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Mantle melt production during the 1.4 Ga Laurentian magmatic event: Isotopic constraints from Colorado Plateau mantle xenoliths

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ABSTRACT

Plutons associated with a 1.4 Ga magmatic event intrude across southwestern Laurentia. The tectonic setting of this major magmatic province is poorly understood. Proposed melting models include anorogenic heating from the mantle, continental arc or transpressive orogeny, and anatexis from radiogenic heat buildup in thickened crust. Re-Os analyses of refractory mantle xenoliths from the Navajo volcanic field (NVF; central Colorado Plateau) yield Re depletion ages of 2.1–1.7 Ga, consistent with the age of the overlying Yavapai and Mazatzal crust. However, new Sm-Nd isotope data from clinopyroxene in peridotite xenoliths from NVF diatremes show a subset of xenoliths that plot on a ca. 1.4 Ga isochron, which likely reflects mantle melt production and isotopic resetting at 1.4 Ga. This suggests that Paleoproterozoic subcontinental lithospheric mantle was involved in the 1.4 Ga magmatic event. Our constraints support a subduction model for the generation of the 1.4 Ga granites but are inconsistent with rifting and anorogenic anatexis models, both of which would require removal of ancient lithosphere.

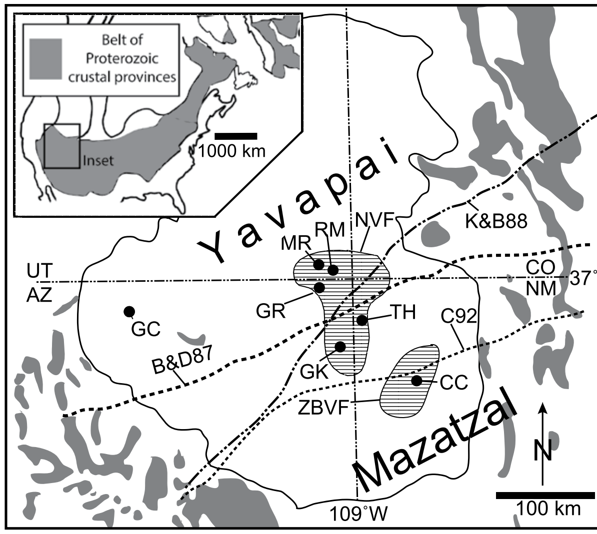

Figure 1. Map of the Colorado Plateau (southwestern United States; modified from Selverstone et al., 1999). Inset map shows the area where Mesoproterozoic plutons occur (modified from Anderson and Morrison, 2005). Shaded gray areas are exposures of Proterozoic rocks; the solid black line encloses the Colorado Plateau. Dashed lines mark different estimates of the Yavapai-Mazatzal boundary: K&B88—Karlstrom and Bowring (1988), B&D87—Bennett and DePaolo (1987), C92—Condie (1992). Striped areas are pertinent volcanic fields: NVF—Navajo Volcanic Field; ZBVF—Zuni-Bandera Volcanic Field. Black dots are xenolith localities mentioned in the text: GC—Grand Canyon Volcanic Field, MR—Moses Rock, GK—Green Knobs, G—Garnet Ridge, RM—Red Mesa, TH—Thumb, CC—Cerro Chato.

INTRODUCTION

Granites are a major component of Precambrian basement in crustal provinces. In the southwestern United States, voluminous granite plutons represent the southwestern extreme of a 1.4 Ga magmatic belt extending >4000 km through Greenland into Fennoscandia (e.g., Anderson and Morrison, 2005); 1.4 Ga plutons intrude the Yavapai (2.0–1.8 Ga) and Mazatzal (1.8–1.6 Ga) provinces (southwestern USA; Fig. 1). These provinces represent the earliest known arc material accreted on the southeastern margin of Laurentia (Bennett and DePaolo, 1987).

