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Archean lithospheric mantle beneath Arkansas: Continental growth by microcontinent accretion

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ABSTRACT

The Cretaceous Prairie Creek lamproites of southern Arkansas intrude Proterozoic crust near the boundary between the 1.5–1.3 Ga Granite-Rhyolite Province and the 1.3–1.0 Ga Grenville orogen. They carry xenocrysts and rare xenoliths derived from the subcontinental lithospheric mantle (SCLM) and the deep crust. U-Pb age dating of groundmass perovskite in the Prairie Creek lamproites gives a poorly constrained Cretaceous age. U-Pb dating and in situ Sr and Nd isotope data show that perovskite xenocrystals in the Twin Knobs #2 lamprophyre are ca. 600 Ma old, and may represent samples of rift-related alkaline magmas derived from a juvenile mantle. A lithologic section constructed from the mantle-derived xenocrysts shows a moderately depleted SCLM that has experienced a high degree of melt-related metasomatism, especially in the depth range 150 to 140 km. In situ Re-Os analysis of sulfide grains in the xenoliths yields model ages ranging up to 3.4 Ga, with major peaks at 1.4–1.5 Ga and 200–300 Ma. Early Paleoproterozoic model ages appear to reflect mixing between residual Archean high-Os sulfides and later low-Os sulfide melts. These data suggest that the SCLM beneath the Prairie Creek area formed in Archean time, and has been progressively refertilized by a series of magmatic events, which appear to correlate in time with events in the overlying crust. The Archean SCLM sampled by the lamproites may represent the mantle root of the Sabine microcontinent, which lies mainly to the south of the lamproite field and is recognizable in seismic tomography as a feature with higher shear-wave velocity (Vs) (100–175 km depth). Seismic tomography also shows several blocks with high Vs beneath the Grenville province to the east, which may represent other microcontinental blocks. These findings suggest that the growth of individual continents is significantly affected by the accretion of older microcontinental blocks, and that the extent of early continental crust therefore may be greater than generally estimated.

INTRODUCTION

Accretion of juvenile crustal terranes is widely thought to be the dominant mechanism for continental growth (e.g., Whitmeyer and Karlstrom, 2007). Continents are generally viewed as amalgams that have grown through multiple supercontinent cycles, and the idea of net crustal growth through time is widely accepted (e.g., Taylor and McLennan, 1985; Chase and Patchett, 1988; McCulloch and Bennett, 1994). However, recent developments in mapping of the subcontinental lithospheric mantle (SCLM; Begg et al., 2009), and Hf-isotope data on large suites of crustal zircons (e.g., Condie et al., 2005; Kemp et al., 2006; Hawkesworth and Kemp, 2006; Hawkesworth et al., 2009; Belousova et al., 2009, 2010), imply that broad regions of Proterozoic and Phanerozoic upper crust may be underlain by cryptic Archean crust and/or by Archean SCLM. If so, popular models for the processes of crustal growth and continental growth require reassessment.

Most diamonds found at Earth’s surface have originated in the SCLM, and have been transported to the surface by rapidly ascending magmas. The stability of diamond in the SCLM requires a relatively thick lithosphere (usually ≥160 km) with a relatively cool geotherm (typically corresponding to surface heat flow of ≤50 mW/m²). As a consequence, diamond-bearing magmatic rocks are generally associated with Archean cratonic blocks (sampled by kimberlites) or their margins (sampled by lamproites and related rocks).

In the Prairie Creek area of SW Arkansas (Fig. 1), a group of weakly diamondiferous Cretaceous lamproites erupted through Paleozoic sediments of the Ouachita orogen, within the broader Mesoproterozoic (1.3–1.5 Ga) Granite-Rhyolite Province that runs SW-NE across the southern and eastern parts of the USA. This belt of crust is commonly regarded as a largely juvenile terrain accreted to the margin of the Laurentian continent (e.g., Whitmeyer and Karlstrom, 2007). The occurrence of diamondiferous magmatic rocks in this terrain therefore raises the question of what sort of SCLM underlies the area.

Griffin et al. (1994) used garnet xenocrysts from two of the lamproites (Prairie Creek and Twin Knobs #1) to characterize the SCLM, and found it resembled that found under some Proterozoic cratons: it appears to be thinner and less depleted than typical Archean cratonic SCLM. However, later studies have shown that many Proterozoic cratons and their SCLM have Archean antecedents, and the SCLM in these examples owes its relatively less depleted nature to repeated metasomatic refertilization through time (Griffin et al., 2009; Begg et al., 2009).

This process involves infiltration of asthenosphere-derived melts and related fluids into older SCLM during tectonic events such as arc magmatism, microplate collision, and rifting. Such findings suggest that post-Archean net continental growth may be less than previously assumed, and emphasize the need to separately evaluate the issues of crustal production (e.g., Clift and Vannucchi, 2004) and continental growth, in order to understand the long-term evolution of continents.

This study represents part of an ongoing program designed to investigate the evolution...
of the lithospheric mantle beneath areas with post-Archaean crust (cf. Begg et al., 2009). We present a reappraisal of the composition and structure of the SCLM beneath the Prairie Creek area, using approaches developed since the work of Griffin et al. (1994). We also have determined the Re-Os systematics of sulfide grains in a suite of mantle-derived xenoliths from one of the lamproites, to constrain the timing of depletion and metasomatism events in the SCLM. U-Pb dating and Sr-Nd isotopic analyses of perovskite in the lamproites help to constrain the age and sources of one magmatic episode in the area. These data, supported by seismic tomography, are used to reevaluate the tectonic history of the mantle beneath the Prairie Creek area, and to discuss its implications for models of continental growth.

GEOLOGICAL SETTING

Regional Geology

The southwestern part of North America can be divided into several orogenic belts based on age and isotopic character (Fig. 1), and the provinces can be further divided into tectonic blocks, defined by regional shear zones and geophysical data. These Proterozoic accretionary belts are thought to record crustal additions to a long-lived convergent margin along the “southern” edge of Laurentia, which extended for thousands of kilometers and may have persisted for ~800 million years. Tectonic style varied along this margin; oceanic and continental arcs, transpressional terranes, and backarc basins all probably existed at different times and places (Karlstrom et al., 2001), culminating with continent-continent collisions during the Grenville orogeny at 1.1–1.0 Ga.

