Cambrian intermediate-mafic magmatism along the Laurentian margin: Evidence for flood basalt volcanism from well cuttings in the Southern Oklahoma Aulacogen (U.S.A.)

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A B S T R A C T

The Southern Oklahoma Aulacogen (SOA) stretches from southern Oklahoma through the Texas panhandle and into Colorado and New Mexico, and contains mafic through silicic magmatism related to the opening of the Iapetus Ocean during the early Cambrian. Cambrian magmatic products are best exposed in the Wichita Mountains (Oklahoma), where they have been extensively studied. However, their ultimate derivation is still somewhat contentious and centers on two very different models: SOA magmatism has been suggested to occur via (1) continental rifting (with or without mantle plume emplacement) or (2) transform-fault related magmatism (e.g., leaky strike-slip faults). Within the SOA, the subsurface in and adjacent to the Arbuckle Mountains in southern Oklahoma contains thick sequences of mafic to intermediate lavas, intrusive bodies, and phreatomagmatic deposits interlayered with thick, extensive rhyolite lavas, thin localized tuffs, and lesser silicic intrusive bodies. These materials were first described in the Arbuckle Mountains region by a 1982 drill test (Hamilton Brothers Turner Falls well) and the best available age constraints from SOA Arbuckle Mountains eruptive products are ~535 to 540 Ma. Well cuttings of the mafic through intermediate units were collected from that well and six others and samples from all but the Turner Falls and Morton wells are the focus of this study. Samples analyzed from the wells are dominantly subalkaline, tholeiitic, and range from basalt to andesite. Their overall bulk major and trace element chemistry, normative mineralogy, and Sr–Nd isotope ratios are similar to magmas erupted/emplaced in flood basalt provinces. When compared with intrusive mafic rocks that crop out in the Wichita Mountains, the SOA well cuttings are geochemically most similar to the Roosevelt Gabbros. New geochemical and isotope data presented in this study, when coupled with recent geophysical work in the SOA and the coeval relationship with rhyolites, indicates that the ~250,000 km³ of early Cambrian mafic to silicic igneous rocks in the SOA were emplaced in a rifting event. This event is suggested to result from the break-up of Pannotia and the formation of the failed arm of a three-armed radial rift system.

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1. Introduction

The Laurentian subcontinent was a component of two, Middle to Late Neoproterozoic supercontinents, Rodinia and Pannotia (or Greater Gondwanaland). Following the break-up of the Rodinia, North Rodinia and South Rodinia collided over a 100 Ma time period with the Congo craton to form the core of Pannotia (Scotese, 2009). The assembly of Pannotia repositioned Laurentia in the southeastern portion of the supercontinent. By the latest Precambrian (560 Ma), Pannotia was rifted into four separate continents and this rifting was accompanied by multiple episodes of intraplate magmatism along the eastern margin of the Laurentian craton (Central Iapetus Magmatic Province; Badger and Sinha, 1988; Badger et al., 2010; Ernst and Bleeker, 2010; McClellan and Gazel, 2014; Puffer, 2002; Youbi et al., 2011). The only evidence of early Cambrian magmatism along the southeastern Laurentian margin is in southern Oklahoma and northern Texas as part of the Southern Oklahoma Aulacogen (SOA; Hanson et al., 2013) (Figs. 1, 2). Early Cambrian rift volcanism is also reported from Morocco (Alvaro et al., 2006; Poulet et al., 2008) but reconstructions of Cambrian paleogeography don’t show a spatial relationship between Morroccan magmatism and the magmatism discussed in this study (Dalziel,
2014; Golonka and Gaweda, 2012; Fig. 1). For example, Thomas and Astini (1996) and Thomas et al. (2012) demonstrate that the Argentine PreCordillera was rifted away from Laurentia adjacent to the SOA (Fig. 1); it is difficult to reconcile this evidence while trying to directly link SOA magmatism to coeval activity in Morocco. The SOA contains extensive igneous rocks that are exposed in the Wichita Mountains and encountered mostly in the subsurface near the Arbuckle Mountains of southern Oklahoma (Fig. 2). These exposures represent the largest magmatic episode related to the opening of the Iapetus Ocean and the break-up of Pannotia, thus warrant study to shed light on how this particular Wilson Cycle evolved.