Granitic plutons of 1.4 Ga age compose ~35% of exposed Proterozoic bedrock in the southwestern United States (Anderson and Cullers, 1999). The predominance of A-type granites (low-Mg# potassic granites enriched in incompatible elements; see Whalen et al., 1987; Anderson and Bender ,1989) and few surrounding deformational structures have been used to argue that the 1.4 Ga magmatic event was anorogenic (Anderson and Cullers, 1999). However, Nyman and Karlstrom (1997) identified deformational structures within and surrounding the 1.4 Ga granites that suggest shortening in a northwest-southeast direction; this is most easily explained by an orogeny along the northeast-southwest margin of Laurentia. Structures previously associated with the 1.8–1.6 Ga Mazatzal orogeny have been reassessed as belonging to the 1.47–1.3 Ga Picuris orogeny, further implicating orogeny during the 1.4 Ga magmatic event (Jones et al., 2010; Daniel et al., 2013; Mako et al., 2015). The dominant models proposed for the 1.4 Ga magmatic event can be divided into three groups: (1) heating in orogenically thickened crust by radioactive heat buildup or mantle heat conduction (e.g., Goodge and Vervoort, 2006); (2) anorogenic magmatism caused by lithospheric thinning and/or rifting (e.g., Corrigan and Hanmer, 1997, Anderson and Morrison, 2005); and (3) orogenic magmatism accompanied by metamorphism and deformation in a continental arc setting (e.g., Nyman et al., 1994; Nyman and Karlstrom, 1997; Whitmeyer and Karlstrom, 2007).

Proterozoic granite and mantle peridotite are present in the Colorado Plateau (CP) as xenoliths carried by diatremes that intrude the Phanerozoic cover. Previous U-Pb zircon and Sm-Nd mineral geochronology show that granite xenoliths from serpentinized ultramafic microbreccia diatremes of the Navajo volcanic field (NVF) have ages and chemistries matching 1.4 Ga granitoids, suggesting that the CP middle and lower crust record evidence of the 1.4 Ga magmatic event (Silver and McGetchin, 1994; Condie et al., 1999; Crowley et al., 2006). We place new constraints on the tectonic regime of the 1.4 Ga magmatic event by focusing on mantle xenoliths. Here we present new Sm-Nd and Re-Os isotope data from NVF peridotite xenoliths that suggest that the original Yavapai-Mazatzal subcontinental lithospheric mantle (SCLM) has not been removed and was isotopically reset by percolating fluids or melts at 1.4 Ga.

SAMPLES AND METHODS

The NVF covers >30,000 km^2 and contains ~50 Oligocene minettes and serpentinized ultramafic microbreccia diatremes, some of which contain mantle xenoliths (McGetchin and Silver, 1970). These xenoliths are

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commonly hydrated and metasomatized (Smith, 1979, 2010; see Appendix DR1 in the GSA Data Repository[1] for sample descriptions). By utilizing isotopic systems that are difficult to disrupt (Re-Os and, to a lesser extent, Sm-Nd) we are able to see through the geochemical overprint of more recent hydration and metasomatism in order to study Proterozoic events. We selected a suite of peridotites from Green Knobs and Moses Rock diatremes that span the full range of observed clinopyroxene (cpx) major element chemistry in serpentinized ultramafic microbreccia mantle xenoliths (Table DR1). All xenoliths are spinel peridotites, with the exception of five samples that either currently contain garnet or are interpreted to have contained garnet in their pre-hydrated assemblage (Appendix DR1). Whole rocks were analyzed for major and trace elements (Table DR2) and Os isotope compositions (Table DR3). Cpx was analyzed for major elements, trace elements (Table DR1), and Nd isotope compositions (Table DR4). See Appendix DR2 for method details.