As in modern plate tectonic analogues, the suture zones between once-separate lithospheric terranes probably occur at larger length scales than the preserved lithospheric blocks. Many of the regional shear zones underwent high strain at ca. 1.4 Ga (Williams et al., 1999; Shaw et al., 2001). The result is that there is still uncertainty regarding the number and character of the accretionary terranes that were assembled to make up the lithosphere of this region.

Much of Arkansas, including the Prairie Creek area, is blanketed by folded Paleozoic sequences of the Permian Ouachita orogenic system, thrust over Proterozoic basement rocks of the 1.55–1.35 Ga Granite-Rhyolite Province (Whitmeyer and Karlstrom, 2007). Van Schmus et al. (1996, 2007) delineated a significant crustal boundary that extends from northwestern Mexico through Texas, Oklahoma, and southeastern Michigan into Ontario (Fig. 1). This boundary divides crust with Sm-Nd model ages >1.55 Ga (NW side) from crust with Sm-Nd model ages <1.55 Ga (SE side). It may represent a major suture recording the collision of a ca. 1.55–1.4 Ga juvenile crustal block against the south- and east-facing margin of Laurentia (the eastern edge of the Mazatzal Province). In the mid-continent area, the 1.55–1.3 Ga crust east of the Sm-Nd boundary has been termed the Eastern Granite-Rhyolite province (Lidik et al., 1966; Bickford and Van Schmus, 1985). Aeromagnetic data suggest that voluminous 1.45–1.35 Ga granite plutons, which stitched the older accretionary belts, also perforate the basement of Arkansas (Whitmeyer and Karlstrom, 2007).

The location of the Grenville-Llano front, marking the northern edge of 1.2–1.0 Ga deformation and magmatism, is poorly constrained in most of south-central North America due to younger cover. However, based on constraints in Texas (Bickford et al., 2000; Reese et al., 2000) and data presented herein, it probably lies just north of the Prairie Creek area (Fig. 1). The Llano Uplift in central Texas is the largest outcrop of Mesoproterozoic rocks in this region. It exposes polymetamorphic schists and gneisses, deformed between 1260 and 1075 Ma, and intruded by pegmatites and granites 1125–1075 Ma ago.

Karlstrom et al. (2001, 2007) and Whitmeyer and Karlstrom (2007) have proposed a tectonic model of Proterozoic continental growth through sequential south-stepping accretion of dominantly juvenile arcs. Discrete orogenic peaks at ca. 1.70 Ga, 1.65–1.6 Ga, 1.45–1.35 Ga, and 1.2–1.0 Ga appear to mark the times of amalgamation of crustal provinces. The Yavapai Province is composed of a series of (mostly) 1.80–1.70 Ga juvenile island arcs (some 1.84 Ga crustal components are known) accreted to the southern margin of Laurentia at ca. 1.70 Ga. The Mazatzal Province is made up of a series of 1.65–1.60 Ga juvenile island arcs.
accreted to the southern margin of Laurentia by ca. 1.6 Ga. Growth and accretion of the Granite-Rhyolite Province are thought to have occurred incrementally between ca. 1.55 and 1.35 Ga and involved outboard juvenile crustal additions related to large-volume inboard magmatism that perforated the Yavapai and Mazatzal provinces. The Grenville orogeny has reworked the Granite-Rhyolite Province and added its own increment of juvenile material to the growing continent. The Appalachian orogeny has resulted in further reworking and addition of terranes along the eastern margin of Laurentia during the early Paleozoic.

Two major, post-assembly, failed rifts are located in Arkansas (the SW-trending Reelfoot rift) and neighboring Oklahoma (the SE-trending southern Oklahoma–Wichita aulacogen; Fig. 1; see Dunn, 2009). Most of the sediments in these rifts were deposited in Cambrian time, and syn-rifting igneous rocks (gabbros, basalts, granites, and rhyolites) range in age from >580 Ma to 525 Ma (Lambert et al., 1988; Hogan et al., 1996). Seismic investigations summarized by Mickus and Keller (1992) indicate that a third (most likely failed) rift exists beneath the southern Ouachita Mountains, encompassing the Prairie Creek area. Regional gravity and magnetic data indicate the three rifts are joined, forming a continuous rift structure more than 1000 km long. Crustal xenoliths from the Prairie Creek lamproites indicate a crystalline lower crust composed of granite and/or rhyolite and amphibolite (with K-Ar ages of 1.32–1.47 Ga), rare possibly Cambrian–Ordovician carbonate rocks, probably from the middle crust, and an upper crust composed of Paleozoic Ouachita sandstone and chert, overlain by Late Cretaceous sediments (Dunn, 2009). These rifts most likely were initiated in Neoproterozoic time (780–685 Ma), during the breakup of eastern Rodinia (Li et al., 2008).

The Ouachita orogeny, a western extension of the broader Appalachian convergence, affected Arkansas, Oklahoma, and the Marathon uplift in west Texas in upper Permian time (Thomas, 1989). It is expressed in the Ouachita Mountains, 30–100 km north of the Prairie Creek area, by intense ENE-WSW–trending folds and associated south-dipping thrusts in Paleozoic sedimentary rocks (Nicholas and Waddell, 1989; Mickus and Keller, 1992). Houseknecht (1986) proposed that the Ouachita sediments represent a forearc sedimentary sequence associated with a southward-dipping subduction zone. Using a combination of gravity and seismic data, Mickus and Keller (1992) confirmed the possibility of a former suture beneath the Ouachita Mountains, and interpreted the crust to the south as an accreted microcontinent and arc.

Figure 2. Local geology; inset at bottom shows stratigraphic cross section through the Twin Knobs #1 body (arrow). The coordinates of Prairie Creek 1 and Twin Knobs #2 are –93.6625W, 34.0384N and –93.6750W, 34.0333N, respectively. Vertical lines in the inset show locations of diamond drill holes.

Local Geology

The Prairie Creek lamproite field lies in SW Arkansas; it straddles the geologic and physiographic boundary between the undeformed Cretaceous sedimentary rocks of the Gulf Coastal Plain and the deformed Paleozoic rocks of the Ouachita Mountains. The field contains seven known intrusions of olivine lamproite aligned along a 5-km NE trend (Fig. 2) subparallel to the Reelfoot Rift ~100 km to the east.

