compositions in volcanic rocks from Mt. Mazama, and even small amounts of assimilation of such extreme compositions should be evident. Moreover, in the case of the ultramafic lithologies, it is expected that they were too refractory to be partially melted and assimilated by basaltic melts from the mantle. The Os isotope composition of the basaltic portions of the ophiolite sequences could represent assimilants only if they had been modified towards more mantle-like compositions prior to being assimilated by injection of more primitive magma—a possible hypothesis, but one difficult to detect.

Osmium isotope compositions measured for the high- γ_{Os} group are consistent with model ages of ~ 16 to 10 Ma for the crustal component (Figure 4), which coincides with an episode of volcanic activity in the ancestral Cascades from 17 to 8 Ma (du Bray and John, 2011; Priest, 1990; Priest and Vogt, 1983). Volcanic activity in the Cascades during this time period was focused in Oregon, and near Crater Lake, the majority of activity was plutonic in nature (du Bray and John, 2011). Granodiorite plutons dated by Power et al. (1981) exposed to the northwest of Crater Lake were emplaced ~ 13 Ma, and if present beneath Mt. Mazama, represent a possible mid- to upper-crustal assimilant for the high- γ_{Os} group.

An alternative approach for determining crustal ages using Os isotope compositions was proposed by Schmidt et al. (2013), who calculate an age range for crustal contaminants based on the decay of ^{187}Re and the range of $^{187}\text{Re}/^{188}\text{Os}$ ratios for a given group of samples. Schmidt et al. (2013) argue that their method for determining ages is more reasonable due to the high Re/Os ratios produced for evolved crustal compositions by the model of Hart et al. (2002), which are greater than those measured for lavas erupted in the Cascades. Hart et al. (2002) indicate,

however, that their model is not as robust for more evolved crustal compositions, as distribution coefficients for Re and Os are not well constrained for andesites to rhyolites. By using the crustal composition produced by 0-60% crystallization to determine possible ages for crust beneath Mt. Mazama as discussed above, we avoid the potential problem of extreme Re/Os ratios. We prefer the model of Hart et al. (2002) as the approach favored by Schmidt et al. (2013) does not account for the highly variable Re and Os abundances that are produced during differentiation and subsequent isotopic evolution in the crust. However, for comparison, we calculated ages based on Schmidt et al. (2013) for both the low- and high- γ_{Os} group. For the low- γ_{Os} group, curves of $^{187}\text{Re}/^{188}\text{Os}$ vs. time were produced for the ingrowth of ^{187}Os from an initial $^{187}\text{Os}/^{188}\text{Os}$ of 0.1403 ($\gamma_{\text{Os}} = 10$) to both the minimum and maximum $^{187}\text{Os}/^{188}\text{Os}$ ratios measured in magnetite (minimum $^{187}\text{Os}/^{188}\text{Os} = 0.16275$, $\gamma_{\text{Os}} = 28$; maximum $^{187}\text{Os}/^{188}\text{Os} = 0.19555$; $\gamma_{\text{Os}} = 53$) (Figure 5). The intersection of these curves with the minimum and maximum $^{187}\text{Re}/^{188}\text{Os}$ ratios measured for the low- γ_{Os} group gives a possible age range for the lower crustal contaminant of ~5–168 Ma. Corresponding curves calculated for the high- γ_{Os} group suggest an age range of ~20–300 Ma for the potential upper crustal contaminant. Interestingly, the low end of the age ranges calculated by the Schmidt et al. (2013) method for Mt. Mazama are remarkably close to the ages given by the Hart et al (2002) model described at the beginning of this section, and although the age ranges overlap, they appear distinct between the low- and high- γ_{Os} groups. Each of these ranges would require assimilation of heterogeneous crust, which could be created by incomplete homogenization of older crust by more recent influxes of magma from the mantle. Although we maintain our preference for the Hart et al. (2002) model, we find that regardless of the modeling approach, it is possible to infer that producing the low- and high- γ_{Os} groups requires assimilation

of distinct crustal compositions that may have been modified in response to fluxes of magma from the mantle during key tectonic and/or magmatic events.