The SOA extends from northeastern Texas through southern Oklahoma, northwestern Texas, and likely across parts of New Mexico and Colorado (Fig. 2). A minimum of 250,000 km$^3$ of compositionally bimodal silicic-mafic magma was emplaced or erupted in the aulacogen (Hanson et al., 2013). Most workers consider the SOA a failed third arm of a triple junction rift system (Hanson et al., 2013). Bounding fault geometry and seismic profiles indicate a rift up to 150 km wide with emplaced/erupted igneous rocks and sedimentary rift fill as thick as 15 km (Hanson et al., 2013; Keller and Stephenson, 2007). Initially, mafic magmatism was thought to be mostly restricted to the emplacement of voluminous layered gabbros in the Wichita Mountains area prior to felsic magmatism. Minor amounts of basalt were known only in scattered subsurface-drilled sections and from outcrops of sills and dikes cutting felsic rocks. Drilling through overthrust sections of rift-related igneous rocks in the Arbuckle Mountains area of southern Oklahoma and recent geological mapping has now documented a much more extensive suite of erupted mafic and intermediate lava packages and phreatomagmatic deposits intercalated with rhyolite lavas, which are likely analogous to the Navajo Mountain Basalt-Splitle Group described in the Wichita Mountains region subsurface...
The igneous history of the SOA in the Arbuckle Mountains is less well understood, primarily due to the paucity of surface exposures of Cambrian igneous rocks; where present, they are limited to rhyolite lavas and pyroclastic deposits similar to those in the Wichita Mountains. Where present, they are limited to rhyolite lavas and pyroclastic deposits similar to those in the Wichita Mountains (539 ± 5 Ma and 536 ± 5 Ma, Hanson et al., 2013; Thomas et al., 2012) and are the subject of this study. Following the cessation of volcanism, the SOA underwent a period of quiescence, followed by post-emplacement alteration, thus they were not processed further.

The geochemical and isotope characteristics of the well cuttings can be used to decipher whether their origin is consistent with rifting and continental break-up. Also, as with all dominantly mafic lavas, geochemistry will give insight into defining potential mantle sources involved in magmatism, and deciphering these sources is a key to understanding more about magma genesis in the SOA. By providing new geochemical and Sr–Nd radiogenic isotope data, this study provides new insights into the petrologic constraints and tectonic implications of SOA mafic volcanism that affected the southern Laurentian margin in the Cambrian.

2. Methods

Studying well cuttings is useful in situations where no equivalent surficial rock outcrops exist and core sampling did not occur (Arce et al., 2013). While there is obvious uncertainty in working with cuttings, they provide the only accessible information about the thick volcanic package in the SOA. The subject wells were drilled with fresh-water based neutral-ph drilling fluids and samples were collected at 3 m intervals. Screening is used to concentrate the size of cuttings produced by the drill bit versus larger cavings from previously penetrated intervals. Thus, potential contamination by younger material was minimal (see below), the specific sample depth of each set of cuttings is known (Fig. 3 and Appendix A), and drilling fluid contamination was not an issue.

All samples were collected from the Oklahoma Geological Survey sample library at the Oklahoma Petroleum Information Center in Norman, Oklahoma. These wells were chosen for the thickness of the mafic packages based on logging, and the depths from which the samples were picked were chosen based on the amount of sample, size of the cuttings, and the amount of mafic material visible under binocular microscope. We did not sample any felsic material, though felsic rocks and sedimentary strata are interspersed within the sampled stratigraphy (Fig. 3). Where available, sensitivity of the produced fluids and samples were collected by correlation to well logs (Fig. 3; Puckett et al., 2014). In total, 40 new samples of well cuttings were collected from three wells in the Western Arbuckle Mountains region: Pan-Am Whyte Unit #1, Blaik Oil Co. #1 and B-13 Morton. On further inspection, the Morton cuttings were too small to effectively work with and ensure sample homogeneity and lack of post-emplacement alteration, thus they were not processed further. Thus 28 new samples were combined with an existing dataset of 47 cuttings from three wells (Brueseke et al., 2014; Bulen, 2012) to yield...
a suite of 76 total samples from five wells. Average sample depths for each well are listed in Appendix A (Supplementary Data) and illustrated in Fig. 3.