Each of the bodies consists largely of pyroclastic lamproite ranging from sandy tuffs to coarse-grained lapilli tuffs, penetrated by hypabyssal dikes. The intrusions are largely vertical, but have shallowly dipping contacts in the upper parts, consistent with the formation of craters and the abundance of pyroclastic rocks. The Prairie Creek lamproite, the largest of the intrusions, has been K-Ar dated at 97–106 Ma (Zartman, 1977; Gogineni et. al., 1978). The Black Lick,
Twin Knobs #2, and Timberlands lamproites were intruded into the Lower Cretaceous Trinity Formation and are overlain unconformably by rocks of the Late Cretaceous Tokio Formation, so that their intrusion age is constrained to between ca. 120 and 85 Ma (Dunn, 2002).

Early mining and evaluation exercises on the Prairie Creek body indicated diamond grades of 15–30 carats/hundred tons (cph), but these grades probably pertained only to crat-facies lamproite and secondarily enriched surface material. Later testing of in situ lamproite suggests grades are closer to 0.5 cph. Waldman et al. (1987) found a grade of <1 cph for the Twin Knobs #1 diatreme. Rare diamonds have also been recovered during bulk sampling of the Twin Knobs #2 and Black Lick lamproites (Dunn, 2002).

**METHODS**

Major-element analyses of xenocrysts and minerals in mantle-derived xenoliths were done using standard electron microprobe techniques. Trace-element data were obtained by proton microprobe analysis, as described by Griffin et al. (1994). In situ U-Pb dating of perovskite was done using a 213 nm laser ablation microprobe (LAM) attached to an Agilent 7400 inductively coupled plasma mass spectrometer (ICPMS); a full description of the method, as applied to the dating of kimberlites, is given by Batumike et al. (2008). Several other studies recently have applied this method to the dating of kimberlites, producing ages that agree with other estimates of intrusion ages (e.g., Yang et al. 2009; Wu et al., 2010). Sr- and Nd-isotope analyses of perovskite were done by LAM-MC-ICPMS using methods described by Batumike et al. (2009), which are similar to those used by Patton et al. (2007). The isotopic data on perovskite are presented in GSA Data Repository Tables DR1 and DR2.

In situ Os-isotope analyses of individual sulfide grains in mantle xenoliths were done using a 260 nm LAM attached to a Nu Plasma multicollector inductively-coupled plasma mass spectrometer (MC-ICPMS); techniques are described in detail by Pearson et al. (2002) and Griffin et al. (2004a). Concentrations of Os and Pt were obtained during the isotopic analysis, by comparison of count rates on samples and a synthetic NiS bead containing 200 ppm of each of the platinum group elements (PGEs). The Re-Os data are reported in Table DR3 (see footnote 1).

**The Mantle Samples**

**Lamproites and Xenoliths**

About 75% of the surface area of the lamproites consists of pyroclastic rocks, including breccias, lapilli tuffs, and sandy tuffs, which collectively have provided many of the xenoliths described below. Hypabyssal lamproite makes up the other 25% of the pipe areas. Subhedral phenocrysts (up to 2 mm) of olivine, variably altered to serpentine, comprise up to 20% of the hypabyssal rocks. Poikilitic phenocrysts (~1 mm) of pale phlogopite account for another 10% by volume. These phenocrysts, and large broken xenocrysts of olivine and ilmenite, sit in a groundmass consisting of abundant phlogopite, serpentine, clinopyroxene (cpx), amphibole, perovskite, and apatite in a finer-grained opaque mesostasis.

Perovskite is especially abundant in the Twin Knobs #2 lamproite, occurring in euhedral to rounded grains 20–300 µm across; some samples contain dense clusters (micronodules) of grains up to 5 x 2 mm in cross section. In two samples of the Prairie Creek lamproite examined for this study (including specimen NMNH 117145-20, donated by the American Museum of Natural History), perovskite is moderately abundant, but few grains are >30 µm in diameter.

Rare crustal- and mantle-derived xenoliths were recovered from the coarse (0.5–3 cm) heavy-mineral concentrate produced during the bulk testing of the Black Lick and Twin Knobs #2 lamproites carried out to determine diamond grades. Approximately 1.5 kg of xenolith fragments were recognized visually and recovered from 260 tons of coarsely crushed lamproite. About 75% of the xenoliths are of crustal origin, and half of these represent known near-surface lithologies. Deeper-crustal xenoliths are mainly amphibolite, with minor granitic rocks. The mantle-derived suite includes dunite (20%), harzburgite (5%), garnet websterite (5%), wehrlite (5%), eclogite (10%), spinel lherzolite (30%), garnet-spinel lherzolite (10%), and garnet lherzolite (15%).

Dunites consist of coarse-grained (>1 cm) olivine, some of which is recrystallized to finer-grained (0.5 mm) polygonal neoblasts. The harzburgite samples consist of olivine (~75%), orthopyroxene (opx; ~20%) and spinel (5%). Garnet websterites are dominated by coarse-grained garnet (70%); pyroxenes (~20% cpx and ~10% opx) occur both as abundant inclusions in garnet and as discrete grains. Eclogites are dominated by cpx (~75%), and may contain up to 5% rutile, both as grains and as needles in garnet. The spinel lherzolites can be divided into groups on the basis of the Cr content of their spinels. Ten low-Cr spinel lherzolites consist of ~45% olivine, ~30% opx, ~15% cpx, and ~10% spinel (red-brown, <30% Cr2O3). Olivine and opx are coarse-grained, whereas cpx tends to be finer grained (<2 mm) and associated with recrystallized spinel. Four mid-Cr spinel lherzolites have similar modes and microstructures; spinel contains 30–45% Cr2O3. Three high-Cr spinel lherzolites are more refractory, with ~60% olivine, ~30% opx, 2% cpx, and ~8% spinel (opaque, ~50% Cr2O3). Four garnet-spinel lherzolites have ~40% olivine, ~25% opx, ~15% cpx, and ~10% each of spinel and garnet. The garnet typically forms rims on corroded spinels, and cpx forms neoblasts replacing opx. The garnet lherzolites typically contain ~45% olivine, ~30% opx, ~10% cpx, and 10%–15% garnet, ranging from purple to pale lilac in color.