RESULTS AND DISCUSSION

Sample Grouping

Peridotitic xenoliths from the NVF range from fertile lherzolites to refractory harzburgites (Al_2O_3 = 4.45–0.41 wt%). Fertile lherzolites typically have concave-down, light rare earth element (LREE) depleted cpx patterns, whereas refractory harzburgites typically have concave-up, LREE-enriched cpx patterns. Samples are divided into three groups defined by the slope of the REE pattern around Nd (Fig. 1; Appendix DR3). Group D (depleted) samples have depleted LREE patterns (normalized to primitive mantle of McDonough and Sun, 1995), defined by $(Ce/Nd)_n < 1$ and $(Nd/Sm)_n < 1$. Group E (enriched) samples have enriched LREE patterns, defined by $(Ce/Nd)_n > 1$ and $(Nd/Sm)_n > 1$. Group T (transitional) samples have spoon-shaped LREE patterns with $(Ce/Nd)_n > 1$ and $(Nd/Sm)_n < 1$.

^{187}Re-^{187}Os and ^{147}Sm-^{143}Nd Age Constraints

Previous work on generation of the 1.4 Ga granites proposed that melts might be generated following lithospheric thinning or delamination (Corrigan and Hanmer, 1997). Because lithospheric thinning or delamination replaces old lithosphere with young lithosphere, this process can be tested using the Re-Os system, which is often used to date melt depletion associated with SCLM stabilization (Lee et al., 2001; Rudnick and Walker, 2009). Mantle melting decreases the Re/Os ratio in residual peridotites. Over time, melt-depleted peridotites will evolve less radiogenic $^{187}Os/^{188}Os$ than fertile peridotites, resulting in correlations between indices of melt depletion and $^{187}Os/^{188}Os$. Because peridotites have much higher Os concentrations than most metasomatic agents, the Os isotope system is typically more difficult to overprint than most other radiogenic systems. However, late metasomatic processes can disturb Re/Os ratios and hence correlations between Re/Os and $^{187}Os/^{188}Os$. Two dating methods are often used to circumvent these problems: the rhenium depletion age (t_{RD}) and aluminachron age ($t_{Al_2O_3}$). The t_{RD} assumes that peridotites evolve with Re/Os = 0, and calculate the time at which the primitive mantle evolution curve matches the measured peridotite composition (Rudnick and Walker, 2009). Alternatively, one can regress correlations between $^{187}Os/^{188}Os$ and whole-rock Al_2O_3 in suites of samples to estimate the initial $^{187}Os/^{188}Os$ for highly refractory peridotites, which likely evolve with Re/Os ≈ 0 (Reisberg and Lorand, 1995; Handler et al., 1997). This inferred $^{187}Os/^{188}Os$ value is then used to infer a mantle depletion age in the same fashion as t_{RD}.

Measured $^{187}Os/^{188}Os$ values of NVF xenoliths are subchondritic, ranging from 0.1140 to 0.1287 (Table DR3). Os isotope ratios correlate with indices of melt depletion. Both $t_{Al_2O_3}$ and t_{RD} ages of the three most refractory samples yield Paleoproterozoic ages (t_{RD} = 2.1–1.7 Ga; Fig. 2; $t_{Al_2O_3}$ = 2.1–1.7 Ga, for Al_2O_3 = 0.0 or 0.7 wt%; cf. Handler et al., 1997), consistent with the age of the overlying Yavapai and Mazatzal crust, and similar to ages reported from other CP xenolith localities (e.g., Cerro Chato, ca. 1.9 Ga; the Thumb, ca. 1.7 Ga; Lee et al., 2001; Byerly and Lassiter, 2012). The presence of xenoliths with 2.1–1.7 Ga t_{RD} ages suggests that the SCLM stabilized at the same time as the overlying Yavapai-Mazatzal crust and survived until the time of diatreme eruption. Group D and E populations appear to form the fertile and refractory ends of a single aluminachron (Fig. 2). It is not clear whether the Al_2O_3-$^{187}Os/^{188}Os$ trend represents melt depletion or refertilization. Regardless, this relationship suggests that the groups D and E xenoliths are genetically related.