All samples were handpicked at Kansas State University using a binocular microscope to remove any mineral fragments, foreign rocks, and/or obviously altered rock cuttings, with the goal of ensuring that
only petrographically homogeneous rock fragments remain for further crushing. After handpicking, samples containing more than 8 g of cuttings were crushed (~200 mesh-size) in a Spex Industries aluminum oxide shatterbox.

Samples were sent to Frankfurt and Marshall College for XRF analysis of major and trace element compositions and loss on ignition (LOI) following the method outlined in Mertzman (2000, 2015) and online at http://www.fandm.edu/earth-environment/laboratory-facilities/instrument-use-and-instructions. One gram of powder from each sample was placed in clean ceramic crucibles and heated at 900 °C for 60–75 min. After cooling to room temperature, samples were weighed and the change in percent was reported as

<table>
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<tr>
<th>Sample</th>
<th>Well</th>
<th>100 mesh-sieve size</th>
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<th>Instrument used and instructions</th>
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| JH14–12 | Blaik |  | University of Kansas | Thermal ionization mass spectrometry (TIMS)
| JH14–16 | Blaik |  | Miami University | Inductively coupled plasma mass spectrometry (ICP-MS)
| JH14–40 | Whyte |  | Franklin and Marshall College | Vacuum spectrometer equipped with a 4 kW X-ray tube

## Table 1

Representative geochemical and isotopic data for SOA well cuttings.

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Notes: Major element concentrations are reported as weight percent oxides and expressed as raw data; trace element concentrations are reported in ppm. Major element analyses were analyzed by XRF (X-ray fluorescence) at Franklin and Marshall College, Miami University. All trace elements were analyzed by XRF at Franklin and Marshall College with the following exception: samples with rare earth data, where all REE results are ICP-MS (inductively coupled plasma mass spectrometry) data run at Miami University. All isotopic data was obtained by TIMS (thermal ionization mass spectrometry) at the University of Kansas and reported to 535 Ma.
of 1% HNO₃. The samples were allowed to dissolve overnight. Following dissolution, samples were then analyzed using a Varian "Red Top" ICP-MS. The ICP-MS was calibrated and internal standardization utilized a 100 ppb solution of Ge, Re, Bi, and In. For each sample, three runs of 30 readings were completed.

Whole rock Sr and Nd isotope analyses were performed by TIMS at the University of Kansas on a subset of seven samples previously analyzed for bulk rock geochemistry by Bulen (2012) (Table 1). Samples were prepared for analysis by using standard HF-HNO₃ and HCl dissolution techniques. Elemental separation was done using ion exchange columns. Sr was isolated and collected using cation exchange columns with BioRad resin. Nd and Sm were purified using Eichrome LN spec resin columns. Samples were analyzed following the procedures of Krogh (1982), and Patchett and Ruiz (1987), details may be found at https://geo.ksu.edu/tims-details. Analyses for Sr and Nd were completed on a VG Sector 54, with internal and external precisions of ± 20 ppm.

After correcting for fractionation using ⁸⁶Sr/⁸⁸Sr = 0.1194, Sr ratios are referenced to a value of 0.710250 for the ⁸⁷Sr/⁸⁶Sr ratio of NBS987. The measured laboratory value was 0.710247 on NBS987 over a 53 run period of analysis. Nd ratios were corrected using an internal standard tied to a value of 0.511860 for ¹⁴⁳Nd/¹⁴⁴Nd for LaJolla Nd. Fractionation was corrected using a ¹⁴⁳Nd/¹⁴⁴Nd ratio of 0.7219. Initial Sr and Nd isotope ratios are reported age-corrected to 535 Ma (Table 1). Given the wide spread of ages reported from SOA rocks, this age represents a minimum age for SOA magmatism and is consistent with the ~535 to 540 Ma ages reported for local Arbuckle Mountains area rhyolite volcanism (Thomas et al., 2012).