The peridotitic xenoliths commonly show variable degrees of recrystallization, especially the development of olivine neoblasts at the expense of coarse-grained olivine, and the growth of cpx neoblasts at the expense of opx. Kelyphitization of garnet is also widespread. These features suggest a thermomechanical perturbation of the mantle rocks shortly before eruption. Attempts to estimate pressure-temperature (P-T) conditions using a range of accepted thermobarometers have produced a wide scatter, suggesting disequilibrium among pyroxenes, olivine, and garnet in most samples.

All of the xenoliths were mounted in epoxy blocks and polished to allow electron-microprobe analysis and to identify sulfide phases for Re-Os analysis. Following the Re-Os analysis of the exposed sulfide grains, or if no sulfides were found, each block was reground (removing 100–200 µm) and repolished at least three times. Where no sulfides were found after three repolishings, the samples were set aside. Sulfides were found in 17 xenoliths (Fig. 3 and Table DR2 [see footnote 1]) as (1) rounded grains enclosed in the primary silicates, (2) rounded to blocky grains in an equilibrated microstructure with primary silicates, and (3) in clearly interstitial positions and secondary veins. In some cases, the original microstructural position is difficult to determine because of extensive serpentinitization of the silicates. Types 1 and 2 are typically mixtures of pentlandite, pyrrhotite, and more Ni-rich sulfides, with patches or rims of minor chalcopyrite; this mineral assemblage reflects the low-T unmixing of high-T monosulfide solid solutions (Alard et al., 2002). Most grains show some degree of alteration to fine-grained sulfide-oxide mixtures around the edges and along cracks (Fig. 3). Type 2 sulfides commonly are associated with Ca-Mg carbonates, in microstructures that suggest the metasomatic introduction of sulfides together with carbonatic...
fluids (Fig. 3). Type 3 sulfides range from pyrite to pyrite-pyrrhotite mixtures, and most do not have measurable Os contents.

**Xenocrysts and the Chemical Tomography Section**

Griffin et al. (1994) used major- and trace-element data on Cr-pyrope garnet xenocrysts, extracted from heavy-mineral concentrates from the Prairie Creek and Twin Knobs #1 lamproites, to study the thermal state and compositional structure of the SCLM beneath the Prairie Creek area. These data can now be reinterpreted using the techniques (“Chemical Tomography”) described in detail by O’Reilly and Griffin (2006), to give a more detailed picture of the SCLM. In this methodology, the temperature at which a garnet grain has equilibrated with olivine is estimated by the Ni-in-gnt thermometer of Ryan et al. (1996). The geochemical information contained in each garnet grain can then be placed in a depth context by projecting the temperature value to a local geotherm, derived as discussed below. Minimum pressures for each grain can also be estimated using the $P_c$ barometer of Ryan et al. (1996).

The xenocrystic garnets show a much wider range of composition than is recorded in the small xenolith suite. Most garnets fall along a typical lherzolitic Ca-Cr trend, extending up to $\approx 15\%$ Cr$_2$O$_3$ (Fig. 4A); there is a small proportion of mildly subcalcic (harzburgitic) garnets. The high-Cr garnets testify to the presence of moderately depleted lithologies at depth. Garnets depleted in Y ($< 10$ ppm) occur over a wide T range (Fig. 4B), in contrast to most SCLM sections worldwide. A plot of Ti in garnet versus $T_{Ni}$ (Fig. 4C) shows a sharp rise in Ti at 900–950 °C, to levels similar to those seen in the garnets of high-T sheared lherzolite xenoliths (e.g., Smith et al., 1993).

In a plot of $T_{Ni}$ versus $P_c$ (Ryan et al., 1996; Fig. 4D), the envelope of highest $P_c$ at any $T_{Ni}$ (assumed to represent Cr-saturated garnets) can be used to constrain the geotherm beneath the area at the time of eruption. The data define a conductive geotherm corresponding to a relatively low surface heat flow ($\approx 37.5$ mW/m$^2$) at low $T$, but at higher $T$, many grains fall at higher $T$ than this model. In cratonic situations such as the Kaapvaal Craton (Griffin et al., 2003) a “kinked” geotherm limb running parallel to the graphite-diamond line (Fig. 4D) has been found to fit P-T estimates on high-T xenoliths. We therefore have “kinked” the Prairie Creek geotherm at 900–950 °C, corresponding to the appearance of garnets with compositions similar to those of typical high-T sheared lherzolites. Perhaps coincidentally, this kinked limb also fits the P-T estimates for several of the strongly depleted high-T garnets. The P-T estimate for the one garnet lherzolite xenolith that gives concordant results for several thermobarometers also falls on this kinked limb. The P-T estimates for the other four xenoliths plot well above the geotherm, but as noted above, these xenoliths clearly are not well equilibrated. The kinked limb of the geotherm lies within the diamond stability field; if the position of the kink is taken as the base of the depleted lithosphere (see below), this lies at $\approx 160$ km depth.

The mean calculated $X_{Mg}$ of the olivine in equilibrium with each garnet (Fig. 4E; Gaul et al., 2000) decreases steadily downward, from a maximum of $0.94$ at 100 km depth to $0.91$ at 160 km; there are many lower values from 160 to 170 km. The Al$_2$O$_3$ content (a useful measure of depletion and fertility) of the peridotite from which each garnet was derived can also be estimated from its Y content (Griffin et al., 1998). Figure 4F shows a relatively depleted upper section (95–115 km) and a strong increase in mean Al$_2$O$_3$ in the middle of the section; many of the rocks in the 120 to 135 km depth range have fertility levels more typical of Phanerozoic mantle sections.
Griffin et al. (2002) used statistical analysis of xenocryst garnet populations, and comparisons with a large xenolith database, to derive algorithms that allow individual garnet xenocrysts to be classified in terms of their original host-rock type and the nature of metasomatic overprints. The Arkansas garnets have been classified into the populations defined by Griffin et al. (2002), and these populations have then been grouped into four types: depleted; depleted/metasomatized (representing the metasomatic refertilization of originally depleted rocks); fertile (probably metasomatic products, but without evidence of earlier depletion); melt-metasomatized (equivalent to high-T sheared lherzolites). When these populations are plotted against depth (Fig. 5), they define a SCLM section in which the upper part (~90–100 km) is a mixture of depleted and fertile lherzolites. The middle part of the section (~100–140 km) is dominated by fertile garnet lherzolites, corresponding to the high Al$_2$O$_3$ contents in this part of the section (Fig. 4F). The deeper parts consist of a range of refertilized lherzolites, many overprinted by melt-related metasomatism. Twenty to thirty percent of the analyzed garnets do not classify into any of the “real” categories of Griffin et al. (2002); in our experience, these grains probably show the effects of several episodes of metasomatism, and thus cannot be simply classified. This SCLM section is similar to several from Proterozoic cratonic areas (Griffin et al., 1998, 2004b). The upper limit of the section is defined by the stability of garnet in moderately depleted rocks; the xenolith suite described above contains abundant spinel peridotites, which probably are derived from shallower levels.

