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Osmium Isotope Constraints on Tectonic Evolution of the Lithosphere in the Southwestern United States

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Abstract

The Re-Os isotope system is increasingly providing new insight into continental dynamics due to the fact that it is the only radiogenic isotope system that provides information on melt depletion events (hence lithosphere formation) in the uppermost mantle. Here we review application of the Re-Os isotopic system to dating melt depletion in peridotites. In particular, we highlight examples of how this system, when applied to mantle xenolith studies, provides information on the timing of lithospheric mantle formation and its replacement beneath the southwestern United States.

Studies of xenoliths from the Sierra Nevada reveal a vertically stratified mantle lid at 8 Ma: cold, old (Proterozoic) lithosphere is preserved just beneath the Moho (~45 km) and is underlain by younger (Phanerozoic) lithosphere that reaches depths of 100 km. The deeper, younger lithosphere shows extensive evidence of cooling, whereas the overlying old, colder lithosphere shows evidence for heating. Collectively, these data suggest removal of the original Proterozoic lithosphere and its replacement by upwelling convecting mantle that cooled against the surrounding lithosphere. The timing of this replacement is not well constrained by Os systematics, but probably occurred during development of the Mesozoic arc. A second deep lithosphere removal event is suggested by the presence of fertile, hot peridotite xenoliths that erupted from the High Sierra in the Pliocene, which have Os isotopic compositions indistinguishable from convecting upper mantle. This later thinning event may be related to Basin and Range extension.

Studies of mantle xenoliths from the Mojavia terrane (southern Basin and Range) and Colorado Plateau provide insights into the origin of the contrasting lithospheric strength between these two regions. The Mojavia terrane is underlain by anomalously fertile, Archean-aged mantle lithosphere. Its high density prohibited formation and stabilization of a thickened lithospheric lid, which, in combination with likely low viscosity, explains why this ancient lithosphere is thin and relatively weak compared to lithosphere from Archean cratons. In contrast, peridotite xenoliths from the Colorado Plateau are Proterozoic in age, but are refractory, and hence chemically buoyant. These properties led to development of a thick and strong lithosphere beneath the Colorado Plateau.

Introduction

THE EARTH IS UNIQUE in our solar system in having a bimodal distribution of crust: thin, low-lying, young oceanic crust, and thick, high-standing, ancient, continental crust. The past half-century of sea-floor exploration and ophiolite studies have demonstrated that the oceanic crust is formed at mid-ocean ridges by basaltic magmatism and is underlain by lithospheric mantle that progressively thickens by conductive cooling as the plate moves off the mid-ocean ridge. Thus, processes responsible for generation of oceanic lithosphere are reasonably well understood.

In contrast, processes that generate the continental lithosphere are poorly known. Continental crust (the portion of the continents extending vertically from the surface to the Moho and laterally beneath the ocean surface to the break in slope on the continental shelves) is extremely diverse lithologically, containing every known terrestrial rock type. We can make some generalizations about the continental crust. It is compositionally stratified, with increasing seismic wave speeds with depth due not only to increasing metamorphic grade, but also increasing proportions of mafic lithologies (Furlong

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and Fountain, 1986; Rudnick and Fountain, 1995). Likewise, heat-producing elements are concentrated in the upper crust, although the distribution of heat-producing elements, and even their absolute abundances in the total crust, is poorly constrained (Rudnick et al., 1998). The crust's bulk composition is intermediate, and it shows a trace-element pattern unique to magmatic rocks erupted in subduction-zone settings (Rudnick, 1995, and references therein). This latter observation requires that a large portion of the continental crust must be generated in convergent margins (at least 80% by mass, Barth et al., 2000). The exact way in which this is accomplished and how these processes may have changed over geological time remain obscure.

The continental crust is underlain by thick (60 to >200 km) mantle lithosphere that generally formed at about the same time (within 200 m..y.) as the overlying crust. The mantle lithosphere of most Archean cratons is observed to be cold, thick (up to ~250 km), and chemically buoyant compared to lithosphere of off-craton regions (Boyd, 1989; Jordan, 1975; Jordan, 1988) and may have played a role in the stabilization of these cratons. Thus, understanding the formation and evolution of the continents requires not only an understanding of the processes responsible for generating the crust, but also requires defining the nature of the underlying mantle lithosphere: its thickness, composition, rheology, density and age, and from these, the processes by which continental crust and lithospheric mantle form.

