Olivine-poor sources for mantle-derived magmas: Os and Hf isotopic evidence from potassic magmas of the Colorado Plateau

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[1]   **Abstract:** The contribution of olivine-poor lithologies (pyroxenite, eclogite, etc.) in the mantle to the composition of mantle-derived melts is a growing topic of discussion in light of results suggesting that some magmatic characteristics are not easily explained by melt derivation solely from peridotitic sources. To investigate this issue, we have examined the Hf and Os isotopic composition of potassic magmas from the Navajo Volcanic Field of the Colorado Plateau. Most of the magmas have Os isotopic compositions much more radiogenic than observed for any uncontaminated oceanic basalt. The Os isotope compositions of these samples overlap those measured for crustal/upper mantle eclogitic xenoliths carried by nearby intrusions. Compositional and Os isotope systematics, however, suggest that the characteristics of the magmas are not determined by crustal contamination, but rather are the result of melting of pyroxene- and mica-rich veins/layers in the lithospheric mantle beneath the plateau. Once generated, the melts of olivine-poor lithologies interacted with surrounding metasomatized peridotite to create the compositional spectrum from katungite to minette. One component of this compositional variation is the appearance of strong relative depletions of high field strength elements in the minette end-member, suggesting that this chemical signature, common in convergent margin magmas, may be caused by melt-wall rock interaction.

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1. Introduction

[2] There is little question that peridotite is the volumetrically dominant constituent of the mantle, but both tectonically exposed sections of mantle [*Menzies et al.*, 1991] and mantle xenoliths [*Schulze*, 1989] show the mantle to contain several volume percent of various olivine-poor lithologies. These range from layers of eclogite that may be remnants of subducted oceanic crust [*Helmstaedt and Doig*, 1975; *MacGregor and Manton*, 1986] to pyroxene/amphibole/phlogopite-rich veins that are the crystal accumulation products of basaltic magmas passing through the mantle [*Irving*, 1980]. Though volumetrically subordinate to peridotite, the various olivine-poor mantle lithologies potentially can make a major chemical contribution to mantle-derived magmas since they contain a large fraction of the incompatible elements in the mantle [*Suen and Frey*, 1987]. Consequently, their contribution to mantle-derived melts has been the subject of investigation for some time [*Hanson*, 1977; *Irving*, 1980; *Foley*, 1992b]. Recently, the signature of garnet involvement during the production of mid-ocean ridge basalt (MORB) has been attributed to preferential melting of garnet pyroxenite veins, which both melt at a lower temperature than surrounding peridotite and stabilize garnet to shallower depth [*Hirschmann and Stolper*, 1996]. Suggestions of non-peridotitic source contributions also have been proffered for other large-volume mantle-derived magmas such as Hawaiian basalts [*Hauri*, 1996; *Kogiso et al.*, 1998] and continental flood basalts [*Wright et al.*, 1989; *Ellam and Cox*, 1991; *Cordery et al.*, 1997; *Takahashi et al.*, 1998].

[3] Defining the importance of olivine-poor sources for mantle-derived melts has proven difficult. One potential discriminant between a peridotitic and an olivine-poor source for a given magma is the Re-Os isotopic system.

Because Re is moderately incompatible and Os is strongly compatible during mantle melting, Re/Os ratios in peridotite generally range from chondritic to much lower than chondritic. In contrast, even primitive mantle melts can have Re/Os ratios as much as 1–2 orders of magnitude higher than chondritic [*Shirey and Walker*, 1998]. Also, because the Os content of peridotite remains high even after melt extraction, later melt infiltration is ineffective at altering the Os isotopic composition of mantle peridotite [*Walker et al.*, 1989; *Carlson et al.*, 1999]. Only when the melt/peridotite ratio becomes very high during melt-peridotite interaction will the Re/Os ratio and Os isotopic composition of the peridotite increase above that expected for primitive mantle [*Becker et al.*, 2001]. Peridotite with superchondritic Re/Os and $^{187}Os/^{188}Os$ has been found [*Brandon et al.*, 1996; *Chesley et al.*, 1999; *Lee et al.*, 2000], but it is rare and reaches only the low end of the $^{187}Os/^{188}Os$ ratios seen in magmas. Consequently, magmas derived from peridotitic sources should have a restricted range in Os isotopic composition, ranging from slightly superchondritic to subchondritic. Highly radiogenic Os in a magma should be a sign either of derivation from a source dominated by an old melt component, now found as an olivine-poor vein/layer in the mantle, or of contamination of the magma by old crust that also will be characterized by radiogenic Os.

[4] Since many olivine-poor lithologies in the mantle have lower solidi than peridotite [*Foley*, 1992b; *Hirschmann and Stolper*, 1996], the clearest expression of their contribution to mantle-derived magmas would be expected in low-degree partial melts, such as mafic-alkalic magmas. This is true even in the Re-Os system since at higher degrees of melting that involve surrounding peridotite, the high Os concentration of the peridotite will easily overwhelm the Os isotopic composition of mafic melts, imparting the Os isotopic signature of the peridotite.

Besides their generally very high incompatible element concentrations, mafic-alkalic magmas also can have relatively high Os concentrations [*Carlson et al.*, 1996] compared to many crustal rocks, which leads their isotope systematics to be relatively insensitive to crustal contamination. For these reasons, we have chosen to examine the importance of olivine-poor lithologies in mantle melt generation by analyzing the Re-Os and Lu-Hf isotope systems in a group of well-studied mafic-alkalic rocks from the Navajo Volcanic Field in the Colorado Plateau, southwestern United States. These small-volume magmas were emplaced into the stable Early Proterozoic continental platform of the Colorado Plateau in the late Oligocene to early Miocene before active extension and the associated voluminous volcanism of the Basin and Range activity began in the southwestern United States. These magmas thus formed during a relatively "low energy" period when mantle melting in the area occurred only to a limited extent, possibly accentuating the contribution from olivine-poor veins or layers in the mantle.