RESULTS

Perovskite: U-Pb Dating and Sr-Nd Isotope Analysis

Analyses of 60 perovskite grains in two samples of the Prairie Creek lamproite show high proportions of initial (“common”) Pb and low U/Pb ratios (Table DR2 [see footnote1]); the data therefore lie along a mixing line between the initial Pb and the radiogenic Pb that has been produced since crystallization of the perovskite. Although the grains define a good regression line on an inverse-concordia plot (Fig. 6A), the
lower intercept (representing the crystallization age) is poorly defined at 112 ± 37 Ma (95% confidence limit). However, this mid-Cretaceous age is consistent with the stratigraphic controls on the intrusion age of the lamproites (Fig. 2). The upper intercept corresponds to a $207\text{Pb}/206\text{Pb} = 0.905$; this is similar to the values predicted for convecting mantle ca. 1 Ga in age, using Model 1 of Stacey and Kramers (1975), but is higher than expected for the convecting mantle in Cretaceous time.

In contrast, the larger and more abundant perovskite grains of the Twin Knobs #2 lamproite have high U/Pb, and thus a higher proportion of radiogenic to common Pb (Table DR1A [see footnote 1]); despite considerable scatter about the regression line (Fig. 6B), analyses of 86 grains give a lower intercept age of 599 ± 15 Ma. This age is clearly not consistent with the stratigraphic controls on the intrusion age of the lamproite, and strongly suggests that the

Figure 5. “Chemical Tomography” section (O’Reilly and Griffin, 2006) showing the relative proportions of depleted and metasomatized rock types versus depth, derived from Cr-pyrope xenocrysts using the techniques described by Griffin et al. (2002). The figure is constructed by calculating the relative proportions of each garnet type at 50 °C intervals, using a sliding window 100 °C wide, to take account of probable uncertainties in the depth estimates. Thin lines within the fields correspond to the subpopulations defined in that work. At each level, the difference between the plotted populations and 100% is made up of garnets that did not classify in any of these populations; this typically reflects complex, multistage metasomatism (Griffin et al., 2002). The relatively high proportion of fertile lherzolites is typical of the subcontinental lithospheric mantle beneath many Proterozoic terranes.

Figure 6. Inverse-concordia ("Tera-Wasserburg") plots of U-Pb data for perovskites from the (A) Prairie Creek and (B) Twin Knobs lamproites, showing mixing lines between initial ("common") Pb and radiogenic Pb; lower intercepts give age estimates. MSWD—mean square of weighted deviates.
abundant, coarse-grained perovskite in the Twin Knobs #2 samples is xenocrystic.

The perovskite grains in the Prairie Creek samples were too small to give useful Sr-Nd isotopic data. Analyses of eight of the larger grains in the samples from Twin Knobs #2 (Table DR1B [see footnote 1]) give weighted mean values of $^{87}\text{Sr}/^{86}\text{Sr} = 0.70335 \pm 0.00012$ (95% confidence), $^{143}\text{Nd}/^{144}\text{Nd} = 0.51244 \pm 0.00002$, and $^{153}\text{Sm}/^{144}\text{Nd} = 0.207 \pm 0.006$. The Sm-Nd data correspond to $T_{ND} = 545$ Ma, or $T_{ND}(150 \text{ Ma}) = 8.7$. These data suggest that the magma from which the Twin Knobs perovskites crystallized was derived from a relatively juvenile source, such as the convecting mantle.

### Sulfides: Re-Os Analysis

Approximately 200 sulfide grains in 25 samples were analyzed; 65 of these (from 17 xenoliths) contained enough Os (4–5 ppm to >1000 ppm; Table DR3 [see footnote 1]) to provide useful data. $^{187}\text{Re}/^{188}\text{Os}$ ranges from 0.001 to >1, but ratios greater than ~0.5 involve large corrections to $^{187}\text{Os}$, and the Os-isotope data must be treated with caution. Platinum contents range from <1 to >200 ppm. The time-resolved signals commonly show spikes reflecting the presence of micronuggets of Pt, which may not be included in the portion of the signal selected for measurement of $^{187}\text{Os}/^{188}\text{Os}$. The Pt data are therefore semiquantitative at best. Many of the low-Os grains that are not reported here contain measurable Re and/or Pt.

These data may be used to calculate two types of model age, based on contrasting assumptions about the behavior of Re. $T_{RD}$ (Rhenium-depletion) model ages are based on the assumption that all measured Re has been added during or after entrainment of the xenolith in the lamproite magma, for instance during weathering or alteration (Fig. 3). The measured $^{187}\text{Os}/^{188}\text{Os}$ therefore is simply projected directly back to a reference line, in this case the hypothetical chondritic uniform reservoir (CHUR). $T_{MA}$ model ages, in contrast, assume that the measured Re contents are intrinsic to the grains, and use the measured Re/Os to project the data back to CHUR. Thus a $T_{RD}$ model age is likely to give a minimum age for the separation of Re and Os during mantle melting processes, whereas a $T_{MA}$ age may give maximum ages (or even future ages, in seriously disturbed systems) for the separation of Re from Os. The parameter $\gamma$Os describes the relationship of the measured $^{187}\text{Os}/^{188}\text{Os}$, to CHUR; grains with $\gamma$Os <1 (i.e., values of $^{187}\text{Os}/^{188}\text{Os}$ <CHUR) can be interpreted as reflecting an ancient melt-extraction event that produced a low-Re/Os sulfide.

Forty-two of the 65 Os-bearing grains have $\gamma$Os <1, and can be used to calculate $T_{RD}$ model ages (Fig. 7A; Table DR3 [see footnote 1]). These ages range from 0 to 3.35 Ga, and their distribution shows major peaks at ca. 270 Ma (mid-to-late Permian), ca. 750 Ma, and 1–1.5 Ga, with a number of single analyses spreading from 1.9 to 2.85 Ga. The oldest $T_{RD}$ is ca. 3.4 Ga.