Some samples showed signs of alteration. Puckett (2011) reported that the samples found in the Turner Falls well were partially altered through multiple processes including carbonate replacement of plagioclase, chloritization of matrix minerals, and epidotization of mafic minerals. Although cuttings that showed obvious alteration were removed during the cleaning and preparation phase, it is possible that the results were still affected by alteration. To rule out potential alteration effects on the geochemistry of these samples, an "alteration filter", proposed by Beswick and Soucie (1978), was applied. This "alteration filter" plots molecular proportions of major element ratios (Al₂O₃/K₂O, SiO₂/K₂O, CaO/K₂O, etc.) on a logarithmic XY-plot (Beswick and Soucie, 1978). Unaltered samples will appear clustered in linear array on these plots whereas any significant variation from the linear array is suggestive of post-eruptive alteration. Two samples (JH-14-21, JH-14-22) did not fall along the linear array on multiple plots that used the alteration filter and both of these samples have been removed from consideration in this study (Hobbs, 2015). Bulen (2012) took an identical approach for the cuttings from the other wells we discuss here.

3. Results

This study provides new major and trace element data from 28 samples, which we combine with major and trace element results (and new REE and Sr—Nd isotope data) from studies previously published by Bulen (2012) and Brueseke et al. (2014) to yield a combined dataset of 76 samples. The samples analyzed by Bulen (2012) and discussed in Brueseke et al. (2014) come from three wells within the SOA that are located along strike, northwest of the Turner Falls well and southeast of the Blaik and Whyte wells (Figs. 2, 3). A complete list of samples and geochemical/isotope results are in Appendix A. Representative geochemical analyses and all Sr-Nd isotope analyses are presented in Table 1.

3.1. Petrography

The cuttings produced by the drilling process are generally less than 5 mm in any dimension. Under stereoscopic microscope examination, basalt is not distinguishable from andesitic composition, however samples display differences in crystallinity and in some cases < 1 mm plagioclase is present. Carbonate alteration is discernable by anomalous light gray color; most of the cuttings are dark gray to black. In thin section, plagioclase is the dominant phenocryst, frequently altered to sericite, epidote, prehnite, and carbonate (Puckett et al., 2014). Mafic silicate phenocrysts (olivine and pyroxene as indicated by pseudomorph shapes) have been mostly replaced by green clay. Groundmass minerals include Fe-Ti oxides, plagioclase, olivine, and clinopyroxene (Puckett et al., 2014). Scattered flow-aligned amygdalues up to 1.5 mm long are present, filled by secondary minerals. A wide range of groundmass textures are observed including quench, intergranular (plagioclase microlites with clinopyroxene), and interstitial (altered glass separating plagioclase microlites) textures. These textures are typical of subaerial basalt lavas and vary with position in the lava and contact with ground water (phreatomagmatic eruption) or flow into shallow lakes (Puckett et al., 2014).

3.2. Geochemical classification

On the total alkalis versus silica (TAS) diagram of LeBas et al. (1986), the new samples plot as subalkaline to transitional (trachy-)basalts to (trachy-)andesites, with SiO₂ values ranging from 47.6 to 61.2 wt.% (Fig. 4). The samples lie along a positive linear array with increasing alkali contents as silica content increases. New data partially overlap with existing data from the Newberry, Jarman, and Williams wells (Fig. 4). The entire Arbuckle suite we sampled ranges from basalt to andesite (Fig. 4). The well cuttings also plot as subalkaline to transitional on the Zr/TiO₂ versus Nb/Y diagram of Winchester and Floyd (1977) (Fig. 4). That the samples yield the same results on both classification schemes is significant and indicates that any alteration has had minimal effect on the behavior of incompatible trace elements and their overall bulk chemistry. CIPW normative compositions of our samples plot as either olivine or quartz tholeiites on the expanded basalt tetrahedron of Thompson et al. (1983) (Fig. 5). Most samples scatter near the projection of the experimental 1 atm olivine + plagioclase + clinopyroxene + liquid cotectic toward normative quartz. However, a group of seven samples (JH14–23 to 29) from the Whyte well are closer to the higher-pressure plagioclase + clinopyroxene ± olivine ± magnetite + tholeiitic andesite liquid cotectic, possibly suggesting a different, deeper, differentiation history. These samples are also from a stratigraphically higher location in the Whyte well (Fig. 3) and as illustrated in Figs. 6 and 7, have lower wt.% CaO and ppm Sr than other rocks in this study, at a given wt.% SiO₂.
3.3. Major and trace element geochemical characteristics