2. Navajo Volcanic Field: Background Geochemical Studies

[5] The Navajo Volcanic Field [*Gregory*, 1917; *Williams*, 1936] comprises numerous dikes, diatremes, and rare volcanic centers scattered over some 30,000 km² of the Four Corners region of the central Colorado Plateau (Figure 1). Magmatism in the Navajo Field occurred from 28.5 to 19.4 Ma [*Roden et al.*, 1979; *Laughlin et al.*, 1986; *Nowell*, 1993] with the emplacement of numerous small-volume flows and shallow intrusions. Compositionally, the Navajo magmas range from serpentinized ultramafic breccias [*Roden*, 1981], including very low silica compositions such as katungite [*Laughlin et al.*, 1986, 1989], to more evolved compositions such as latite [*Esperança and Holloway*, 1986]. The main volume of magma

ranges from melanephelinite to minette in composition [*Alibert et al.*, 1986]. Many of these eruptive centers also carried crustal and mantle xenoliths [*McGetchin and Silver*, 1970; *Smith*, 1979; *Esperança and Holloway*, 1984; *Roden et al.*, 1990; *Wendlandt et al.*, 1993], testifying to quick transit through the crust.

[6] A number of studies have examined the compositional and isotopic variation of these magmas [*Roden and Smith*, 1979; *Roden*, 1981; *Alibert et al.*, 1986; *Laughlin et al.*, 1986, 1989; *Roden et al.*, 1990; *Nowell*, 1993; *Beard and Johnson*, 1997]. Most of the samples analyzed here were studied previously for their major and trace element compositions and Sr, Nd, and Pb isotopic variation by *Nowell* [1993], who also lists detailed petrographic descriptions of the samples. Our analyses are restricted to the more primitive compositions studied by *Nowell* [1993], those that were argued to represent near-primary mantle melts that had experienced minimal differentiation in the crust. The sample set includes the katungites analyzed for major and trace element composition by *Laughlin et al.* [1989] and two samples of the Buell Park minette [*Roden and Smith*, 1979].

[7] Summarizing from the compositional and isotopic results presented by *Nowell* [1993], the Navajo samples show decreasing MgO, TiO₂, Fe₂O₃, CaO, and P₂O₅ and increasing SiO₂ and Al₂O₃ in the order katungite, nephelinite, mafic minette (Figure 2). All compositions are strongly light rare earth element (LREE) enriched with similar smooth REE patterns. Only the minettes show significant depletion of the high field strength elements Ta, Nb, and Hf with K/Ta ratios in excess of 10,000 compared to the nephelinites and katungites, which have K/Ta ratios generally between 1800 and 5000, within the range seen for MORB and ocean island basalts. Sr isotopic compositions of the katungites and nephelinites range
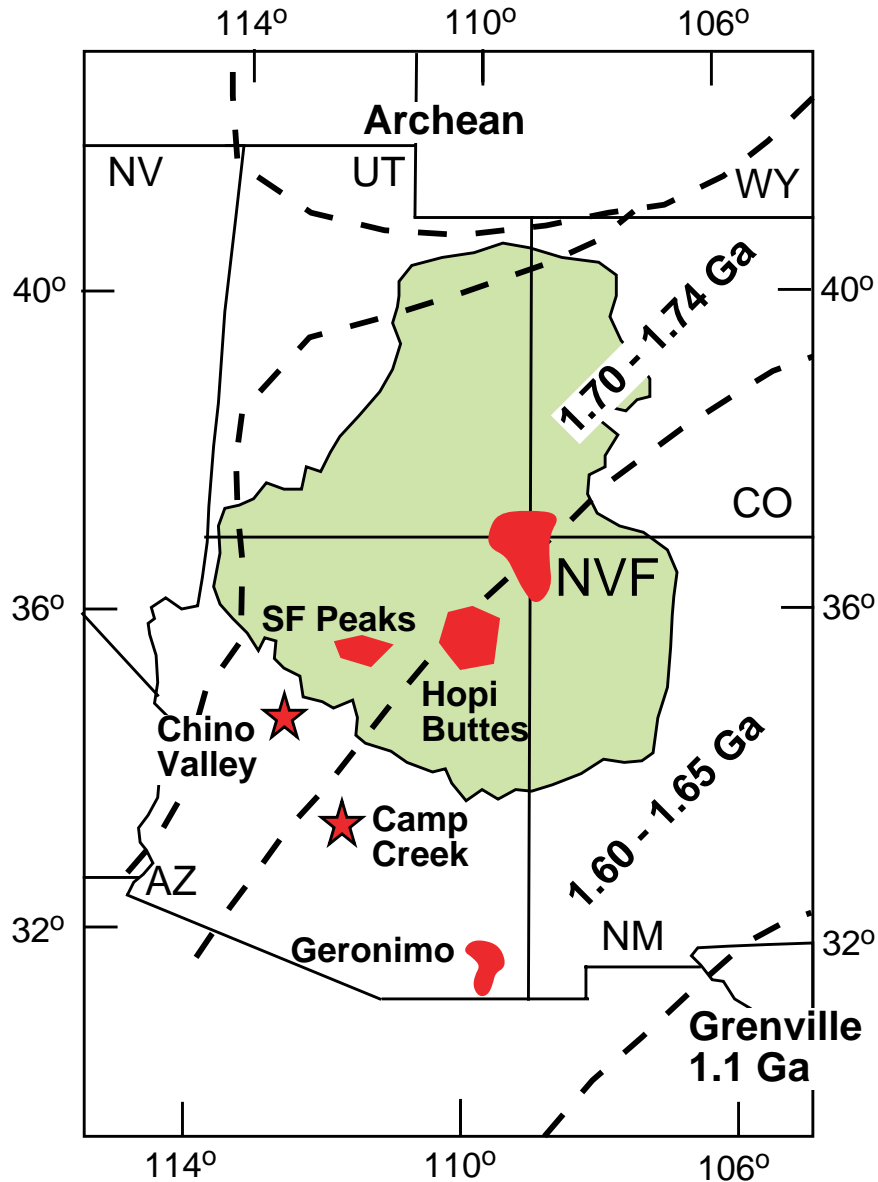
Figure 1. Map showing the location of the Navajo Volcanic Field (NVF), Hopi Buttes, and San Francisco Peaks volcanic areas in the middle of the Colorado Plateau (green field) and the Geronimo basaltic field to the south of the plateau. Red stars show the location of two latite intrusive centers containing crustal/shallow mantle xenoliths [*Arculus and Smith*, 1979; *Esperança and Holloway*, 1984; *Smith et al.*, 1994]. The dashed lines show approximate boundaries of basement terranes of varying age [*Zartman*, 1974; *Bennett and DePaolo*, 1987].