The nature of the deep lithosphere has largely been studied through remote sensing techniques such as surface heat flow measurements, electrical resistivity soundings, gravity surveys, and seismological investigations. Such studies provide important information on the physical state of the lithosphere over broad regions, which can be interpreted in terms of the gross structure of the lithosphere and its lithological composition. However, the link between lithology and physical properties (e.g., P- or S-wave speeds) is non-unique (Fountain and Christensen, 1989; Rudnick and Fountain, 1995), inasmuch as temperature, the presence of fluids, and the mineralogical composition of rocks all exert influence on the bulk and shear moduli of rocks. Furthermore, geophysical surveys provide insights into the present-day lithosphere, but can only provide indirect evidence regarding its temporal evolution.

More direct information on the nature of the deep continental lithosphere can be gained through studies of deep-seated xenoliths, which are literally "foreign" rock fragments carried to the Earth's surface in magmas such as basalts and kimberlites that ascend rapidly from the mantle. The mineralogy of these xenoliths reflects their formation under the high pressures and temperatures found in the continental lithosphere, and they thus provide a means of independently verifying geophysical interpretations of this region of the Earth. Moreover, under favorable circumstances, xenolith studies can provide direct information on the lithosphere's secular evolution.

U-Pb geochronology provides the best constraints by far on the crystallization and metamorphic ages of deep-seated crustal xenoliths (e.g., Chen et al., 1994; Davis, 1997; Moser and Heaman, 1997; Rudnick and Williams, 1987). Unfortunately, only rarely do accessory minerals suitable for U-Pb dating occur in xenoliths from the upper mantle. Where they do occur, they are generally associated with magmatic events occurring well after the original formation of the lithosphere (Dawson et al., 2001; Kinny and Dawson, 1992; Rudnick et al., 1999) and thus do not provide information on when the lithosphere formed.

Within the last 15 years, the Re-Os isotopic method has been increasingly applied to understanding the age of mantle xenoliths and hence continental mantle lithosphere. In this paper, we review Re-Os systematics and illustrate the potential of this method for unraveling lithospheric mantle history through several case studies of mantle xenoliths from the southwestern United States.

Terminology and Assumptions

Because this paper is written for a broad audience, we have attempted to avoid specialist jargon whenever possible. However, some specialized terminology inevitably must be used, and we define these terms in a glossary, which can be found in the Appendix. In particular, it is important to define the different types of mantle we discuss here. *Lithospheric mantle* (italics indicate terms that are defined in the appendix) is that portion of the mantle, assumed to be comprised primarily of peridotite, that is mechanically coupled to the overlying crust and translates with it as the plate moves over the surface of the Earth. Its upper boundary is the Moho, but its lower boundary is less well defined.

We take the lower boundary as: (1) the transition from conductive to adiabatic thermal gradient; and (2) the transition from mechanical coupling with the rigid overlying plate to convective flow in the underlying *asthenospheric* or *convecting mantle*. Thus we use the terms "convecting mantle" and "asthenospheric mantle" synonymously.

Inasmuch as we are interested in understanding the evolution of continental lithosphere, particularly the mantle portion of this lithosphere, we examine here how this lithosphere is likely to be created. Continental lithospheric mantle is typically chemically depleted (*refractory*) relative to the convecting mantle (Jordan, 1975; McDonough, 1990), due to extraction of certain chemical components (e.g., Fe, Al, and Ca) into basaltic melts. This results in the lithospheric mantle's intrinsic buoyancy (at constant temperature) relative to convecting mantle. Because the degree of chemical buoyancy in lithospheric mantle does not correlate with topography or gravity anomaly, there must be another factor that essentially pulls these regions of intrinsically buoyant lithosphere downward. This other factor is temperature—Archean cratons are characterized by low surface heat flow and seismically fast root zones that are generally attributed to cold temperatures (Jordan, 1975; Jordan, 1988). The combination of cold temperatures and chemical depletion results in increased viscosity and permits the development of a thick mantle lid that is gravitationally stable relative to asthenospheric mantle, unlike thickened fertile mantle lithosphere that has grown by conductive cooling. The presence of such a lid or "lithospheric keel" greatly increases the strength of the lithosphere.

Evidence for chemical depletion of continental lithospheric mantle is prevalent in xenolith studies. We therefore assume that the continental lithospheric mantle grows by melt extraction as well as by simple conductive cooling, as in the ocean basins. If this is true, then the timing of lithospheric mantle formation can be determined using Re-Os isotopic systematics, which are described below.