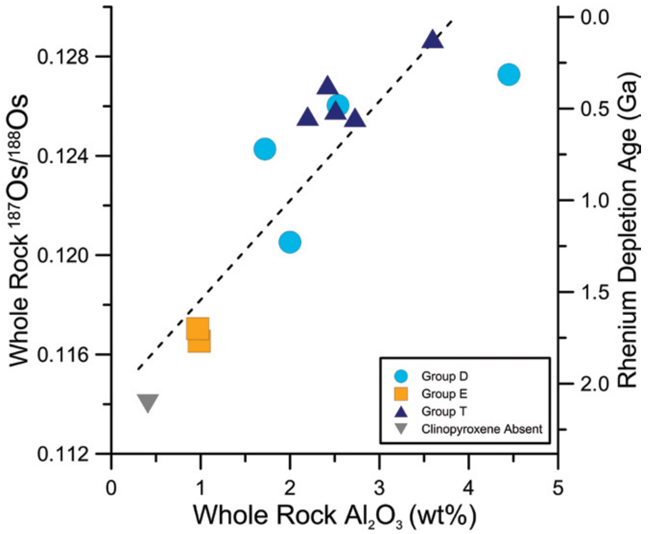

Figure 2. Plot of whole-rock Al_2O_3 versus $^{187}Os/^{188}Os$. The dashed line is the aluminachron (see text). Lithosphere produced in a single melt depletion event should trend along a single aluminachron line. The most Al_2O_3-poor sample does not contain clinopyroxene, and cannot be categorized into a geochemical group.

The Sm-Nd system is more easily disturbed by metasomatism or melt-rock interaction than the Re-Os system. Green Knobs and Moses Rock peridotites have ε_{Nd} values ranging from −2.6 to +405. Group E samples have ε_{Nd} values between −2.6 and 12.4 and have subchondritic Sm/Nd values that do not correlate with Nd isotopes. The combination of suprachondritic Nd isotopes and subchondritic Sm/Nd in most group E samples suggests recent (i.e., Phanerozoic) LREE enrichment. Previous studies have suggested Farallon slab–derived melts or fluids metasomatized portions of the southwestern United States SCLM during flat slab subduction (Alibert, 1994; Lee, 2005).

In contrast, group D samples display a strong correlation between Sm/Nd and $^{143}Nd/^{144}Nd$ (Fig. 3; R^2 = 0.9997, mean square of weighted deviates = 7.1, n = 7) with ε_{Nd} values from 9.6 to 405. In principle, this correlation could be due to recent metasomatism by the same isotopically enriched melt or fluid that affected the group E samples. If this were the case we would expect a mixing trend that intersects with the group E samples. Instead, group E samples are systematically more radiogenic at a given Sm/Nd than the trend defined by group D samples. Given this and the LREE-depleted patterns of the group D samples, this Sm-Nd trend likely represents an isochron.

The slope of the group D isochron regression yields an age of 1439 ± 55 Ma. The DMM (depleted MORB [mid-oceanic ridge basalt] mantle) model age (1500 ± 150 Ma) of the isochron y-intercept is consistent with the isochron slope age. Similarity between the DMM extraction age and the slope age supports interpretation of the group D correlation as an isochron rather than a mixing trend, because there is no a priori requirement for mixing to generate consistent slope and model extraction ages. Melt extraction coupled with melt and/or fluid percolation through the

[1]GSA Data Repository item 2017164, petrologic descriptions, methods, supplementary figures, and Tables DR1–DR4, is available online at http://www.geosociety.org/datarepository/2017/ or on request from editing@geosociety.org.