between $^{87}Sr/^{86}Sr = 0.7045$ and 0.7058 with a very narrow range in $^{143}Nd/^{144}Nd$ (0.51272–0.51280) (Figure 3). The minettes have $^{87}Sr/^{86}Sr$ at the high end of this range with slightly lower $^{143}Nd/^{144}Nd$. Pb isotopes show a very narrow range of $^{206}Pb/^{204}Pb$ (19.04–19.25) and $^{208}Pb/^{204}Pb$ (38.86–39.18) with a nearly vertical trend in $^{207}Pb/^{204}Pb$ versus
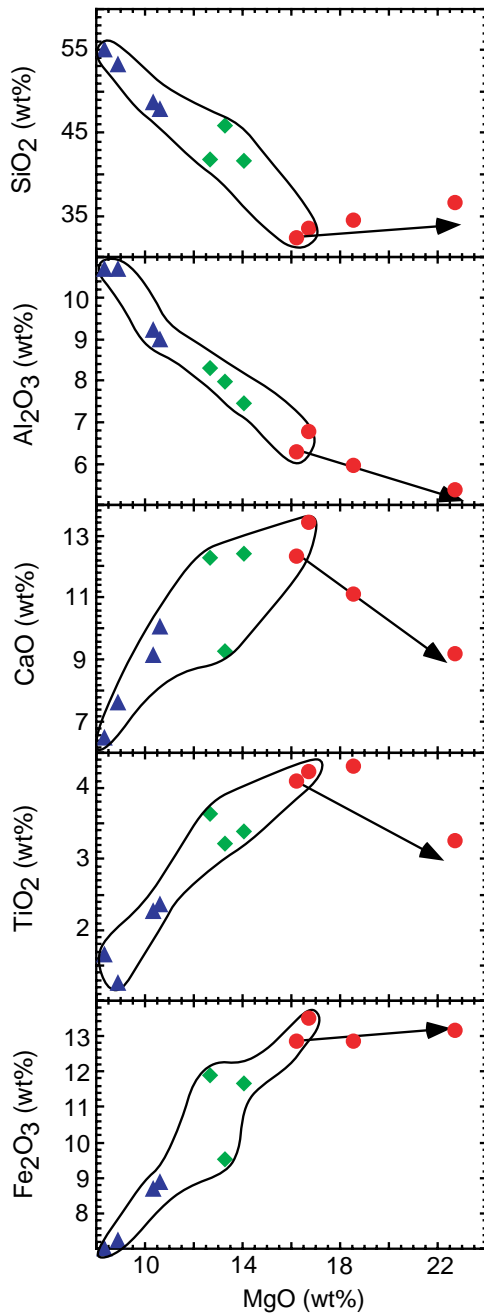
Figure 2. Major element variation diagrams using the data reported by *Nowell* [1993]. Hasbidito Creek katungites [*Laughlin et al.*, 1989] are shown as red circles, the Newcombe melanephlinites are shown by green diamonds, and the Barber Peak minettes are shown by blue triangles. Arrows show the vectors caused by the addition of average continental peridotite to the AWL-5-86 katungite.

^{206}Pb/^{204}Pb (Figure 3). In Pb isotopic composition the katungites lie within the field seen for MORB, whereas the nephelinites and minettes plot above the MORB field in the direction of ocean sediments and more evolved minette compositions from the Navajo field [*Alibert et al.*, 1986; *Roden et al.*, 1990]. Though displaying considerably more variation, eclogite xenoliths from the Colorado Plateau [*Wendlandt et al.*, 1993, 1996] and from just south of the plateau [*Esperança et al.*, 1988; *Smith et al.*, 1994] overlap in Sr, Nd, and Pb isotopic composition with the Navajo magmas (Figure 3).

[8] Perhaps the most intriguing correlation between elemental and isotopic variation is seen in ^{87}Sr/^{86}Sr and Ba/Nb versus Al$_2$O$_3$ concentration [*Nowell*, 1993] (Figure 4). With increasing Al$_2$O$_3$, the Navajo magmas show increasing ^{87}Sr/^{86}Sr and strongly increasing Ba/Nb. These trends are very distinct from those shown by nephelinites from the nearby Hopi Buttes [*Alibert et al.*, 1986] and the much larger volume alkalic basalts of the Geronimo field [*Menzies et al.*, 1985]. The Geronimo basalts, in particular, have Al$_2$O$_3$, ^{87}Sr/^{86}Sr, and Ba/Nb approaching those of MORB, whereas the high Al$_2$O$_3$ and Ba/Nb end of the Navajo array has elevated ^{87}Sr/^{86}Sr in the direction observed for mafic lower crust and upper mantle xenoliths from just south of the plateau (*Esperança et al.*, 1988; *Smith et al.*, 1994].