Dating Mantle Lithosphere with Re-Os

The Re-Os system, in which ^{187}Re decays to ^{187}Os with a half life of ~42 Ga, differs from all other commonly applied radiogenic isotope systems in one important way: Os is compatible during melting, whereas all other daughter products are highly incompatible. For example, in the Sm-Nd, Rb-Sr,

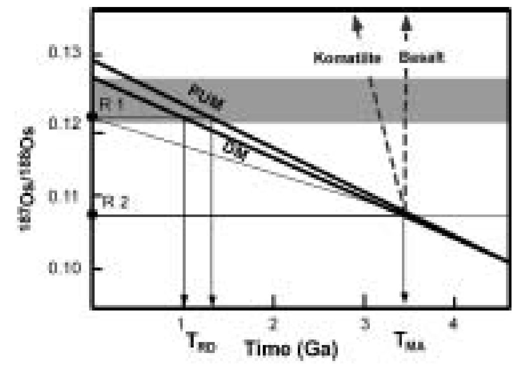

FIG. 1. Re-Os isotopic evolution of the mantle through time, after Walker et al. (1989). Bold lines represent two different estimates of the Os isotopic evolution in convecting upper mantle. The upper line (PUM) has the composition of "primitive upper mantle" (Meisel et al., 2001), whereas the lower line (DM for "depleted mantle") is derived from the Os isotopic composition of ophiolites through time, and may represent an upper mantle slightly depleted by production of oceanic crust over the time span of Earth history (Walker et al., 2002). The grey shaded field depicts the range of $^{187}Os/^{188}Os$ observed in abyssal peridotites. See text for discussion of T_{MA} and T_{RD} ages.

and U-Pb isotope systems both parent and daughter isotopes are highly incompatible during mantle melting, leading to significant depletion of both parent and daughter in the refractory mantle residue and their enrichment in the complementary melts. Because of their very low abundances in peridotites, these elements are readily overprinted in peridotite residues by later processes such as melt-rock reaction and melt infiltration. For example, peridotite xenoliths from Archean cratons rarely preserve Archean Nd model ages (see summary in McDonough, 1990), even though it is clear from a number of lines of evidence that the mantle lithosphere in these regions formed in the Archean (Richardson et al., 1984; Pearson et al., 1995a, 1995b).

In contrast, Re is only moderately incompatible during mantle melting, so Re is preferentially partitioned into the melt, while Os remains behind in the residue (Walker et al., 1989). Melting events thus lead to large fractionations in parent/daughter ratio between basaltic melts and peridotitic residues, typically a factor of 1000 or more: melts have high Re/Os and low Os abundances and the residual mantle has low Re/Os and high Os abundances (Fig. 1).

For example, a partial melting event at 3.5 Ga produces melts with high Re/Os and low Os con-

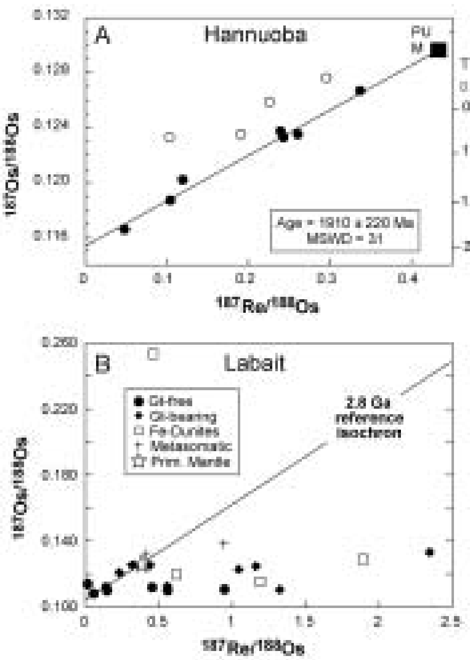

FIG. 2. Examples of Re-Os isochrons for mantle xenolith suites. A. Probably the best isochron for a suite of xenoliths from the Hannouba volcanic center, North China craton (Gao et al., 2002). Open symbols do not follow the trend (in one case due to Re loss from sulfide breakdown) and were consequently not included in isochron regression. B. A more typical Re-Os isochron plot for a suite of mantle xenoliths from Labait volcano, Tanzanian craton (Chesley et al., 1999). Os model ages and measurements of chromites suggest that lithosphere formation occurred at 2.8 Ga. Most of the data lie to the right of the line, indicating recent Re enrichment.