4.1.2. Constraints on the assimilation process beneath Mt. Mazama

Approximating the age and composition of the continental crust using the Os isotope compositions of erupted materials requires that magmas were able to attain their isotopic composition via assimilation. The feasibility of assimilation of young (7–2.5 Ma), mafic lower crust beneath Mt. Mazama to explain the Os isotope compositions observed in the low- γ_{Os} group was evaluated using assimilation fractional crystallization (AFC) models from DePaolo (1981). We focus our models on assessing lower crustal contributions for those samples in Th-excess, as samples in U-excess (LSr scoria and Sharp Peak) likely acquired their U-Th isotope composition via more recent upper crustal processes, as discussed in the beginning of section 4.1. Additionally, a link between Th-excesses and radiogenic Os isotope compositions was proposed for Mt. Adams by Jicha et al. (2009b). Assimilation fractional crystallization models are preferred over simple mixing as fractional crystallization is required to reduce the Os concentration in mantle melts in order for them to acquire the Os isotope composition of a given assimilant. Moreover, simple mixing curves, while able to reproduce the U-Th isotope compositions as in Ankney et al. (2013), do not reach high enough γ_{Os} values to explain those measured for the low- γ_{Os} group (Figure 6).

To reproduce the Os and U-Th isotope compositions of the low- γ_{Os} group, we modeled AFC between a mantle melt (200 ppt Os, $\gamma_{\text{Os}} = 10$, 0.568 ppm Th, $(^{230}\text{Th}/^{238}\text{U}) = 1.004$) and a crustal melt (5 ppt Os, $\gamma_{\text{Os}} = 58$, 10.15 ppm Th, $(^{230}\text{Th}/^{238}\text{U}) = 1.54$), with a crystallizing assemblage of cpx + plag + ol + mt in proportions of 33:33:29:5. The mineralogy of this assemblage is based on that of the basalts and basaltic andesites at Mt. Mazama (Bacon, 2008),

and the proportions are estimated to provide a reasonable fit for the data. The Os isotope composition assumed for the mantle is representative of an average mantle-wedge derived magma taken from Hart et al. (2003). This value is also consistent with the minimum value measured for olivine separates at Mt. Mazama ($\gamma_{\text{Os}} = +9$), which may be appropriate for the initial mantle composition as olivine would be an early fractionating phase from melts rising from the mantle. The γ_{Os} value for the crustal melt is taken from the radiogenic Os growth model of Hart et al. (2002) for a 7 m.y. old crust, which was determined in section 4.1.1. An Os concentration for the crustal melt was calculated for a 15% batch partial melt of the crust composition produced by the growth model (99 ppt Os). Finally, the U-Th concentrations and isotope compositions of the mantle melt and crustal assimilant were calculated using the non-modal batch melting approach of Ankney et al. (2013) for a 20% melt of a spinel lherzolite mantle (51% ol, 23% cpx, 21% opx, 5% spinel) and 15% melt of an amphibolite lower crust (67% amph, 33% plag). We stress that this modeling approach allows for the development of large Th-excesses due to the production of garnet in the residuum. It also provides a mechanism to explain the presence of a garnet signature when experimental work indicates that garnet is not a fractionating phase in basaltic compositions in the Cascade lower crust (e.g., Mercer and Johnston, 2008). Melting mode (P) values and partition coefficients used match those from Ankney et al. (2013). The assumed mantle melt fraction (20%) is 5% higher than that used by Ankney et al. (2013). In addition, the initial Th and U concentrations of the spinel lherzolite mantle source were adjusted to slightly lower values (Th from 0.005 to 0.004 and U from 0.145 to 0.116). These adjustments provide a better fit for the data collected for this study, as well as the Ankney et al. (2013) data, under the new AFC model.