3. Procedures and Results

[9] Re and Os isotopic compositions and concentrations were measured on aliquots of the same powders analyzed by *Nowell* [1993] with the results given in Table 1. Sample digestion and chemical separation of Re and Os were done using the procedures described by *Carlson et al.*, 1999). Mass spectrometry of Re and Os was performed on the Department of Ter-
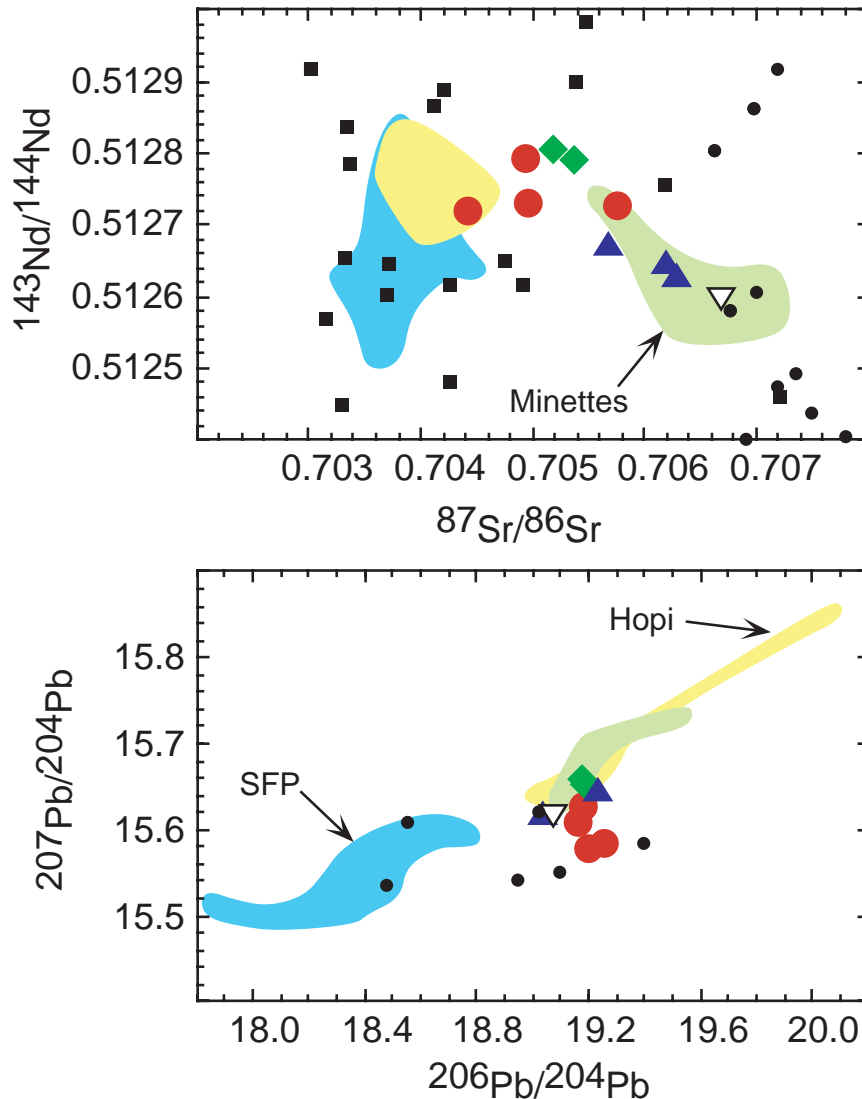
Figure 3. Nd, Sr, and Pb isotopic variation of the analyzed Navajo magmas [*Nowell*, 1993] in comparison to a broader set of Colorado Plateau magmas [*Alibert et al.*, 1986], including Navajo minettes (green field), Hopi Buttes monchiquites (yellow field), and basalts from San Francisco Peaks (SFP) and the Grande Canyon area (blue field). Symbols are as defined for Figure 2 with the addition of open upside-down triangles for the Camp Creek and Chino Valley latites [*Esperança et al.*, 1988]. The small black circles correspond to data for eclogitic xenoliths from the Colorado Plateau [*Wendlandt et al.*, 1993] and surrounding areas [*Esperança et al.*, 1988; *Smith et al.*, 1994]. The black squares are data for mafic lower crustal granulites from the Colorado Plateau [*Wendlandt et al.*, 1993, 1996].

restrial Magnetism (DTM) 38 cm thermal ionization mass spectrometer analyzing OsO_3^- and ReO_4^- with procedures similar to those outlined by *Pearson et al.* [1995]. Hf isotopic compositions were analyzed by inductively coupled plasma–mass spectrometry (ICP-MS) at NERC Isotope Geosciences Laboratory (NIGL) using the Thermo Elemental P54 with
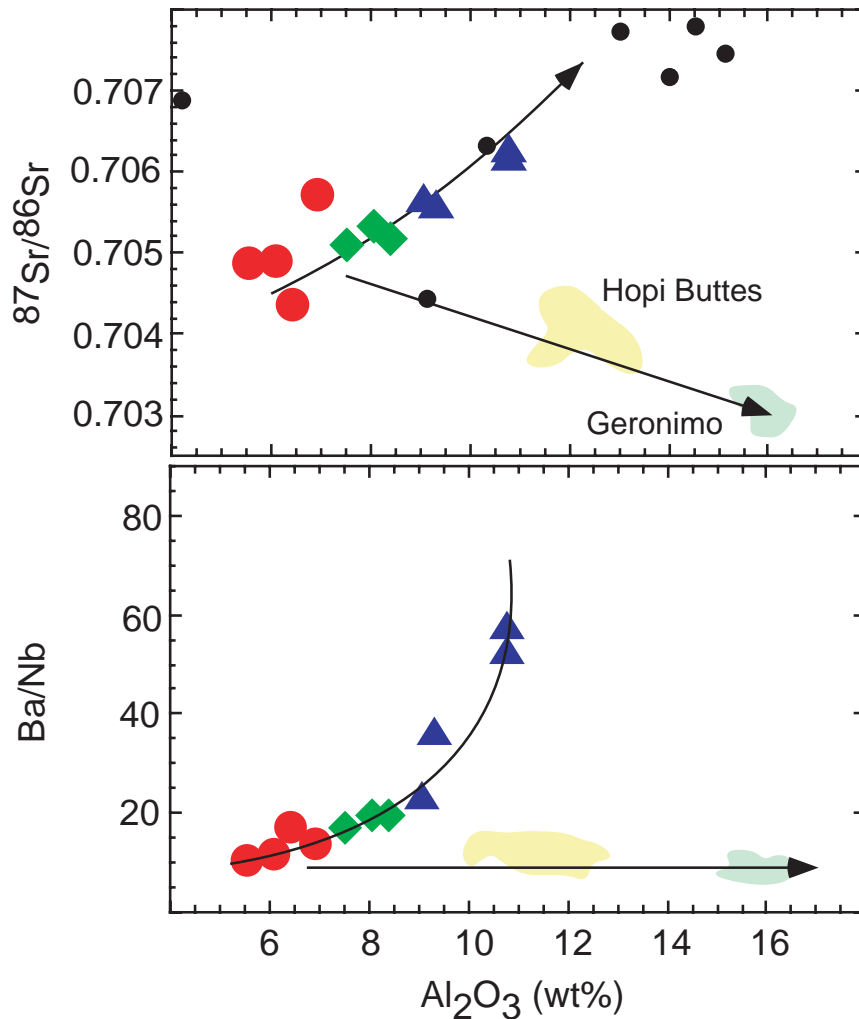
Figure 4. Sr isotopic composition and Ba/Nb ratio versus Al_2O_3 concentration in the Navajo samples in comparison to the Hopi Buttes monchiquites [*Alibert et al.*, 1986] and the Geronimo alkalic basalts from southern Arizona [*Menzies et al.*, 1985]. Figure is modified from that of *Nowell* [1993]. Small black circles are data for lower crustal xenoliths from Camp Creek [*Esperança et al.*, 1988].

procedures described by *Nowell et al.* [1998] and *Nowell et al.* [1999]. Hf isotopic compositions are reported relative to $^{176}Hf/^{177}Hf =$ 0.282160 for the JMC475 standard. Lu and Hf concentrations (Table 1) used to age correct the Hf isotopic compositions are from *Nowell* [1993].