tents that evolve to very high $^{187}Os/^{188}Os$ ratios with time, due to ß decay of the parent ^{187}Re (dashed lines in Fig. 1). In contrast, the residues from this melting event will have low Re/Os and high Os concentration and evolve to $^{187}Os/^{188}Os$ values that are lower than mantle that has not experienced melt extraction ("PUM" in Fig. 1). The Re/Os (and hence time-integrated $^{187}Os/^{188}Os$ ratios) of both melt and peridotitic residue depends on the degree of melting. Residue 1 (R1) results from basalt extraction, where some amount of Re is retained in the residue. This residue thus experienced significant in-growth of ^{187}Os over time. In contrast, residue 2 (R2) is produced by very high degree melting responsible for komatiite generation, and its $^{187}Os/^{188}Os$ is essentially "frozen" at the time of melting due to complete removal of Re by the melt. Importantly, because of the one to two orders of magnitude higher concentration of Os in residual peridotites compared to melts, Os isotopic compositions of peridotite residues are difficult to overprint by later processes, such as melt infiltration, which have such dramatic effects on other radiogenic isotope systems. For this reason, Os isotopes have proven useful in dating lithosphere formation, assuming that lithosphere formation goes hand-in-hand with melt extraction (see Shirey and Walker, 1998), for a recent review).

There are several ways in which Re-Os data can be used to derive the age of lithospheric mantle, and we outline these in the next several paragraphs. A Re-Os isochron will develop if the peridotites underwent melt extraction from the same mantle source at the same time, and no Re or Os mobility has occurred subsequent to melting (Fig. 2A). However, mantle xenoliths typically exhibit evidence of Re mobility in the form of Re introduction from the host magma or through mantle metasomatic processes (Fig. 2B; Walker et al. 1989; Chesley et al., 1999) or Re loss due to sulfide breakdown (Lorand, 1990; Handler and Bennett, 1999). Coupled with the possibility of multiple mantle sources (having variable $^{187}Os/^{188}Os$) and melting events, Re mobility means that Re-Os isochrons are only rarely observed for peridotite xenolith suites. That shown in Figure 2A is the best isochron so far observed for any suite of mantle xenoliths, and is likely due to the unusual preservation of sulfides (which host both Re and Os) in these samples (Gao et al., 2002).

Alternatively, the time of melt depletion can be determined for individual peridotites by using the observed Re/Os ratio and calculating when the sample had a $^{187}Os/^{188}Os$ matching primitive upper mantle (these are referred to as "T_{MA} ages", Fig. 1; Walker et al., 1989). These model ages are completely analogous to Sm-Nd model ages (e.g., DePaolo and Wasserburg, 1976), but rely on Re immobility, which is typically a problem for mantle xenoliths, as discussed above.

Another method, which provides a minimum estimate of the timing of melt depletion, is to compare the $^{187}Os/^{188}Os$ of the sample (corrected using the measured Re/Os to the time of xenolith host eruption) to a mantle evolution model. The time at which the mantle source had this $^{187}Os/^{188}Os$ composition is referred to as the T_{RD} age, or "Re-depletion" age (Fig. 1; Walker et al., 1989). If all of the Re was removed at the time of melting, then the T_{RD} age should equal the T_{MA} age, assuming no subsequent Re addition. This is the case for residue 2 in Figure 1. Thus, T_{RD} ages are generally good approximations to the time of melting for highly refractory peridotites, such as cratonic xenoliths (e.g., Carlson et al., 1999). But in less refractory material, where some Re remains in the residue (e.g., R2 in Fig. 1), T_{RD} ages are minimum ages. In addition, there is a rather large uncertainty regarding the $^{187}Os/^{188}Os$ evolution of the mantle source for lithospheric peridotites (Reisberg and Lorand, 1995), highlighted by the fact that oceanic mantle, as sampled by abyssal peridotites, exhibits a rather large range in $^{187}Os/^{188}Os$ (grey field in Fig. 1). Thus a peridotite with the Os isotopic composition of residue 1 (R1 in Fig. 1) has a T_{RD} age of 1.0 to 1.3 Ga (depending on which mantle evolution curve is chosen), but could equally well be interpreted to have derived recently from depleted upper mantle, as sampled by abyssal peridotites. It remains unclear how and when this depleted oceanic upper mantle developed (e.g., Walker et al., 2002)

Finally, one way to circumvent the problem of Re mobility is to plot $^{187}Os/^{188}Os$ against an immobile element that exhibits a similar degree of incompatibility as Re during mantle melting. Elements meeting this criterion include Al_2O_3, CaO, heavy rare earth elements (HREE), and Y (Reisberg and Lorand, 1995; Handler et al., 1997). If the data form a positive trend, then the $^{187}Os/^{188}Os$ of the intercept (Reisberg et al., 1991) or the $^{187}Os/^{188}Os$ present at the lowest likely Al_2O_3 concentration (e.g., 0.5 wt% Al_2O_3) (Handler et al., 1997) can be used as the initial ratio, and this ratio is compared to a model mantle evolution trend to determine the time of melting (Fig. 3). Again, this approach assumes coeval melt extraction for all samples and subsequent closed-system behavior for Os.