Partition coefficients for the AFC modeling are summarized in Table 1. The Os isotope compositions produced by the model are highly dependent on the bulk partition coefficient used for Os. Previous studies have utilized a range of bulk partition coefficient values (D_{Os}) from 7–21.4 (e.g., Chesley et al., 2002; Hart et al., 2002; Saal et al., 1998; Schmidt et al., 2013). Schmidt et al. (2013) propose a value for D_{Os} of 21.4, which is appropriate when a small amount of sulfide is present (0.03%), likely as a trace phase in magnetite. Abundant sulfide inclusions have been observed in magnetite and other phases as well as in contact with groundmass in silicic magmas and climactic scoria at Mt. Mazama (Bacon, 1989; Wright et al., 2012), and it is possible that they are also present in mafic magmas. Sulfides are predicted to be stable at $fO_2 \sim QFM$ (Carroll and Webster, 1994; Schmidt et al., 2013), although they are found in silicic magmas and scoria of the climactic eruption at Mt. Mazama at higher fO_2 's of $\Delta NNO = \sim 0.3$ – 1.1 and sulfur concentrations measured in melt inclusions are consistent with sulfide saturation (Wright et al., 2012). We therefore use the higher bulk partition coefficient for Os ($D_{Os} = 21.4$) to model AFC for the low- γ_{Os} group.

The parameters described above approximate the Os and U-Th isotope compositions of the low γ_{Os} , high Th excess lavas over a range of r (rate of mass assimilated/rate of mass crystallized) of 0.05 to 0.40 (Figure 7). This range of r also produces a reasonable fit for the majority of Th concentrations measured for the low γ_{Os} group (Figure 8). Extending the range of r to 0.8 encompasses nearly the full range of U-Th isotope compositions (Th-excess up to 44%) and Th concentrations for the Mt. Mazama system when we combine data from this study with values from Ankney et al. (2013).

The modeling curves, even at the lowest r values, cannot account for the exceedingly low Th concentration measured for sample MBCL38 (Th = 0.094). This sample, along with samples

MBCL39 and 42, are HAOT basalt lavas erupted from three distinct vents associated with Castle Point. Bacon (2008) denotes these vents as vent 1 (MBCL38), vent 2 (MBCL42), and vent 3 (MBCL39). Vent 3 has a more evolved composition than Vent 1, which Bacon et al. (1994) propose may be due to crustal contamination based on petrographic evidence, Sr and Pb isotopes, and incompatible element concentrations. In this study, we find that γ_{Os} , Th-excess, U and Th concentrations, and $^{87}\text{Sr}/^{86}\text{Sr}$ ratios increase from Vent 1 to Vent 3. Vent 2 has an Os isotope composition that is roughly equal to that of Vent 1, but has Th-excess, $^{87}\text{Sr}/^{86}\text{Sr}$, and U and Th concentrations that are more consistent with Vent 3. We therefore propose that these samples represent variable crustal contamination of a distinct mantle composition relative to that used in the AFC models. Alternatively, they could be explained by mixing of a distinct mantle melt with calc-alkaline magmas that have high Th-excesses and higher Th concentrations due to crustal contamination (e.g., basaltic andesites of Red Cone or basalt of Williams Crater). This scenario may be supported by Bacon (1990), who notes that there is a continuum between HAOT and calc-alkaline lavas. In either case, the high Th-excesses and γ_{Os} values of these samples still suggest some role for a more radiogenic (crustal) component in generating their compositions.

Assimilation of crustal melts with garnet in the residuum should produce characteristic trace element trends in the resulting magma. Ankney et al. (2013) observe that the highest La/Yb ratios in Mt. Mazama volcanic rocks are found in units with Th-excess. Both La and Yb are sensitive to garnet fractionation (garnet $D_{\text{La}} = 0.005$, and $D_{\text{Yb}} = 26.3$, Qian and Hermann, 2013) and thus high La/Yb ratios are produced during dehydration melting of the crust where garnet is produced in the residuum. La/Yb ratios for the low- γ_{Os} samples in Th-excess are consistent with the trend observed for basalts and basaltic andesites by Ankney et al. (2013). In general, the AFC model can reproduce the La/Yb ratios measured for the low- γ_{Os} samples (Figure 9), as well as

other Th-excess samples from Mt. Mazama, although we note that it requires the use of relatively high partition coefficients for Yb for clinopyroxene and plagioclase. An appropriate K_D for clinopyroxene was obtained from values calculated for scoria of the climactic eruption by Bacon and Druitt (1988), while the K_D for plagioclase is for a basaltic andesite composition from Ronov and Yareshevskiy (1976).