Many of the grains with $\gamma$Os <1 have low $^{187}\text{Re}/^{188}\text{Os}$, and give potentially meaningful $T_{MA}$ model ages. Some sulfides with $\gamma$Os >1 have high $^{187}\text{Re}/^{188}\text{Os}$, and thus allow calculation of $T_{MA}$ ages between 0 and 4.5 Ga. The distribution of $T_{MA}$ ages (Fig. 7B) is broadly similar to that of the $T_{RD}$ ages, with significant peaks in Neoproterozoic, Mesoproterozoic, and Paleoproterozoic to Neoarchean time.

In general, the older (Archean and Paleoproterozoic) $T_{RD}$ ages are found in high-Os sulfides, many of which are enclosed in the primary silicates. However, clearly enclosed sulfides also appear in most of the other prominent age populations, whereas some of the older model ages are found in intergranular or even interstitial sulfides. In particular, the mid-Permian and Neoproterozoic populations each include several sulfides, either enclosed or intergranular, with 50–200 ppm Os. The highest $^{187}\text{Os}/^{188}\text{Os}$ values occur in interstitial or intergranular sulfides, which typically contain 10–30 ppm Os.

### DISCUSSION

#### Xenocrystic Perovskite: A Record of Rift Magmatism?

The ca. 600 Ma U-Pb ages clearly suggest that the abundant, coarse-grained perovskite in the Twin Knobs #2 lamproite is xenocrystic; this is consistent with the occurrence of micronuggets of granular perovskite. The U-Pb age and the mean $T_{ND}$ model age (545 Ma) overlap those (585–552 Ma; Lambert et al., 1988) recorded for syn-rift igneous rocks in the southern Oklahoma aulacogen, west of the Prairie Creek area (Fig. 1). The eNd of the perovskite at 545–600 Ma is +7.6 to +8.7, and its initial $^{87}\text{Sr}/^{86}\text{Sr}$ is 0.7034 ± 1 (Table DR1B [see footnote 1]); these values are similar to those reported for the Glen Mountains layered complex in the southern Oklahoma aulacogen (eNd = +3.6 to +5.4, 0.70359 ± 2; Lambert et al., 1988). On this basis, we suggest that the Twin Knobs xenocrystic perovskites crystallized 545–600 Ma ago in a crustal magma chamber, which probably contained alkaline to carbonatic rocks; this would imply synrift magmatism beneath the Prairie Creek area. Development of rifting at ca. 600 Ma in an “Ouachita” aulacogen in the Prairie Creek area supports a structural link with the southern Oklahoma aulacogen to the west, and with the Reelfoot rift to the east (Fig. 1). Extensive regional alkali magmatism is associated with this event, extending northwest into New Mexico and Colorado (McMillan and McMleore, 2004). However, we note that this event is not recorded in the sulfide Re-Os data.

#### Sulfide Model Ages and SCLM History

Several of the younger model-age ($T_{RD}$) populations among the sulfides can be correlated with crustal events in the region. The Permanian population corresponds to the Ouachita orogeny, the last event in the region, while the (small) peak at ca. 750 Ma is coincident with the probable initiation of rifting on the Oklahoma and Reelfoot aulacogens. The abundance of late Mesoproterozoic model ages (1.0–1.25 Ga) suggests that the Grenville orogeny has affected the SCLM. This is consistent with the (poorly constrained) position of the Grenville Front just north of the Prairie Creek area (Fig. 1). The 1.3–1.5 Ga population coincides with the main development of the crust in the Granite-Rhyolite province that underlies the area. K-Ar ages averaging 1.42 Ga on four amphibolite xenoliths from Twin Knobs are believed to represent the formation of the lower crust (Dunn, 2009), consistent with possible modification of the 1.4 Ga Moho via underplating beneath much of the southern Mazatzal and Granite-Rhyolite provinces (Keller et al., 2005).

The model ages ≥1.7 Ga are older than any known crust in the area, and clearly imply the existence of an SCLM that predates the generation of the 1.5–1.3 Ga Granite-Rhyolite Province. However, it is not clear which, if any, of these older model ages correspond to real events. The interpretation of sulfide Re-Os model ages in terms of geological events depends on two assumptions (Alard et al., 2002; Griffin et al., 2004a): (1) high-Os sulfides residual after partial melting events will tend to retain their original Os-isotope signatures and record the timing of melt depletion; (2) sulfides introduced in later metasomatic events will carry the Os-isotope signature of the convecting mantle, and hence their model ages will record the timing of the metasomatism. In some cases the coincidence between sulfide model-age populations in mantle-derived xenoliths and known thermal events in the overlying crust provides a validation of these assumptions (Griffin et al., 2003, 2004a, 2004b; Alard et al., 2002).

Five sulfides from two xenoliths give $T_{RD}$ model ages that are Archean (>2.5 Ga). However, in the older sulfides analyzed here ($T_{RD} = 3.35–2.3$ Ga; $n = 10$), there is a distinct negative correlation between $^{187}\text{Os}/^{188}\text{Os}$ and Os content...
(Fig. 7C), which has not been observed in other xenolith suites that we have studied. This pattern suggests mixing or reaction between residual high-Os sulfides with TRD > 2.8 Ga, and younger sulfide melts or S-bearing fluids with lower Os contents and more radiogenic Os. The microstructures of peridotites can evolve with time and changes in stress patterns, leading to both grain-size reduction (shearing) and grain growth (annealing). Formerly interstitial sulfides may become enclosed in silicates as grain boundaries migrate, while originally enclosed sulfides may become interstitial, and hence exposed to infiltrating fluids. If this is the case, many of the early Paleoproterozoic TRD values (Fig. 7A) may be meaningless, and the proportion of Archean grains would be higher (ten grains in five xenoliths) than indicated by the distribution of the analytical data. We therefore feel confident in arguing that the SCLM beneath the Prairie Creek area is originally Archean in age, but we are less confident about its evolution in the early Paleoproterozoic.