Even considering the above uncertainties, Os isotopes can provide broad age constraints on the formational history of lithospheric mantle. As with any isotopic system, Re-Os is most powerful when coupled with other lines of evidence, such as thermal histories of xenoliths, to deduce lithospheric history. In the remainder of this paper, we summarize recent Os isotopic studies of mantle xenoliths from the western United States that illustrate the types of information that can be gained by integrated studies of mantle xenoliths.

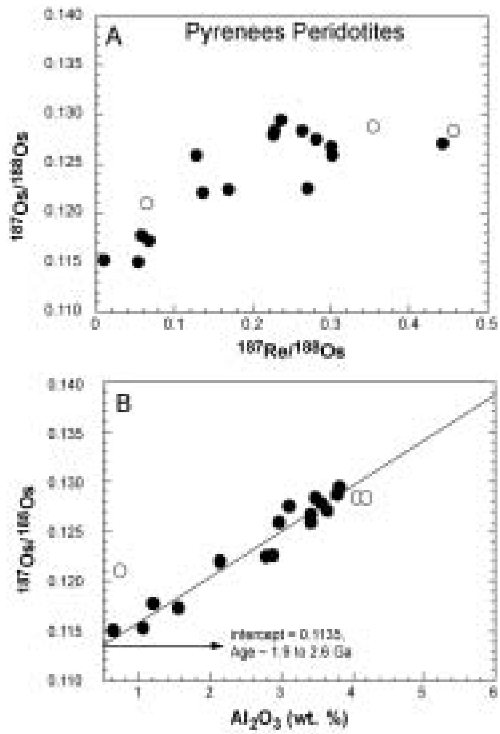

FIG. 3. A Re-Os isochron diagram (A) is compared to a $^{187}Os/^{188}Os$ versys Al_2O_3 plot (B) for massif peridotites from the Pyrenees (from Reisberg and Lorand, 1995). Aluminum is less mobile than Re and the intercept of the good correlation in (B) can be used to infer an age of the melting event. This age is dependent upon what mantle evolution curve is chosen. Using a primitive mantle curve gives an age of 2.6 Ga, whereas using a depleted mantle curve, based on abyssal peridotite data, gives a significantly younger age (1.9 Ga).

Deep Lithosphere Replacement beneath the Sierra Nevada

Mantle xenolith studies from the central Sierra Nevada arc provide evidence for lithosphere replacement and thinning (Ducea and Saleeby, 1996; Lee et al., 2000, 2001a). One episode of replacement occurred before eruption of the Late Miocene Big Creek diatreme, which brought up lithospheric samples in the central Sierra Nevada (Fig. 4). The other episode appears to post-date the eruption of this pipe, and may be associated with lithospheric thinning due to Basin and Range extension.

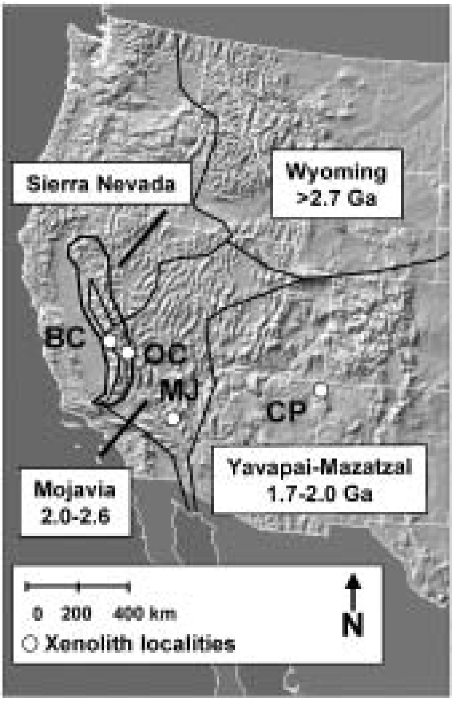

FIG. 4. Shaded relief map of the western United States showing xenolith localities (filled circles) discussed in the text. Different crustal provinces are delineated on the basis of the isotopic compositions of the crust (after Bennett and DePaolo, 1987). Abbreviations: BC = Big Creek, central Sierra Nevada; OC = Oak Creek, eastern Sierra Nevada; MJ = Cima volcanic field, Mojave Desert; CP = The Thumb diatreme, Colorado Plateau.