An alternative explanation for the low γ_{Os} values measured for mafic lavas with high Th excesses is that they were produced by small amounts of assimilation of the high- γ_{Os} crustal component ($\gamma_{Os} = \sim 119$), thus indicating the presence of a homogeneous crustal column with regard to Os isotopes beneath Mt. Mazama. Using this higher γ_{Os} value for the crustal assimilant and the parameters noted above, we are able to reproduce the range in Os and U-Th isotope compositions in the low- γ_{Os} group over a range of r of 0.08 to 0.40. This cannot, however, approximate the higher end of the Th concentration range (>2.5 ppm). It also does not replicate the higher La/Yb ratios (>10) when they are plotted relative to γ_{Os} .

Overall, AFC models suggest that a combination of crustal assimilation and fractional crystallization can produce the U-Th and Os isotope compositions of the low- γ_{Os} group at Mt. Mazama. Although AFC models allow for assimilation of the higher (older) γ_{Os} crust, the range of Os isotope and U-Th isotope and elemental compositions appear to be better approximated by models for AFC that involve a lower (younger) γ_{Os} crust composition, especially when we consider trace elements such as La and Yb.

4.2. Crustal variability in the Cascades

Previous Os isotope studies at Mt. Adams in the northern part of the Cascade arc, the North Sister and Little Brother volcanoes in the central Oregon Cascades, and at Lassen volcanic center in the southern part of the arc, have also documented intracrustal heterogeneity and

hybridization, reflecting variability in the age and composition of the crust along the arc (Hart et al., 2003, 2002; Schmidt et al., 2013). Lavas at both Mt. Adams and Lassen have remarkably high γ_{Os} values of up to +342 and +224, respectively. At Mt. Adams, Jicha et al. (2009b) also identify a correlation between high Th-excesses (up to 48%) and high γ_{Os} values. They call upon assimilation of partial melts of a high- γ_{Os} lower crust that is garnet-bearing to explain the high Th-excesses and highly radiogenic Os isotope compositions. We observe similar Th-excesses at Mt. Mazama, but unlike at Mt. Adams, the Th-excesses belong to samples that are thought to have assimilated partial melts of rock that underwent garnet fractionation in the last few 100 k.y. (Ankney et al., 2013). Because high γ_{Os} values such as those observed at Mt. Adams and Lassen volcanic field can be created in only a few million years due to high Re/Os ratios in the lower crust (e.g., Hart et al., 2003, 2002), we suggest that the lower γ_{Os} values measured for magmas at Mt. Mazama may be explained by assimilation of even younger lower crustal compositions than elsewhere in the Cascades and/or lower crust that has experienced greater amounts of homogenization towards more mantle-like γ_{Os} values. The more mantle-like composition of the lower crust in some parts of the Oregon Cascades is also recognized by Schmidt et al. (2013), who measured γ_{Os} values of +11 to +46 in basalts from the North Sister and Little Brother volcanoes. These non-radiogenic Os isotope compositions are consistent with those of the mafic lavas erupted from monogenetic volcanoes near Mt. Mazama. In general, mantle-like imprints on the lower crust in the Cascades are likely associated with a higher basaltic flux from the mantle due to the extensional environment present across much of the arc. This imprint may be less well-developed or more difficult to distinguish in other continental arcs where the crust is thicker and/or more evolved.