[10] Hf isotopic compositions of the Navajo samples measured here show a very narrow range (ε_{Hf} = +1.9 to +5.9), with no clear correlation with rock type (Figure 5). These results overlap but generally extend to higher ε_{Hf} compared to data reported by *Beard and Johnson* [1997], who found three minettes from the Navajo field to have ε_{Hf} between +1.1 and +1.9. The samples plot in the middle of the Nd-Hf mantle array [*Vervoort and Blichert-Toft*, 1999], overlapping the isotopic compositions observed for ocean island basalts

Table 1. Concentration and Isotopic Results for Navajo Samples[a]

Sample	Latitude	Longitude	Location	Rock Type	MgO wt %	Re, ppb	Os, ppb	$\frac{^{187}Re}{^{188}Os}$	$\frac{^{187}Os}{^{188}Os}$	±	Lu, ppm	Hf, ppm	$\frac{^{176}Lu}{^{177}Hf}$	$\frac{^{176}Hf}{^{177}Hf}$	ε_{Hf}	$\Delta\varepsilon_{Hf}$
AWL-5-86	36°38′	109°20′	Hasbidito Creek	katungite	22.59	0.081	0.243	1.61	0.14125	0.00043	0.16	8.36	0.00273	0.282893	4.9	−2.8
BOL-4-84	36°38′	109°20′	Hasbidito Creek	katungite	16.61	0.503	0.048	52.78	0.41998	0.00497	0.26	10.50	0.00353	0.282857	3.7	−2.3
BOL 8-84	36°38′	109°20′	Hasbidito Creek	katungite	18.45	0.340	0.195	8.43	0.14648	0.00017	0.15	8.94	0.00239	0.282876	4.3	−1.7
BOL12-84	36°38′	109°20′	Hasbidito Creek	katungite	16.09	0.161	0.064	12.16	0.33909	0.00245	0.19	9.09	0.00298	0.282840	3.0	−2.7
90NM-4	36°20′43″	108°41′21″	Newcombe	nephelinite	13.99	0.048	0.038	6.23	0.32920	0.00389	0.20	9.00	0.00317	0.282899	5.1	1.9
90-NM-1	36°16′49″	108°42′10″	Newcombe	nephelinite	13.22	0.639					0.14	11.10	0.00180	0.282878	4.3	−3.2
90-NM-3	36°20′43″	108°38′29″	Newcombe	nephelinite	12.62		0.072		0.29254	0.00160	0.21	10.10	0.00296	0.282922	5.9	−2.0
90-NM-11	36°34′13″	108°41′17″	SE Barber Peak	minette	10.28	0.415	0.066	30.64	0.24860	0.00103	0.21	10.10	0.00296	0.282807	1.9	−1.3
90-NM-28	36°05′18″	108°52′29″	Washington Pass	minette	8.28	0.044	0.097	2.33	0.26578	0.00088	0.20	9.24	0.00308	0.282817	2.3	−1.1
90-NM-48	36°44′19″	110°07′05″	Church Rock	minette	8.80	6.622	0.350	94.27	0.38515	0.00378						
90-NM-55	37°05′	110°06′	Mexican Hat	minette	10.52	0.198	0.065	14.99	0.33060	0.00218	0.25	9.83	0.00362	0.282879	4.4	−0.1
N72-BP	35°57′	109°06′	Buell Park	minette		0.051	0.062	3.98	0.20332	0.00036						
N314-BP	35°57′	109°06′	Buell Park	minette		0.0093	0.150	0.30	0.22617	0.00060						