The Big Creek diatreme sampled a lithosphere that was stratified in terms of both age and thermal history 8 m.y. ago. Figure 5 shows the Os isotopic results for the Big Creek peridotites (from Lee et al., 2000). The samples do not lie on a Re-Os isochron, and there is only very poor correlation between $^{187}Os/^{188}Os$ and indicators of melt depletion, such as Mg# (Fig. 5). Indeed, all but two samples fall within the $^{187}Os/^{188}Os$ range of oceanic upper mantle (shaded field in Fig. 5), and thus most may have been recently derived from asthenospheric mantle.

The most important observation regarding the Os data for the Big Creek peridotites is that their Os isotopic compositions correlate with thermal history. Peridotites derived from deeper lithospheric levels (45–100 km) are recognized on the basis of the presence of garnet and the relatively high temperatures recorded in their minerals. These xenoliths show extensive petrographic evidence for cooling from temperatures >1100°C to temperatures as low as 700°C. This evidence includes garnet rims on spinel, garnet exsolution lamellae in clinopyroxene and orthopyroxene, and strongly zoned pyroxenes with high temperature (~1000°C) cores and lower temperature (~750°C) rims (Lee et al., 2001a). Although these samples record a range of melt depletion (as evidence by their olivine Mg# between 88.6 and 91), they have an $^{187}Os/^{188}Os$ ratio that is indistinguishable from modern asthenospheric mantle (Fig. 5), suggesting they formed recently (within the past few 100 Ma) from melting of convecting, oceanic-type mantle.

In contrast, the shallowest peridotites (~45 km) contain no garnet, equilibrated under relatively cold conditions (~700°C), but show subtle evidence for heating (e.g., slight Ca increases on the rims of orthopyroxenes; Lee et al., 2001a). These two samples are quite refractory (olivine Mg# > 91) and have the lowest $^{187}Os/^{188}Os$ ratios of the suite. The T_{RD} ages of these samples range from 1.0 to 1.6 Ga. The least radiogenic sample falls well below any $^{187}Os/^{188}Os$ observed in abyssal peridotites, and thus must reflect an ancient melting event. These samples provide strong evidence for the presence of Proterozoic lithosphere beneath this portion of the Sierra Nevada arc.

The above observations are best explained by relatively rapid removal of an original Proterozoic mantle lid, and its replacement by hot asthenospheric mantle, which intruded or underplated the remaining cold, overlying lithosphere (Lee et al., 2000, 2001a). Although the timing of this event is not well constrained from the Os isotopic data, geological observations and thermal modeling predict it was likely associated with Mesozoic arc magmatism, and may well have provided the heat source responsible for the Cretaceous magmatic pulse observed in the Sierran arc (Ducea, 2001).

A possible second lithosphere replacement event is recorded by mantle xenoliths carried in a Pliocene basalt flow originating in the High Sierra (Oak Creek, Fig. 4). These peridotites are all hot (>1000°C), of shallow origin (spinel facies only), and are relatively fertile (Mg# = 90). The $^{187}Os/^{188}Os$ ratios of these peridotites are indistinguishable from those of oceanic mantle (Fig. 5). Such xenoliths may represent lithospheric mantle formed by conductive cooling following Cenozoic Basin and Range thinning (e.g., Wernicke et al., 1996) of the

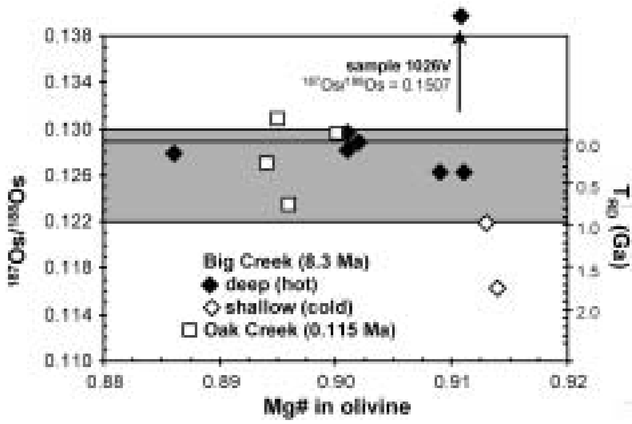

FIG. 5. Mg# (molar Mg/(Mg+Fe)) in olivine (an indicator of melt depletion) versus $^{187}Os/^{188}Os$ for peridotite xenoliths from the Sierra Nevada. T_{RD} model ages are shown on the right axis. Shaded band represents the range of $^{187}Os/^{188}Os$ compositions of modern convecting upper mantle (abyssal peridotites and primitive upper mantle). Horizontal line at $^{187}Os/^{188}Os = 0.129$ represents PUM of Meisel et al. (2001). All of the Oak Creek and all of the hot Big Creek xenoliths plot within the field of modern mantle. Only the shallow, cold Big Creek xenoliths show evidence of having been derived by an ancient melting event. From Lee et al. (2000).

refractory, stratified lithosphere, sampled in the Miocene.