The rocks are characterized by SiO$_2$ ranging from 47 to 62 wt.% and MgO values from 2.0 to 7.1 wt.% (Mg# defined as [100 MgO/(MgO + FeO)] in mole %, = 29 to 50) (Fig. 6). As wt.% SiO$_2$ increases, so do wt.% Na$_2$O and K$_2$O and wt.% MgO, CaO, FeO and Fe$_2$O$_3$ decrease. TiO$_2$ concentrations range from 1.7 to 3.9 wt.% and high (TiO$_2$ > 2.5 wt.%) and low wt. % TiO$_2$ groups are present. Samples with high wt.% TiO$_2$ (Newberry, Blaik, and some Jarman samples) also have higher wt.% P$_2$O$_5$ concentrations at a given silica concentration. Furthermore, it is apparent that some samples cluster together on these diagrams (e.g., high wt.% FeO’ [total Fe expressed as FeO] Newberry samples, high wt.% TiO$_2$ Newberry and Blaik, high wt.% MgO Whyte and Williams) this may reflect the occurrence of separate magma batches in the eruptive systems that are recorded in/across multiple wells. Sample suites from individual wells also show coherent patterns; for example differentiation arrays (e.g., increasing wt.% SiO$_2$ and decreasing wt.% MgO, FeO’, TiO$_2$, CaO, Na$_2$O, P$_2$O$_5$, and increasing wt.% K$_2$O) appear to exist among samples in most wells. Lidiak et al. (2014) demonstrated that Cambrian diabase dikes that are found just east of our study area are characterized by high FeO’/MgO and are high-Fe tholeiites. Our samples have overlapping FeO’/MgO ratios and support the assertion of Lidiak et al. (2014) that the dikes likely represent feeders for a synmagmatic LIP (e.g., the cuttings are from the erupted lavas).

Trace element concentrations (in ppm) are plotted against wt.% SiO$_2$ in Fig. 7. Sample concentrations decrease in Sr, Ni, Y, and Sc, and they increase in Zr, La, Nb, and Ba with increasing wt.% SiO$_2$. Overall, samples from individual wells generally overlap with each other. A primitive mantle-normalized multi-element diagram (Fig. 8) shows that the suite of samples has broadly the same overall enrichments and depletions (e.g., LILE enrichment, negative Sr anomaly) though variability is present. For example, Newberry samples are among the most enriched and most depleted compositions. The overall patterns show that the rocks are more enriched than mid-ocean ridge basalts and instead resemble ocean-island basalts (Fig. 8). Fig. 9 illustrates that most samples have similar enrichment in light rare earth elements (LREE) compared to the heavy rare earth elements (HREE), are characterized by negative Eu anomalies consistent with plagioclase fractionation, and have flat HREE patterns. However, CB-PAW-1 (Williams) and CB-PAN-20 (Jarman) have slightly positive or no Eu anomalies; this coupled with their higher (relative to other samples) Sr concentrations, may reflect plagioclase accumulation (CB-PAW-1) or lack of plagioclase fractionation (CB-PAN-20).