[a] Isotopic compositions are measured values. Average $^{187}Os/^{188}Os$ for the DTM JM Os standard is 0.1740. Hf isotopic compositions are reported relative to $^{176}Hf/^{177}Hf = 0.282160$ for the JMC475 standard. Re and Os concentrations are uncertain to ~1%. MgO, Lu, and Hf concentration data are from *Nowell* [1993]. The ε_{Hf} value is calculated at the eruption age relative to a modern-day chondritic $^{176}Hf/^{177}Hf = 0.282772$. $\Delta\varepsilon_{Hf} = \varepsilon_{Hf} - (1.3\varepsilon_{Nd}) + 3.3$ [*Johnson and Beard*, 1993]. Sample positions approximate for those listed to minute precision.
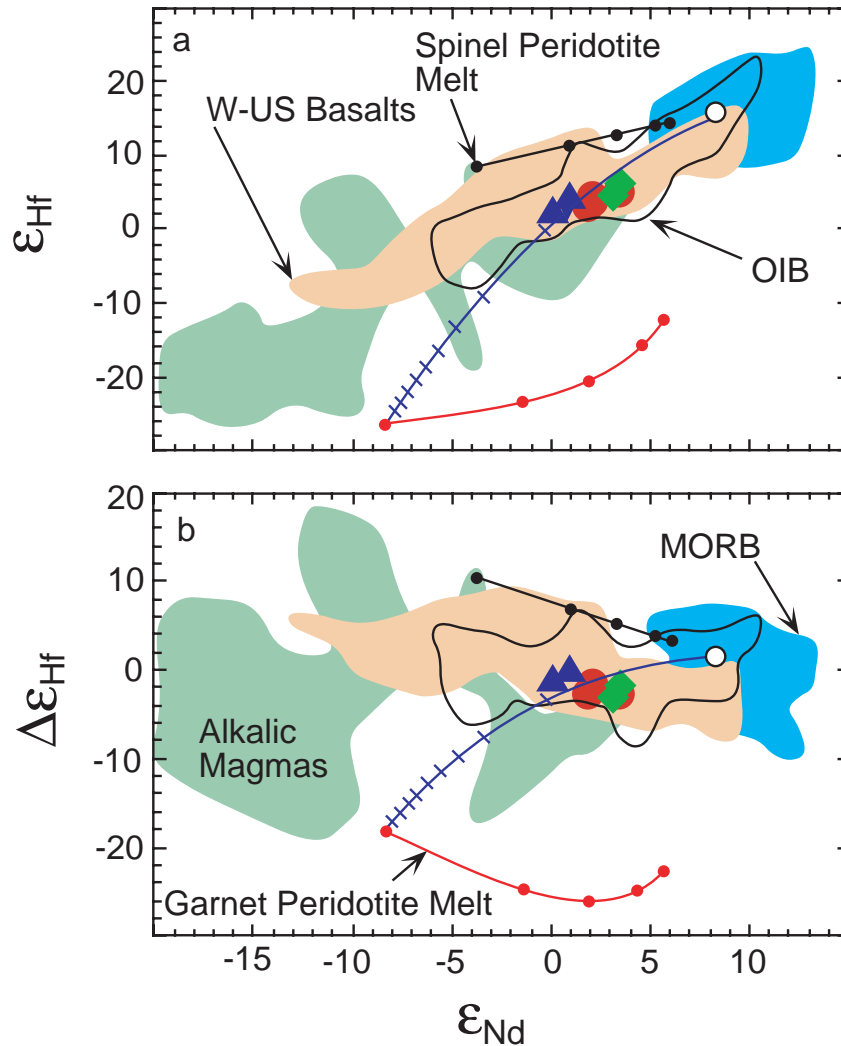
Figure 5. Hf versus Nd isotopic composition of the analyzed Navajo samples in comparison to the fields for mid-ocean ridge (blue) and oceanic island (outlined field) basalts [*Vervoort and Blichert-Toft*, 1999], various continental mafic-alkalic magmas (green) [*Nowell et al.*, 1999], and a number of Cenozoic basalts from the western United States (brown) [*Beard and Johnson*, 1993, 1997]. Following the model presented by *Beard and Johnson* [1993], the black and red lines show the present-day isotopic compositions of melts produced by melting spinel (black) and garnet (red) peridotite that has depleted mantle compositional characteristics that would cause the unmelted source today to plot at the point indicated by the open circle. Melt compositions are calculated for nonmodal batch melting using the clinopyroxene and garnet distribution coefficients and melt modes given by *Salters and Hart* [1989] with a source peridotite composition having the mode calculated for the fertile peridotite PHN1611 [*Jordan*, 1979]. Dots along the lines show the composition of 1, 5, 10, 20, and 30% partial melts. These calculations assume a melt formation age of 1.6 Ga. The blue curve shows the mixing trajectory between a 1.6 Ga 1% melt of garnet peridotite and depleted mantle. Dots along these curves reflect 10% increments of mixing.
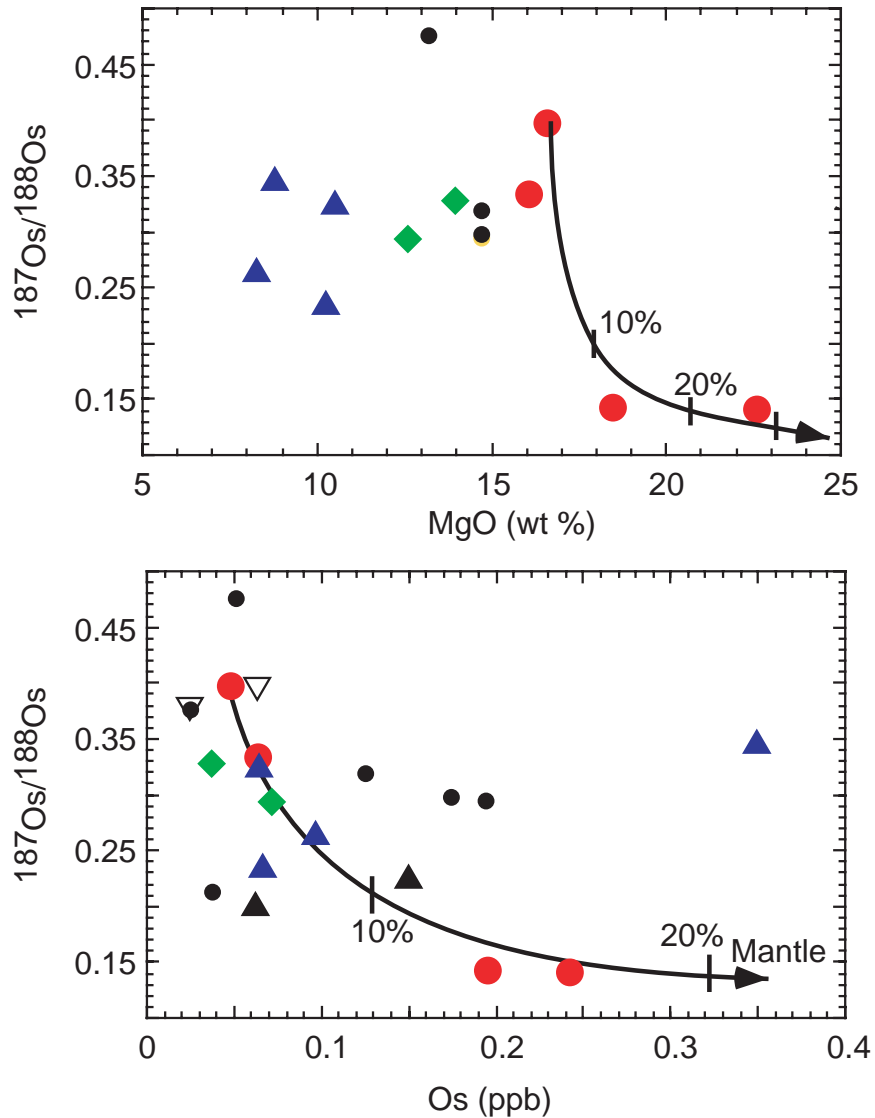
Figure 6. Os isotopic composition versus MgO and Os concentration. Symbols are as defined for Figures 2 and 3 with the addition of the black triangles for the Buell Park minettes. The curve shows the mixing trajectory between katungite AWL-5-86 and a peridotite with MgO = 43 wt %, Os = 2 ppb, and $^{187}Os/^{188}Os = 0.117$.

as well as a variety of Cenozoic basalts from the western United States [*Beard and Johnson*, 1997]. The Navajo samples do not extend significantly beneath the Nd-Hf array (Figure 5b) as is observed for kimberlites and lamproites, including some from Montana [*Nowell et al.*, 1999]. Hf isotopic composi-

tions show no correlation with MgO content of the magmas, whereas the samples do display a rough negative correlation between MgO and $^{87}Sr/^{86}Sr$.