Mojavia versus Colorado Plateau: A Contrast in Strength

The tectosphere model of Jordan (1975, 1988) explains the stability of Archean cratons in terms of the presence of a strong, cold, refractory lithospheric keel. Thus, it was a surprise to discover that the mantle lithosphere (from Moho to ~90 km) underlying the Mojavia terrane, situated in the southern Basin and Range (Fig. 4), in fact possesses Archean Re-Os model ages (both T_{MA} and T_{RD}) (Fig. 76 in Lee et al., 2001a). Archean rocks are not exposed at the surface of this terrane, although 1.7 Ga metamorphics yield Paleo-Proterozoic to Late Archean Nd model ages (Bennett and DePaolo, 1987; Ramo and Calzia, 1998). Furthermore, unlike stable Archean cratons, this region has high heat flow and has experienced extensive tectonism from the Proterozoic to the present.

Mantle xenoliths sampling the Mojavian lithospheric mantle (Fig. 6) are distinct from typical Archean cratonic mantle. Although melt depletion has occurred (as reflected in Mg#s of 89 to 90, which are higher than that of the primitive mantle at 88), Mojavia peridotites still contain significant Fe, and thus have higher densities than cratonic mantle. In addition, no garnet-bearing lithologies are observed, implying a thin mantle lid, which is consistent with the high heat flow. The lack of extreme melt depletion typical of Archean cratonic mantle resulted in the Mojavian lithospheric mantle being denser and therefore thinner than typical Archean cratonic lithosphere; it may never have achieved the great thicknesses observed for Archean cratons or, if thickened, it was thinned due to the negative thermal buoyancy of such relatively fertile lithosphere once it cooled. This thinness, in turn, resulted in a weaker lithosphere that could not withstand the influence of tectonic forces acting upon it, perhaps explaining the highly tectonized character of the Mojavia province.

In contrast, the adjacent mid-Proterozoic Colorado Plateau province (Fig. 6) is underlain by a thick (= 150 km), refractory Proterozoic mantle keel akin to many Archean cratons (Ehrenberg, 1982; Lee et al., 2001b). This may explain why the Colorado Plateau has been tectonically stable, like an Archean craton, even though it was formed in the mid-Proterozoic. An outstanding question is whether the Mojavia block is a remnant of an initially far more extensive, thin Archean lithosphere that was mostly recycled due to its lack of a thick, insulating mantle keel, or whether Mojavia is an anomaly, exemplifying the role of mantle lithosphere composition in controlling continent stability.