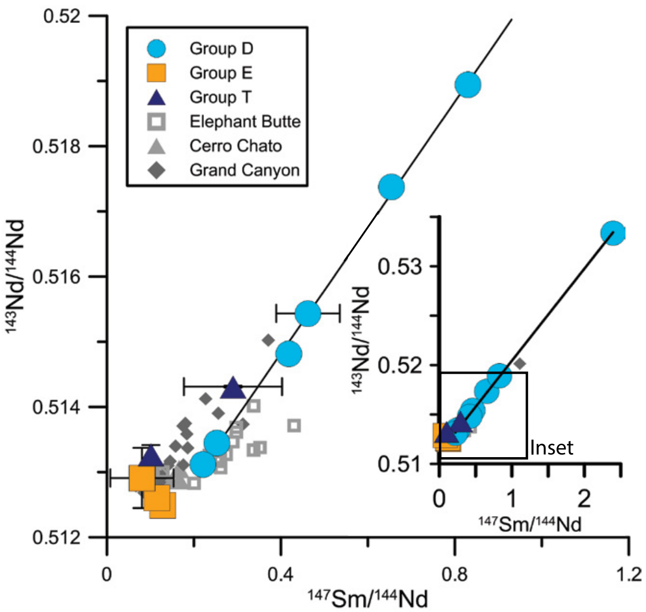

Figure 3. Sm-Nd isochron plot of clinopyroxene (cpx) compositions. The solid regression line is plotted through the group D (depleted) cpx. The group E cpx plot at lower Sm/Nd compositions than the group D cpx, and do not plot on the group D regression. Error bars (2σ) are calculated from instrument error or sample replication error, whichever was larger. Error bars are smaller than the symbols for most samples. Data from Elephant Butte and Cerro Chato are from Byerly and Lassiter (2012); data from the Grand Canyon are from Alibert (1994) and Riter (1999).

lithosphere at 1.4 Ga could generate depleted REE patterns, similar to melting and/or percolation processes that produce depleted REE patterns in abyssal peridotites, while simultaneously rehomogenizing Nd isotopes in the SCLM. The isochron age recorded by the group D xenoliths is consistent with the range of zircon crystallization ages (1475–1339 Ma) reported for A-type granites associated with the 1.4 Ga magmatic event (Anderson and Bender, 1989; Goodge and Vervoort, 2006). Overlap of the mantle isochron and granite crystallization ages supports models for granite formation that involve contemporaneous melt production in the mantle.

Tectonic Setting of the 1.4 Ga Magmatic Event

Os isotopes suggest that the original 2.1–1.7 Ga SCLM was at least partially preserved until the eruption of the serpentinized ultramafic microbreccia diatremes at ca. 25 Ma. However, Sm-Nd systematics suggest that the CP SCLM was isotopically reset by percolating fluids or melts at ca. 1.45 Ga, corresponding to the crystallization age of the A-type granites. These observations place new constraints on tectonic models for the production of granites at 1.4 Ga.

Anatexis due to radioactive heat buildup in orogenically thickened continental crust (e.g., Goodge and Vervoort, 2006) does not predict concurrent melt or fluid generation or migration in the SCLM. Evidence for mantle resetting at 1.4 Ga therefore is inconsistent with the anorogenic anatexis model because anatexis alone would not generate the mantle melts or fluids necessary for mantle isotopic resetting.

Extension and/or lithospheric mantle thinning have also been proposed for generation of the 1.4 Ga granites (e.g., Anderson and Morrison, 2005; Corrigan and Hanmer, 1997). Thinning or removal of the SCLM would increase heat flow from the mantle, elevating the crustal geotherm and potentially triggering anatexis. Generation of mantle melts could account for the observed Sm-Nd isotope resetting at this time. However, 2.1–1.7 Ga Re-Os ages in the most refractory xenoliths indicate that portions of original Yavapai-Mazatzal lithosphere survived the 1.4 Ga event, suggesting that the lithosphere was not completely removed at 1.4 Ga, although partial thinning or removal cannot be ruled out. As discussed here, the analyzed xenoliths yield a single whole-rock Al_2O_3-$^{187}Os/^{188}Os$ correlation consistent with a single period of SCLM formation. Partial replacement of older SCLM at 1.4 Ga would be expected to produce two distinct Al-Os correlations reflecting different ages of melt depletion; however, this is not observed. Furthermore, recent studies present evidence for a period of compressional deformation and metamorphism beginning at 1490–1450 Ma and extending to ca. 1440–1350 Ma (Picuris orogeny; Jones et al., 2010; Daniel et al., 2013; Mako et al., 2015); such results are inconsistent with a rifting model for generating the 1.4 Ga granites.