Bulen (2012) and Hobbs (2015) observed within-well geochemical changes as a function of sampling depth and suggested this is due to the presence of distinct lava (flow) packages sampled by the drilling. For example, in the Whyte well, there is a gap of ~200 m between JH14–29 and JH14–31 which separates samples into a shallow group (samples JH-1423 through JH-1429) and a deep group (samples JH14–31 through JH14–41) (Fig. 3). The shallow group samples tend to have similar geochemical traits, while the deeper samples show ranges (Fig. 10). The shallow Whyte cluster overlaps with the least evolved compositions observed for the deep cluster: Zr between 175 and 225 ppm, Ni between 60 and 75 ppm, La between 12 and 18 ppm and SiO$_2$ between 50 and 52 wt.% (Fig. 10). In the deep group, wt.% SiO$_2$ decreases with ascending depth, while Ni, FeO’, and MgO increase while incompatible elements (e.g., Zr, La) decrease in concentration (Fig. 10). This kind of variation (e.g., less-evolved toward the surface) may represent the tapping + eruption of an evolving magma body that was (re)-filling with more primitive magma through time and is consistent with the type of recharge and crystallization scenarios observed in mafic layered intrusions and areas of voluminous mafic volcanism (Shervais et al., 2006). As mentioned, similar variations, both at the scale of specific depth ranges in individual SOA wells, and throughout the entire mafic-intermediate stratigraphy encountered by wells, indicates that the wells intersected different lava packages. TiO$_2$ vs. P$_2$O$_5$ differences have been used in other flood basalt provinces to distinguish between individual lavas and packages (Hooper, 2000) and these variations for the cuttings are in Fig. 11. It is apparent that Newberry and Blaik samples overlap in wt.% TiO$_2$ vs. P$_2$O$_5$ space; both wells are adjacent to each other (Fig. 2) and most of the Newberry samples are stratigraphically equivalent to the Blaik samples (Fig. 3). These samples also plot in similar positions in the Harker diagrams depicted in Figs. 6 and 7. Thus, it is likely that both wells intersected the same lava package, which is continuous across a portion of the SOA as expected in a flood basalt province. The chemostratigraphic variations also illustrate that while the wells are located in close proximity
to each other, they encountered the products of numerous eruptive loci
(Brueseke et al., 2014; Bulen, 2012; Hobbs, 2015). In this context,
Brueseke et al. (2014) suggested that SOA volcanism may have
resembled “plains-style” volcanism characterized by eruptions from
fissures and shield volcanoes similar to the Cenozoic basalts in the
northwestern United States (U.S.A.) from the Snake River plain and

Fig. 6. Harker diagrams illustrating representative major element variations of the well cuttings.
eastern Oregon (e.g. Bondre and Hart, 2008; Brueseke et al., 2007; Greeley, 1982; Hughes et al., 1999).

### 3.4. Sr and Nd radiogenic isotopes

Fig. 12 illustrates the age-corrected (to 535 Ma) $^{87}$Sr/$^{86}$Sr and $\varepsilon$Nd values of five Arbuckle samples with both Sr and Nd isotope results. One sample (CB-PAJ-13) has $^{87}$Rb/$^{86}$Sr = 5.26, which yields an unrealistic $^{87}$Sr/$^{86}$Sr ratio = 0.66693; we interpret this to reflect Rb addition and Sr loss, likely due to post-emplacement alteration. Overall, $^{87}$Sr/$^{86}$Sr values range from 0.70319 to 0.70877 and $\varepsilon$Nd range from +1.9 to 4.1. Sample CB-PAN-20 from the Newberry well has the least radiogenic $^{87}$Sr/$^{86}$Sr value (0.70319) and the highest $\varepsilon$Nd (+4.1). The sample suite defines an array that extends to more radiogenic

Fig. 7. Harker diagrams illustrating representative trace element variations of the well cuttings.
4. Discussion

4.1. Geochemical constraints and relationship to other Cambrian mafic rocks of the SOA

The bulk chemistry and isotope characteristics of the cuttings overlap with worldwide continental flood basalts/OIBs (Figs. 8, 9, 12). On the tectonic discrimination diagram of Meschede (1986), the samples plot as intraplate tholeiitic basalts (Fig. 13). They also plot in the "within plate" field of Pearce and Norry (1979), based on their Zr and Y concentrations. Other discrimination diagrams (Mullen, 1983; Pearce and Cann, 1973) classify the samples in a similar way (Bulen, 2012; Hobbs, 2015). These results are consistent with intraplate mafic volcanism and, coupled with the existing geophysical and stratigraphic constraints, LIP formation. εNd for Arbuckle-area Mesoproterozoic granitoids average + 3.6 (Rohs and Van Schmus, 2007) but there are no published ⁸⁷Sr/⁸⁶Sr ratios for these rocks, thus making detailed comparison with our samples impossible. The εNd values of these granitoids overlap with our least evolved samples, but εNd does generally decrease with increasing wt.% SiO₂ (Table 1). Also, the sample with the most radiogenic Sr isotope value (CB-PAJ-10) does not have the lowest εNd, indicating that something other than simple crustal interaction accounts for the isotope values of some of these samples. Furthermore, ⁸⁷Sr/⁸⁶Sr ratios increase with decreasing Ba/Nb and Ba/Th, opposite to the relation expected for ⁸⁷Sr/⁸⁶Sr if the variation were solely due to contamination by upper continental crust. As a result, it is likely that some of the more radiogenic ⁸⁷Sr/⁸⁶Sr ratios may reflect postmagmatic alteration (e.g., fluids, low-T metamorphism) that did not substantially affect the Nd isotope ratios (e.g. Cousens et al., 1993; Halliday et al., 1984). It is our interpretation that sample CB-PAN-20 represents the best view into the dominant mantle source of these cuttings. This sample is a tholeiitic basalt, with relatively high wt.% MgO and low SiO₂ (for this sample suite), has ⁸⁷Sr/⁸⁶Sr = 0.70319, and εNd = 4.1.