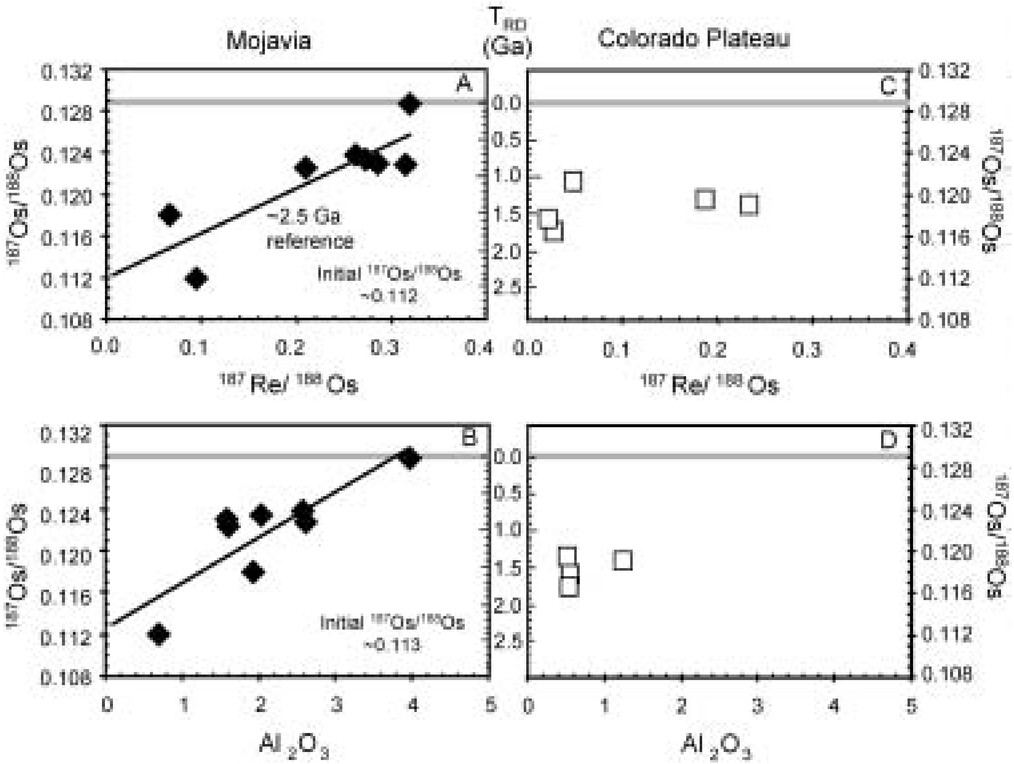

FIG. 6. Comparison of Re-Os isochrons and $^{187}Os/^{188}Os$ versus Al_2O_3 plots for mantle xenoliths from the Mojavia terrane (southern Basin and Range) and the Colorado Plateau. Even though the Mojavia terrane is underlain by an Archean lithospheric mantle, peridotites here are not highly refractory, as is the case for typical cratonic lithosphere. In contrast, mantle lithosphere beneath the Colorado Plateau is Proterozoic (~1.8 Ga) but more refractory than Mojavia, approaching the composition and thickness of Archean cratonic lithosphere. These differences in lithospheric mantle composition have controlled the thickness of the mantle lid and ultimately the strength of the lithosphere. From Lee et al. (2001b).

Conclusions

Re-Os isotope investigations of peridotite xenoliths provide unique information on the timing of lithosphere formation. When combined with petrological evidence of thermal histories and regional geologic information, Os isotope investigations provide important insights into the geodynamics of continental lithosphere.

Re-Os and petrological studies of mantle xenoliths from the Sierra Nevada record replacement of the deep lithosphere, probably associated with the last major episode of arc magmatism during the Cretaceous. Post-Miocene thinning beneath the High Sierras may have resulted in new mantle lithosphere formation via conductive cooling.

Similar studies of mantle xenoliths from the Mojavia terrane, southern Basin and Range, and the Colorado Plateau provide insights into the origin of the contrasting lithospheric strength between these two regions. Mojavia is underlain by thin (<90 km), anomalously fertile, Archean-aged mantle lithosphere. The high density of this mantle lid prohibited formation and stabilization of a thickened lithospheric lid, which, in combination with likely low viscosity, explains why this ancient lithosphere is thin and relatively weak compared to typical Archean tectosphere. In contrast, peridotite xenoliths from the Colorado Plateau are Proterozoic in age, but are refractory, and hence chemically buoyant. These properties led to development of a thick, strong lithosphere, more akin to Archean tectosphere than the weak Archean lithosphere of the Mojavia terrane.

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APPENDIX. Glossary of Terms

Asthenospheric mantle—literally, the "weak" mantle. Used here as synonymous with convecting upper mantle.

Compatible element—assuming equilibrium between solid and melt, a compatible element is a trace element that partitions preferentially into the solid.

Convecting mantle—that portion of the mantle below the lithosphere, which moves due to convective currents and through which heat flows along an adiabatic gradient.

Incompatible element—assuming equilibrium between solid and melt, an incompatible element is a trace element that partitions preferentially into the melt.

Metasomatism—chemical change produced to a solid rock due to interaction with fluids or melts.

Mg#—100 * Mg/(Mg+Fe), where Mg and Fe represent moles. Mg#, when applied to a peridotite, reflects chemical depletion of the rock. Mg# of primitive mantle is ~88. As more and more melt is extracted from a peridotite, Mg# increases. The highest Mg#s observed in peridotites are ~94.

Primitive mantle—a hypothetical mantle composition that reflects the silicate portion of the Earth (crust plus mantle) before any differentiation occurred. A nearly synonymous term is pyrolite (Ringwood, 1975), which was derived from mixing 2/3 alpine peridotite with 1/3 basalt.

Refractory—an adjective used here to describe peridotite that has lost a melt component. A refractory peridotite is one that has higher Mg# and lower CaO, Al_2O_3, and Na_2O than primitive mantle.