5. Conclusions

Together, Re/Os and U-Th isotopes may be used to trace key intracrustal processes in arcs, such as homogenization and assimilation by mantle melts rising through the crust. The new Os isotope data for Mt. Mazama allow us to offer possible constraints on the age and compositions of the lower and (mid to) upper crust, as well as improve our understanding of its role in the petrogenesis of magmas erupted in the buildup to, and during, the caldera-forming eruption. Osmium model-ages of 7 to 2.5 Ma for lower crustal rocks and 16 to 10 Ma for the mid to upper crustal rocks are younger than the onset of Cascade volcanism in Oregon (~40 Ma), and thus may record shifts in the composition of the upper and lower crust in response to injection of magmas from the mantle due to subduction and extensional tectonics. Identification of young, mafic lower crust is supported by Th excesses, which may be explained by assimilation of melts produced in conjunction with recent (<300 ka) garnet production via dehydration melting of mafic lithologies (Ankney et al., 2013). Lower crustal evolution in the Cascades therefore appears to have involved multiple stages, including intrusion of mafic magmas during extensional tectonics (7 to 4 Ma), followed by dehydration melting within the last few 100 ka through more recent injection of basaltic magma; such inferences are only possible through the combination of Os and Th isotopes. Importantly, these results allow us to move beyond simple identification of signatures of crustal contamination in erupted magmas towards an understanding of the influence of extensional tectonics and magmatism on the compositional evolution of the Cascade crust that is not obtainable by other isotope systems.

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TABLE 1. PARTITION COEFFICIENTS FOR AFC MODELS*

	cpx	plag	ol	mt	D _{Bulk}
U	0.023	6.0E-05	9.5E-06	0.004	0.0078
Th	0.019	3.0E-04	6.0E-05	0.004	0.0066
La	0.12	0.32	0.008	0.003	0.1477
Yb	2.0	0.4	0.013	0.25	0.8083
Os	-	-	-	-	21.4

*Sources: Schmidt et al. (2013), Bacon and Druitt (1988), Ronov and Yareshevskiy (1978) and compilations by Ankney et al. (2013) and Conrey et al. (2001)

Figure Captions

Figure 1. A. Map of the Quaternary volcanic rocks of the Cascade arc (gray) from Mt. Rainier south. Triangles indicate major volcanoes. Modified from Jicha et al. (2009a). B. Map of the location of monogenetic vents surrounding Mt. Mazama (circles) and the extent of Mt. Mazama lavas (gray). Filled in circles represent the source of basalt and basaltic andesite units analyzed in this study. Additional units studied include the andesite and basaltic andesite of Hillman Peak, dacite of the Watchman, dacite of Munson Valley, rhyodacite of Sharp Peak, Holocene preclimactic rhyodacite (Cleetwood), and deposits of the climactic eruption. Modified from Bacon (1990).

Figure 2. $^{87}\text{Sr}/^{86}\text{Sr}$ vs. γ_{Os} for volcanic rocks erupted at Mt. Mazama. We note that neither the high or low γ_{Os} groups show a significant correlation between Os and Sr isotope compositions. This is likely due to the relatively short timescales required to produce the measured γ_{Os} values, which are indicated by the “Modeled crust age (Ma)” on the right side of the figure. Modeled ages were produced using a mass- and concentration-weighted crystal fractionation model from Hart et al. (2002). Model parameters were taken from Stage 1 (0-60% crystallization) in Table 2 of Hart et al. (2002). Additionally, we used an initial $^{187}\text{Os}/^{188}\text{Os}$ ratio of 0.14 ($\gamma_{\text{Os}} = +10$). Errors are typically smaller than symbol size, and are noted with black bars where they are larger.

Figure 3. $(^{230}\text{Th}/^{238}\text{U})_0$ vs. γ_{Os} for volcanic rocks erupted at Mt. Mazama. The high-Os group is consistent with assimilation of older, mid to upper crust, whereas the low-Os group may represent assimilation of younger, lower crust. Circles and squares correspond to Os isotope compositions measured in magnetite separates and triangles correspond to Os isotope compositions measured in olivine separates. The U-Th isotope compositions are all taken from whole rock measurements on the same samples. $(^{230}\text{Th}/^{238}\text{U})_0$ indicates $(^{230}\text{Th}/^{238}\text{U})$ ratios corrected for ingrowth of ^{230}Th since eruption. Data for Mt. Adams are from Jicha et al. (2009b). Contrary to Mt. Adams, high ^{230}Th -excesses at Crater Lake are thought to be associated with assimilation of partial melts of low γ_{Os} lower crust. The highest γ_{Os} values for Mt. Adams are not shown at this scale. Errors are typically smaller than symbol size, and are noted with black bars where they are larger.