Lambert et al. (1995) carried out Re-Os isotopic analyses of the Prairie Creek lamproites and derived model ages of 0.9–1.2 Ma, which they interpreted as the age of stabilization of the SCLM (the proposed source of the lamproites). However, the Os-isotope systematics of the SCLM are strongly controlled by sulfides (Alard et al., 2002; Pearson et al., 2002), and the data from the mantle-derived xenoliths (Fig. 7) show a mixture of sulfide populations with a wide range of model ages. The mean model age of those analyzed here (Table DR2 [see footnote 1]) is 1.4 Ga, and the inclusion of the abundant low-Os sulfides (which generally contain quite radiogenic Os) would lower this estimate. This is broadly consistent with the data from the lamproites themselves; it suggests that the model age derived by Lambert et al. (1995) represents an average value with no geological meaning, rather than an “age of stabilization” for the SCLM.

**Chemical Tomography:**

**Origin of the SCLM**

The Chemical Tomography section for the SCLM beneath the Prairie Creek area (Fig. 5) is typical of many such sections from Proterozoic shields (“Protons”; Griffin et al., 1998, 1999, 2004b). It differs from typical Archean SCLM in lacking the strongly subcalcic garnets derived from highly depleted harzburgites, and in having a higher proportion of garnets from fertile lherzolites. On the other hand, it is much more depleted than the type of SCLM found beneath Phanerzoic mobile belts (“Tectons”); it contains very Cr-rich lherzolitic garnets, and some...
mildly subcalcic garnets with low Y contents (Fig. 4). The garnet data can be used to calculate a mean mantle composition (Griffin et al., 1998) with 2.1\% CaO and 2.4\% Al₂O₃ in the middle of the range of Proton SCLM (Fig. 8).

The apparent secular evolution of the SCLM from highly depleted Archean compositions, through moderately depleted Proton SCLM to fertile Tecton SCLM (Fig. 8) previously has been interpreted as reflecting a progressive change in the processes that produce the SCLM. However, accumulating evidence suggests that many Proterozoic shield areas contain Archean crust at depth (e.g., Condie et al., 2005; Kemp et al., 2006; Hawkesworth and Kemp, 2006; Zhang et al., 2006; Hawkesworth et al., 2009; Belousova et al., 2009; Begg et al., 2009), and that their SCLM was originally Archean as well; this implies that the apparent secular evolution in SCLM composition largely reflects the progressive refertilization of relict Archean SCLM (Griffin et al., 2009; references therein).

The Archean Tref ages reported here suggest that the Prairie Creek area represents another example of Archean SCLM that has been strongly refertilized by Proterozoic to Phanerozoic metasomatic events. The section still shows relatively high XMg values in its upper part, zoic metasomatic events. The section still shows strongly refertilized by Proterozoic to Phanerozoic SCLM that the Prairie Creek area represents an.

Our findings indicate that either the SCLM north of the Sabine block is Archean, or the Sabine Block SCLM itself is Archean. At the least, an Archean SCLM lies beneath this part of the southern USA, beneath crust strongly affected by 1.5–1.3 Ga Granite-Rhyolite Province magmatism. The Twin Knobs lamproite lies within the broader crustal suture zone on the northern edge of the Sabine Block, but at subcrustal depths the position of the Twin Knobs lamproite relative to this suture is unclear, and depends on the dip of the suture. The position of the lamproite on the north flank of a coherent seismic tomography feature that fits the expected shape of the Sabine Block (as defined by Mickus and Keller, 1992; equivalent to the Ouachita Salient of Thomas, 2006), argues that the lamproite probably has sampled Sabine Block SCLM. The following discussion is based on this interpretation.

There is uncertainty concerning the timing of the accretion of the Sabine microcontinent to North America. The discussion above, and the 600 Ma age for perovskite micronodules in the Twin Knobs lamproite, suggest that this block was already part of Laurentia and was invaded by rift-related alkalic magmas at 600 Ma. In this model, a Mesoproterozoic (ca. 1.6 or 1.3–1.0 Ga) collisional boundary may have been reactivated as an aulacogen during the ca. 600 Ma Neoproterozoic breakup of the Rodinia supercontinent (Li et al., 2008), and inverted during the Ouachita orogeny (cf. Dunn, 2009).

Another possibility is that this terrane boundary is a collisional suture formed during the Permian Ouachita orogeny (Mickus and Keller, 1992). Thomas and Astini (1996, 1999), Thomas (2006), and others (e.g., Whitmeyer and Karlstrom, 2007) have proposed that the modern Argentine Precordillera occupied the region south of the Prairie Creek area, extending through Louisiana and eastern Texas. If the collision of the Sabine block occurred during the Ouachita orogeny, then this proposal may be still valid, with the Precordillera removed during earlier breakup of the Rodinia supercontinent. However, our Re-Os data indicate a strong Mesoproterozoic overprint on the SCLM of the Sabine block, as might be expected for a block that was in approximately its current setting as part of the North American margin. Coupled with the presence of 1.5–1.3 Ga lower-crustal xenoliths in the Prairie Creek lamproites (Dunn, 2009), and the minor shortening ascribed to the Ouachita orogeny (Keller et al., 1989), we therefore find it more likely that the Sabine block was accreted to Laurentia at ca. 1.6 Ga, possibly as part of the Mazatzal orogeny (e.g., Whitmeyer and Karlstrom, 2007), prior to or the development of the 1.5–1.3 Ga Granite-Rhyolite Province. The presence of old SCLM beneath southern Arkansas, and most likely extending south through Louisiana, does not preclude a relationship between the Precordillera and southern Laurentia, but argues against the specific connection proposed by Thomas and Astini (1996, 1999). A reexamination of the Precordillera connection therefore may be required.

Regional Extent of Archean SCLM

The benchmarking of seismic velocity data against xenolith suites allows recognition of depleted Archean SCLM in seismic-tomography images (Deen et al., 2006); it provides a complement to direct detection by age dating, and enables extrapolation over continent-scale areas. However, the reliability of such extrapolations depends on the interpretation of complex variations in mantle velocity. In some areas, for example oceanic rifts, low mantle velocities are uncontroversially associated with high temperature and buoyant upper mantle asthenosphere.
By analogy, high T, low viscosity, and low density are sometimes ascribed to low-velocity domains in continents as well, for example the Rio Grande rift (Gao et al., 2004; Sine et al., 2008; Wilson et al., 2005).