Mafic dikes locally cross-cut Precambrian granitoid and gneiss northeast of the study area in the Mill Creek quarry (Lidiak et al., 2014). These dikes have SiO₂ values lower than 52 wt.%, and MgO values between 4.3 and 7.3 wt.%, overall, they are less evolved than the well cuttings. La/Nb values for these samples are between 0.9 and 1.1, staying within the accepted EMI values (Weaver, 1991), and at the higher end of the other Arbuckle dikes (Lidiak et al., 2014). The Mill Creek dikes have age corrected (to 535 ma) ⁸⁷Sr/⁸⁶Sr values of 0.70392 to 0.70436 and εNd = 2 to 5.1 (Fig. 14; Lidiak et al., 2014). Lidiak et al. (2014) suggest that the dikes have experienced minor (if any) crustal interaction, thus their trace element and isotope characteristics reflect their mantle source that is interpreted to reflect primarily both depleted and OIB-type mantle components (Lidiak et al., 2014). We suggest these same components are present in the samples from this study, especially CB-PAN-20 (Jarman), the least radiogenic sample reported.

Farther west in the Wichita Mountains (Fig. 2), the Glen Mountain Layered Complex and the Roosevelt Gabbrs record Cambrian mafic magmatism. Published data for these units are scarce, however some geochemical data from the Roosevelt Gabbrs can be compared to the well cuttings from this study (Gilbert and Hughes, 1986; Shapiro, 1981). Roosevelt Gabbr outcrops are present throughout the Wichita Mountains and give a glimpse into the intrusive component of the magmatism that produced the lavas associated with the proposed flood basalt event in this study (Hanson et al., 2013). The Roosevelt Gabbrs show similar geochemical trends to the well cuttings from the Arbuckle Mountains (Fig. 14), although the Roosevelt Gabbrs tend to be more primitive, with generally higher wt.% MgO and lower wt.% K₂O. Zr/Nb values are > 7 and overlap with some of the cuttings at > 55 wt.% SiO₂; these Zr/Nb values generally resemble EMI OIB (4–12; Weaver, 1991). Some of the other Arbuckle cuts have slightly lower Zr/Nb (< 6–7; Fig. 12). K/P values, which are < 3.5 for basaltic rocks not contaminated by K-rich upper crust (Carlson and Hart, 1987), for the intrusives are generally lower than the well cuttings but do overlap at low K/P and low wt.% SiO₂ (Fig. 14). Sr and Nd isotope ratios from the Glen Mountain Layered Complex provide further insight into the similarities between the Wichita and Arbuckle Mountains within the SOA. The overlap between the Glen Mountains Layered Complex and the least radiogenic well cutting (CB-PAN-20) is evident on Fig. 14. These samples also broadly overlap in Sr and Nd isotope space with regional dikes. As a result, it is likely that the Roosevelt Gabbrs, the Arbuckle well cuttings, and the dikes are part of the same magmatic event with a broadly similar mantle source(s), as proposed by Hanson et al. (2013).
4.2. Implications for a large igneous province