Figure 4. Variations in γ_{Os} over the crystallization range of 0–60% calculated from the mass- and concentration-weighted model of Hart et al. (2002) for fractionation of magmas injected into the base of the crustal column. The fields denote the range of values for the high and low γ_{Os} group at Mt. Mazama. We note that the low γ_{Os} field includes only the magnetite separate analyses.

Figure 5. Plots of $^{187}\text{Re}/^{188}\text{Os}$ vs. age (Ma) based on the model of Schmidt et al. (2013) for determining an age range for potential crustal contaminants. The curves are calculated for the decay of ^{187}Re needed to generate the highest and lowest $^{187}\text{Os}/^{188}\text{Os}$ values for the low and high- γ_{Os} group. The blue and red fields are constrained by the low and high $^{187}\text{Re}/^{188}\text{Os}$ ratios for the low- and high- γ_{Os} groups, respectively. The minimum and maximum points at which they intersect the decay curves give possible age ranges for each group.

Figure 6. γ_{Os} vs. $(^{230}\text{Th}/^{238}\text{U})_0$ plot showing simple mixing curves between a mantle melt and two different high Th excess crustal melts with both a low (+58) and high (+119) γ_{Os} crust. The Os

and U-Th compositions for the mantle and crustal melts were calculated according to the parameters given in the text. The small squares indicate the percent crustal melt included in each mixture. Symbols match those in Figure 3.

Figure 7. γ_{Os} vs. $(^{230}Th/^{238}U)_0$ plot showing AFC curves for crystallization of a mantle melt and assimilation of a low γ_{Os} (+58) crustal melt that were calculated based on equations from DePaolo (1981). The curves are shown relative to low- γ_{Os} samples from Mt. Mazama. The tick marks on each curve indicate the percent crystallization that has occurred. The end point of each curve is at 95%. These curves are for an initial Th content of 0.57 ppm and r values of 0.05, 0.15, 0.40, and 0.80 with $D_{Os} = 21.4$, and $D_{Th} = 0.0066$. The U excesses observed in the rhyodacite and LSr scoria sample are explained in the text. Symbols match those in Figure 3.

Figure 8. γ_{Os} vs. Th (A) and $(^{230}Th/^{238}U)_0$ vs. Th (B) plots showing AFC curves for crystallization of a mantle melt and assimilation of a low γ_{Os} (+58), high Th-excess crustal melt that were calculated based on equations from DePaolo (1981). The curves are shown relative to low- γ_{Os} samples from Mt. Mazama, with additional data from Th-excess samples from Ankney et al. (2013) included as small, gray squares in B. The tick marks on each curve indicate the percent crystallization that has occurred. These curves are for an initial Th content of 0.57 ppm, and were calculated based on r values of 0.05, 0.15, 0.40, and 0.80 with $D_{Os} = 21.4$, and $D_{Th} = 0.0066$. The mingled climactic rhyd./HSr scoria is not shown at this scale.

Figure 9. γ_{Os} vs. La/Yb (A) and $(^{230}Th/^{238}U)_0$ vs. La/Yb (B) plots showing AFC curves for crystallization of a mantle melt and assimilation of a low γ_{Os} (+58), high Th-excess, high La/Yb crustal melt calculated based on equations from DePaolo (1981). The curves are shown relative to low- γ_{Os} samples for which trace element data are available, with additional data from Th-excess samples from Ankney et al. (2013) included as small, gray squares in B. The tick marks on each curve indicate the percent crystallization that has occurred. These curves are for an initial La/Yb ratio of 1.7, and were calculated based on r values of 0.05, 0.15, 0.40, and 0.80 with $D_{Os} = 21.4$, $D_{Th} = 0.0066$, $D_{La} = 0.1477$, and $D_{Yb} = 0.8083$. Trace element data are not available for the rhyodacite of Sharp Peak and the climactic LSr scoria, so they are not shown.

Figure 1

Figure 2

Figure 3

Figure 4

Figure 6

Figure 7