[11] Re and Os concentrations for most samples are lower than expected given the relatively

high MgO concentration of these samples. The most magnesian samples, the katungites, split into two groups, one with high MgO and Os contents, but low $^{187}Os/^{188}Os$, the other with MgO still higher than the nephelinites and minettes, but with low Os concentrations and among the most radiogenic Os isotopic compositions in the data set. Re/Os ratios for all samples are considerably higher than fertile mantle values ($^{187}Re/^{188}Os = 0.42$ [*Meisel et al.*, 1996]) as expected for a melt given the incompatibility of Re and compatibility of Os. With the exception of two of the katungites, all the Navajo samples have $^{187}Os/^{188}Os$ much higher than seen in ocean island basalts, which rarely exceed $^{187}Os/^{188}Os$ of 0.15 [*Hauri and Hart*, 1993; *Reisberg et al.*, 1993; *Widom and Shirey*, 1996]. Os isotopic compositions show some correlation with Os content, with the higher Os content samples generally having lower $^{187}Os/^{188}Os$ (Figure 6). The nephelinite sample 90-NM-48 is the exception as it has the highest Os content and nearly the highest $^{187}Os/^{188}Os$ of any sample analyzed. The higher Os isotopic compositions of the samples measured here approach the values determined for the evolved latites from just south of the Colorado Plateau [*Esperança et al.*, 1997].

4. Discussion

4.1. Crustal Contamination?

[12] Radiogenic Os isotopic compositions are seen for many continental basalts [*Hart et al.*, 1997]. Continental crust also is characterized by radiogenic Os; consequently, trends of increasing $^{187}Os/^{188}Os$ with decreasing Os content (Figure 6) are often indicative of crustal contamination. *Nowell* [1993] presented several arguments against the influence of crustal contamination for the more primitive members of the Navajo magmas. These arguments were based on (1) the high Mg number of the samples, 2) the fact that some intrusions carry

mantle xenoliths to the surface, testifying to rapid transport through the crust, and 3) the fact that these magmas have much higher incompatible element contents than most crustal materials, which renders their Sr, Nd, Hf, and Pb isotopic systems relatively immune to contamination. This latter argument does not necessarily hold for the Os isotopic composition in these rocks because of their low Os contents. Nevertheless, several features argue against crustal contamination being responsible for the Re-Os characteristics of these rocks.

[13] In evaluating the consequences of crustal contamination, one normally would look to the most MgO-rich samples as the most primitive magmas since both simple mixing with the crust and assimilation coupled with fractional crystallization should strongly reduce MgO contents of an evolving magma that crystallizes olivine. In the Navajo sample suite the two katungites with highest MgO contents also have dramatically lower $^{187}Os/^{188}Os$ compared to the other samples, in the direction expected if these two samples had experienced less crustal contamination. However, at least one of these two katungites (AWL-5-86) contains xenocrystic olivine with forsterite contents of 89–91% [*Laughlin et al.*, 1989], possibly derived from disaggregated peridotitic xenoliths. The mixing curves in Figures 2 and 6 show the compositional and isotopic trends that would be expected if disaggregated mantle peridotite were added to a magma similar in composition to the two less magnesian katungites. As can be seen in Figures 2 and 6, addition of up to 25% peridotite to the BOL-4-84 katungite creates mixing curves that explain the major element variation of the katungites as well as the observed variation between $^{187}Os/^{188}Os$ and both Os and MgO content. Consequently, we suggest that the low $^{187}Os/^{188}Os$ of the two high-MgO katungites does not reflect the liquid composition, but rather a mixture between a parental magma similar to the low-MgO katun-

gites and disaggregated peridotite from the lithospheric mantle.

[14] If the two high-MgO katungites are thus eliminated from discussion of parental magma compositions, Figure 6 shows that the Os isotopic composition of the remaining samples is, at best, slightly positively correlated with MgO content and negatively correlated with Os concentration. As mentioned previously, crustal contamination, particularly if accompanied by fractional crystallization, would be expected to produce steeply negative trends between MgO content and Os isotopic composition. The lack of such a trend and the fact that the most magnesium samples (excluding the two high-MgO katungites) have the most radiogenic Os isotopic compositions imply that the parental magmas for these rocks also had radiogenic Os. Nevertheless, the negative correlation between Os concentration and Os isotopic composition could be suggestive of contamination, but the amount of crustal contaminant needed to raise the Os isotopic composition to the $^{187}Os/^{188}Os$ = 0.40 of the most radiogenic katungite is unrealistically large. For example, assuming a parental magma with $^{187}Os/^{188}Os$ = 0.117, as expected for a melt of Proterozoic lithospheric peridotitic mantle, and a crustal component equal to the eclogite xenolith 7025 from Camp Creek, just south of the Colorado Plateau ($^{187}Os/^{188}Os$ = 0.921; Os concentration of 0.027 ppb [Esperança et al., 1997]), 50, 66, or 91% eclogitic component must be added to a parental melt with Os concentration of 0.05, 0.1, or 0.5 ppb, respectively, to reach $^{187}Os/^{188}Os$ = 0.40. Using an even more extreme composition, such as the shallow mantle websteritic xenolith PRT-5g from nearby Chino Valley ($^{187}Os/^{188}Os$ = 1.102; Os concentration of 0.10 ppb [Esperança et al., 1997]) would still require large amounts (16, 28, or 66%) of crustal component for parental magma Os concentrations of 0.05, 0.1, or 0.5 ppb, respectively, to raise the $^{187}Os/^{188}Os$ of the melt to 0.40. To reach

$^{187}Os/^{188}Os$ = 0.347 at an Os concentration of 0.35 ppb, as measured for minette 90-NM-48, would require over 51% contamination from a composition like PRT-5g. Given the very high quantities of crust that would have to be added to explain the Os isotopic compositions of the Navajo magmas, we suggest that the radiogenic Os in the Navajo samples does not result from crustal contamination since this amount of contamination would result in magmas with dramatically different major element compositions than actually observed. Instead, the primary Navajo magmas appear to be derived not from melting of lithospheric peridotite, but from melting of an olivine-poor lithology introduced into the lithospheric mantle of this area either by subduction of mafic oceanic crust or by injection of mafic melts. If so, the negative trend between Os isotopic composition and Os concentration shown in Figure 6 could reflect mixing of hybrid vein-peridotitic sources in the mantle. For example, the most radiogenic end of the array might most clearly reflect the vein/layer component, whereas the decreasing Os isotopic composition on going from katungite to nephelinite to minette could reflect an increasing contribution from, or degree of interaction with, lithospheric peridotite. The similar Sr, Nd, Hf, and Pb isotopic composition of all these magmas reflects the fact that these incompatible element based radiometric systems will be dominated by the olivine-poor lithology in such a mixed source.