The inferred eruptive styles of the rocks in this study conform to the definition of flood basalt volcanism discussed by Walker (1993), even though it may be challenging to trace individual lavas across the SOA or constrain the erupted volumes of these lavas because of lack of exposure. This interpretation is supported by the geochemical characteristics of the subsurface mafic-intermediate lavas discussed in this study and prior geophysical work. The cuttings exhibit primarily tholeiitic, intraplate affinities, which are typical of continental rift and flood basalt volcanism (Basaltic Volcanism Study Project, 1981; Hoffman et al., 1974). Volcanism occurring due to a leaky transform fault system, as was suggested by Thomas (2011), is characterized by small-volume alkaline (to transitional) magmatic affinities (Skulski et al., 1991, 1992) and there is no evidence that such eruptive products exist in the SOA. Thus, we suggest that the mafic through intermediate composition rocks in this study were derived from a mantle source consistent with LIP formation and flood basalt volcanism during the formation of the SOA. Subsequent magma evolution processes (e.g., variable amounts of fractional crystallization and crustal interaction) can account for the more evolved compositions of some of the rocks. While more geochronology is needed to better constrain the timing of SOA magmatism, especially the eruptive packages we have studied, it is interesting that the existing ages overlap with the End-Ediacaran extinction event and Cambrian boundary at 541 ± 1.0 Ma (Chen et al., 2014; Cohen et al., 2013; Darroch et al., 2015; Schroder and Grotzinger, 2007; Walker et al., 2013). Recent work suggests that this extinction event occurred due to biological processes (Darroch et al., 2015). However, it might be possible that like other mass extinction events on Earth that have been linked to LIP formation/flood basalt volcanism and associated global environmental change (Jones et al., 2016; Rampino, 2010; Saunders, 2005; Schoene et al., 2015; Self et al., 2014; White and Saunders, 2005), the End-Edicaran event could have also been partially stimulated by SOA magmatism. Continued study of the well cuttings, including more comprehensive radiogenic and stable isotope studies, are needed to decipher the mantle and crustal components of SOA mafic magmatism, to better relate the coeval rhyolites to the mafic-intermediate rocks studied here, and to refine tectonomagmatic models for formation of the SOA.

5. Conclusions

1. Cambrian well cuttings from the Southern Oklahoma Aulacogen are dominantly subalkaline, tholeiitic, basalts to andesites; their primitive mantle normalized trace element compositions resemble ocean island basalts and flood basalts. Overall, \( ^{87}\text{Sr}/^{86}\text{Sr} \) values from the cuttings range from 0.70319 to 0.70877 and \( \varepsilon_{\text{Nd}} \) range from +1.9 to 4.1. CB-PAN-20 from the Newberry well has the least radiogenic \( ^{87}\text{Sr}/^{86}\text{Sr} \) value (0.70319) and the highest \( \varepsilon_{\text{Nd}} \) (+4.1).

2. Chemically distinct and stratigraphically controlled samples (e.g., within-well geochemical changes) exist in the subsurface, which are interpreted to represent distinct lava packages. In some cases, these packages appear to record recharge and differentiation events.
3. The new results presented here, coupled with existing geophysical data and geochemical and isotope data from other mafic rocks in the SOA (e.g., Wichita Mountain area intrusives and subsurface basalts, as well as dikes from the Arbuckle region), and studies of SOA rhyolites, clearly document the presence of an additional flood basalt province in North America where Cambrian SOA magmatism is the outcome of rifting and LIP formation along the southern Laurentian margin.

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**Fig. 13.** Tectonic discrimination diagrams after (A) Meschede (1986) and (B) Pearce and Norry (1979); E-MORB: enriched mid-ocean ridge basalt (MORB). Note how the cuttings fall in the same general fields (e.g., intraplate) on both diagrams.

**Fig. 14.** Wt.% K2O, wt.% MgO, Zr/Nb ratios, and K/P ratios vs. wt.% SiO2 for the well cuttings and the Roosevelt Gabbros of the Wichita Mountains (tan field; data from Aquilar, 1988; Gilbert and Hughes, 1986; and Shapiro, 1981). Notice the overlap at low wt.% SiO2 on all diagrams.
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References

Ernst, R.E., Bleeker, W., 2010. Large igneous provinces (LIPs), giant dyke swarms, and mantle plumes: significance for breakup events within Canada and adjacent regions, to 2.5 Ga to present. Canadian Journal of Earth Sciences 47, 695–739.