However, much of the velocity variation beneath continents can be linked to compositional variation in the SCLM. The geotherm, lithospheric thickness, and lithospheric composition all affect seismic velocities, but these parameters do not vary independently (O’Reilly and Griffin, 2006). The temperature at the lithosphere-asthenosphere boundary typically lies near 1300 °C. Depleted Archean SCLM typically has a high Mg#, which produces higher seismic velocities. It also typically is thick and has low internal heat production; its upper parts, at least, have temperatures (geotherms) well below the world average, and hence higher seismic velocities. Xenolith data show that beneath many Proterozoic cratons or mobile belts, the SCLM is more fertile than Archean SCLM. The SCLM is thinner beneath Archean cratons, and hence generally lies on a higher geotherm; all these factors contribute to lower seismic velocities than those seen beneath the Archean cratons.

These correlated variations in SCLM fertility, lithospheric thickness, and geotherm reinforce the effects of each on seismic velocity, and produce more rapid lateral variations in seismic response than would result from thermal effects alone. From undisturbed cratons to young mobile belts, there is an inverse correlation between the degree of melt-related refertilization (characterized by addition of Fe, Ca, and Al; Fig. 8) and Vs, so that Archean SCLM volumes subjected to tectonic overprinting have lower Vs than better preserved volumes (Deen et al., 2006; Begg et al., 2009). The multiple Proterozoic magmatic events that have affected the southern and eastern parts of North America are therefore likely to have extensively modified any underlying Archean SCLM, resulting in lowered Vs and higher mantle density.

The Prairie Creek lamproite field lies on the northern flank of an equidimensional domain of moderately high velocity surrounded by regions of lower Vs (Fig. 1). These Vs variations suggest a remnant core of depleted SCLM, variably refertilized by the passage of melts, especially along its margins (cf. the Sahara metacraton; Begg et al., 2009). This interpretation is supported by the ancient Re-Os ages of the sulfides in the xenoliths analyzed here. We therefore interpret this higher-velocity domain as the remnant Archean lithospheric root of the Sabine Block. The occurrence of the lamproites on the edge of this higher-velocity zone is similar to the settings of kimberlites and lamproites elsewhere (e.g., Fig. 1; Jaques and Milligan, 2004; Begg et al., 2009; Griffin et al., 2009), and reflects the localization of mantle-derived magmas along older trans-lithospheric structures. Thus the low-mantle Vs to the north of the lamproite field may reflect further refertilization of the SCLM along the old suture that the Ouachita orogen followed through the Prairie Creek area, and it suggests that the suture dips to the north beneath the continent.

Beneath most of the Mesoproterozoic Granite-Rhyolite Province and the tract of lithosphere affected by the Grenville orogeny, the seismic velocity is significantly lower than beneath the Paleoproterozoic Mazatzal and Yavapai provinces and the Superior craton to the north. The position of late Neoproterozoic to Cambrian aulacogens along the margins of, and between, higher velocity domains suggests that these may represent rift zones that have preferentially reactivated former sutures.

This “compositional” explanation for many of the velocity gradients in eastern USA is preferred here because the geochronology shows the great antiquity of the last tectonic events. In contrast, the low velocities in western North America (Fig. 1) coincide with the region affected by Cenozoic convergent margin events and can largely be ascribed to present-day high heat flow, reflected in the presence of Quaternary volcanic centers. Figure 1 also shows the inverse correlation in the eastern USA between buoyant high-velocity SCLM and the thickness of Phanerozoic sedimentary cover. The observation that thicker sediments cover regions that have lower Vs at a depth of 100–175 km is consistent with crust underlain by higher-density (less buoyant) SCLM, resulting in low-lying (post-peneplanation) land that is prone to marine incursions.

If the Sabine Block is accepted as a microcontinental underlain by modified Archean SCLM, this interpretation potentially can be extended to other higher-Vs volumes, lying farther to the east under the Grenville belt and portions of the Appalachian belt (Fig. 1). This emphasizes the potential role of microcontinent accretion in the development of the North American lithosphere, and underscores the need to refine arc accretion models for the assembly of continents (Bickford et al., 2000; Bickford and Hill, 2007; Karlstrom et al., 2007). Microplates of older material are to be expected in accretionary orogens of all ages, and our data suggest that Archean SCLM roots commonly may underlie crust of Proterozoic age. These results emphasize that the bulk of continental crustal growth may have taken place during the Archean, as proposed by Armstrong (1981, 1991).

Thus, additional work is needed to discern the geometry and age of any older blocks via multidisciplinary approaches that combine improved mantle seismic images with direct studies of the ages and isotopic character of crustal blocks and SCLM xenoliths. For the mid-continent region of the USA, the EarthScope program (www.earthscope.org) should provide higher-resolution mantle velocity images in areas where existing data suggest the presence of large velocity contrasts. Because of the lack of recent tectonism (heating), these velocity variations are most likely to represent compositional variations between contrasting Precambrian terranes. Valid interpretations of the lithospheric structure and evolution of central North America (the goal of EarthScope) will require additional petrologic and geochronological studies of xenoliths and drill core data.

CONCLUSIONS

The Cretaceous lamproites of southern Arkansas have sampled a moderately depleted SCLM that has experienced a high degree of melt-related metasomatism, especially in the depth range 150 to 140 km. The TRD model ages derived from in situ Re-Os analysis of sulfide grains in the xenoliths extend back to 3.4 Ga, and most of the early Paleoproterozoic model ages appear to reflect mixing between residual Archean high-Os sulfides and later low-Os sulfide melts. This ancient depleted SCLM was refertilized in several episodes, especially ca. 1.4–1.5 Ga and 200–300 Ma, corresponding to events in the overlying crust. This Archean SCLM is interpreted as the mantle root of the Sabine microcontinent, which lies mainly to the south of the lamproite field, where it is imaged as a moderately high-Vs block. The Sabine block thus represents another example of relatively young (Proterozoic) crust underlain by older SCLM (Zheng et al., 2004, 2006; Begg et al., 2009). It most likely accreted to Laurentia at ca 1.6 Ga. The seismic tomography indicates that other such high-Vs blocks may also occur beneath the Grenville province to the east, implying the presence of other ancient microcontinental blocks. Their existence suggests that the accretion of ancient microcontinental blocks is a major contributor to the growth and restructuring of individual continents, and thus that some crustal-growth models may have underestimated the extent of early continental lithosphere.

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