4.2. Source Character and Origin

[15] Because garnet has a high distribution coefficient for Lu, melts produced from a garnet-bearing source will have very low Lu/Hf but relatively less fractionated Sm/Nd, causing the Hf-Nd isotopic evolution of such melts to trend well below the Hf-Nd mantle array (Figure 5). In contrast, melts produced in the spinel stability field will have Sm/Nd and Lu/Hf ratios that will cause their Nd-Hf isotopic

compositions to evolve parallel to, or slightly less steep than, the mantle array (Figure 5). The extensive Hf-Nd isotopic data set for western U.S. basalts presented by *Beard and Johnson* [1993, 1997] defines a field just slightly less steep than the Hf-Nd array defined by ocean island basalts. On the basis of this observation, *Beard and Johnson* [1993] suggested that the variation in Hf-Nd isotopic composition seen in western U.S. basalts reflects basalt sources formed by the intrusion into lithospheric peridotite of small volume melts produced in the spinel stability field. The range in isotopic compositions observed was then attributed to different mixing ratios between intruded melt and surrounding peridotite.

[16] The Hf-Nd range seen in the Navajo samples studied here is but a small fraction of the range seen in the basalts studied by *Beard and Johnson* [1993, 1997]. Nevertheless, the Navajo samples also show the slight negative correlation between $\Delta\varepsilon_{Hf}$ and ε_{Nd} (Figure 5) seen in the larger field defined by western U.S. basalts, consistent with a source containing a component produced by melting in the spinel stability field. However, the very steep REE patterns of all the Navajo magmas strongly indicate the involvement of garnet in their formation. *Beard and Johnson* [1993] saw similar features in their studies of western U.S. basalts and attributed the garnet signature to metamorphic garnet formation in the melt-metasomatized lithosphere caused by cooling with continent maturation.

[17] In order to reach the Hf-Nd isotopic compositions seen in the Navajo samples by involving a source component derived from melting garnet peridotite, the intruded magmatic component in the source would be required to mix with surrounding depleted lithospheric peridotite. The blue line in Figure 5 shows such a mixing trajectory and indicates that a mixture of 95% peridotite plus 5% of a 1.6 Gyr old 1%

partial melt of garnet peridotite will have Hf and Nd isotopic compositions overlapping those observed in the Navajo samples. Such a mixture, however, would have Os isotopic composition essentially identical to the peridotite end-member, which for a 1.6 Ga depleted peridotite would be approximately $^{187}Os/^{188}Os$ = 0.117. For example, a mixture between a peridotite with $^{187}Os/^{188}Os$ = 0.117 and Os concentration of 3.3 ppb and a magmatic layer/vein component with Os systematics similar to the PR-149 eclogite xenolith from Chino Valley, just south of the Colorado Plateau ($^{187}Os/^{188}Os$ = 0.652; Os concentration of 0.104 ppb [*Esperança et al.*, 1997], would have $^{187}Os/^{188}Os$ below 0.20 at an eclogite:peridotite ratio of 85:15 and below 0.15 at 65:35. At these high relative abundances of vein/layer component to peridotite, the Sr, Nd, Hf, and Pb isotopic composition of the mixture would be nearly indistinguishable from that of the vein/layer component alone. Consequently, the combined Os-Hf-Nd systematics of the Navajo samples are best explained by a source composed of a lithospheric vein/layer component produced by melting in the spinel stability field and injected into the Colorado Plateau lithospheric mantle. Given the limited Sm-Nd and Lu-Hf fractionation caused by melting in the spinel stability field, in order to reach the Nd and Hf isotopic compositions observed for the Navajo samples starting from a depleted mantle similar to that which produced the crust of this area [e.g., *DePaolo*, 1981], this vein/layer component would have to be introduced into the Colorado Plateau lithosphere long before the Navajo activity, possibly during initial lithosphere formation in this area in the mid-Proterozoic [*Beard and Johnson*, 1993].

4.3. Vein Melt-Wall Rock Interaction: Chemical and Isotopic Features

[18] The major element characteristics of the samples studied here range from the very low

SiO_2 and Al_2O_3 and high CaO katungites to the higher SiO_2 and Al_2O_3 and lower CaO minettes. The compositional spectrum thus crosses from the kamafugite (katungites) to lamproite (minettes) fields of ultrapotassic rocks as defined by *Foley* [1992a]. As discussed by *Foley* [1992a], the very low SiO_2 content of rocks like the Navajo katungites most likely reflects mica-clinopyroxene source lithologies with CO_2 as an abundant volatile phase. In contrast, the compositional characteristics of the lamproite end-member point toward a depleted mica-harzburgite source with H_2O as the dominant volatile phase. These petrologic predictions match the observed isotopic and trace element variation in the Navajo samples quite well. The katungites have the most radiogenic Os isotopic compositions, suggestive of a source containing the least influence from lithospheric peridotite. Decreasing $^{187}Os/^{188}Os$ and increasing Os concentration on going from katungite to minette (Figure 6) are consistent with an increasing contribution from depleted lithospheric peridotite. Similarly, the increasing $^{87}Sr/^{86}Sr$ from katungite to minette may reflect the higher Rb/Sr expected for a mica-harzburgite compared to a mica-clinopyroxenite.

[19] As shown in Figure 4, the trend from katungite to minette also is one of strongly increasing depletion in high field strength elements (HFSE). This suggests that the HFSE depletion comes not from the vein component but from wall rock peridotite, or at least interaction between the vein melt and surrounding peridotite. Increasing K_2O/Na_2O and Ba/Nb from katungite to minette is suggestive of dissolution of phlogopite from the wall rock peridotite since phlogopite can be the main repository of K and Ba in a metasomatized harzburgite. Reaction between the vein melt and the Cr-rich peridotite also can stabilize alkali-chrome titanates [*Haggerty*, 1983; *Foley*, 1992b], which will effectively remove HFSE from the melt. Thus the chemical and isotopic data for the Navajo alkalic magmas fit very well the expectations of the vein-wall rock melting scenario outlined by *Foley* [1992b]. The katungites reflect the lowest-degree melts involving primarily the vein components, whereas the minettes reflect slightly higher degrees of melting where the peridotitic wall rock begins to interact with the vein melts. This model also is consistent with the very small volumes of katungite erupted on the Colorado Plateau in comparison to the more voluminous minettes.

Acknowledgments

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