Tectonic reconstructions of the Columbia supercontinent at 2.1–1.8 Ga position the Yavapai and Mazatzal crustal provinces of Laurentia at the supercontinent margin (Rogers and Santosh, 2002; Whitmeyer and Karlstrom, 2007; Evans and Mitchell, 2011). Several tectonic models propose subduction along the Laurentian margin during the 1.6–1.3 Ga breakup of Columbia (e.g., Rogers and Santosh, 2002; Whitmeyer and Karlstrom, 2007). We propose that the 1.4 Ga Sm-Nd isochron reflects subduction-related melt production and melt-lithosphere interaction. Subduction-derived basaltic melts ponded at the Moho, which heated the lower crust and triggered anatexis (see Anderson and Bender, 1989; Crowley et al., 2006). This subduction model accounts for the >4000-km-long distribution of 1.4 Ga granites along the Laurentian margin, supports proposed compressional deformation, explains Nd isotopic resetting in the SCLM, and is consistent with Re-Os mantle extraction ages that suggest preservation of the original Yavapai-Mazatzal SCLM. Unlike in modern subduction environments, calc-alkaline granites are not abundant in the 1.4 Ga magmatic event. Instead, A-type granite magmatism in the southwestern part of the magmatic belt and anorthosite-mangerite-charnockite-granite (AMCG) magmatism in the northeastern part of the magmatic belt are typical (Anderson and Morrison, 2005). As suggested in Bybee et al. (2014), AMCG suites may result from subduction of dry slabs, possibly due to elevated Proterozoic geotherms or rapid seafloor spreading resulting in subduction of young, hot and dry oceanic lithosphere.

CONCLUSIONS

Several different tectonic models have been proposed for the generation of the 1.4 Ga magmatic belt that extends from the southwestern United States to Fennoscandia. These models make different predictions regarding the role of SCLM in the generation of the 1.4 Ga granites. Refractory mantle xenoliths from the CP record 2.1–1.7 Ga Re-Os mantle extraction model ages, suggesting that the original Yavapai-Mazatzal SCLM remains intact beneath the CP, precluding complete lithosphere removal at 1.4 Ga. However, a subset of weakly metasomatized CP xenoliths record a 1.45 Ga Sm-Nd isochron, which suggests that the SCLM was isotopically reset at this time, most likely in response to mantle melting or melt and/or fluid migration through the SCLM. Granite production by anatexis due to radiogenic heat buildup in orogenically thickened crust would not generate melts or fluids in the SCLM. This model is therefore inconsistent with evidence for concurrent SCLM isotopic resetting. Similarly, anatexis triggered by SCLM removal or by rifting and resultant increased mantle-crust heat flow is inconsistent with evidence for preservation of the original Yavapai-Mazatzal SCLM.

In contrast, generation of mantle melts in a subduction environment could account for the observed 1.4 Ga Sm-Nd isotopic resetting and the preservation of the original SCLM. Mantle-derived melts likely ponded at the crustal Moho, triggering lower crustal anatexis and emplacement of the 1.4 Ga granitic belt. Combined with previous suggestions that the Yavapai-Mazatzal crustal provinces probably represent accreted arcs, and that recent subduction of the Farallon slab resulted in hydration and metasomatism of the SCLM beneath southwestern North America, this model further highlights the important role subduction has played in shaping the chemical and physical evolution of North America over the past 2 b.y.

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