Major- and trace-element constraints on Cambrian basalt volcanism in the Southern Oklahoma Aulacogen from well cuttings in the Arbuckle Mountains region, Oklahoma (U.S.A.)

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INTRODUCTION

The Cambrian Southern Oklahoma Aulacogen (SOA) is a >500-km-long northwest-southeast-trending rift zone that extends across southern Oklahoma, Texas, New Mexico, and Colorado (Powell and Phelps, 1977; Larson et al, 1985; Keller and Stephenson, 2007; Thomas, 2011; Hanson et al., 2012). Igneous rocks are grouped within the Wichita Province and include large exposures of tholeiitic gabbros and A-type rhyolite lavas and granites that are well exposed in the Wichita Mountains, Oklahoma (Fig. 1). The origin of the magmas that formed these rocks has been attributed to the formation of the SOA during the Cambrian breakup of the supercontinent Pannotia (Scotese, 2009; Hanson et al., 2012). However, Thomas (2011) proposed an alternative origin for the SOA and suggested that it represents an intracratonic "leaky" transform fault zone. Surface evidence for the SOA is limited in the Arbuckle Mountains region and its existence is based primarily on data from wells penetrating the igneous rocks (Ham et al., 1964; Puckett et al., this guidebook), geophysical anomalies, structural evidence of Cambrian extension and subsequent structural inversion in the late Paleozoic, sparse exposures of northwest-southeast striking Cambrian diabase dikes, and Cambrian Carlton Rhyolite exposures in the Arbuckle Mountains (Ham et al., 1964; Ham, 1969; Denison, 1995; Keller and Stephenson, 2007; Puckett, 2011; Hanson et al., 2012; Eschberger et al. paper, this guidebook). Critical to understanding the entire Wichita Igneous Province is better understanding the Cambrian magmatic record that exists in the subsurface of the Arbuckle Mountains area.

During the last ~60 years, wells drilled into the Arbuckle Mountains region for oil and gas exploration encountered thick (>4000 m in the Hamilton Brothers 1A-18 Turner Falls well [NE NW SW sec. 18, T. 1 S., R. 1 E.]) packages of igneous material (mafic and felsic compositions based on visual inspection) and sedimentary strata that are interpreted as rift fill (Ham et al., 1964; Puckett,

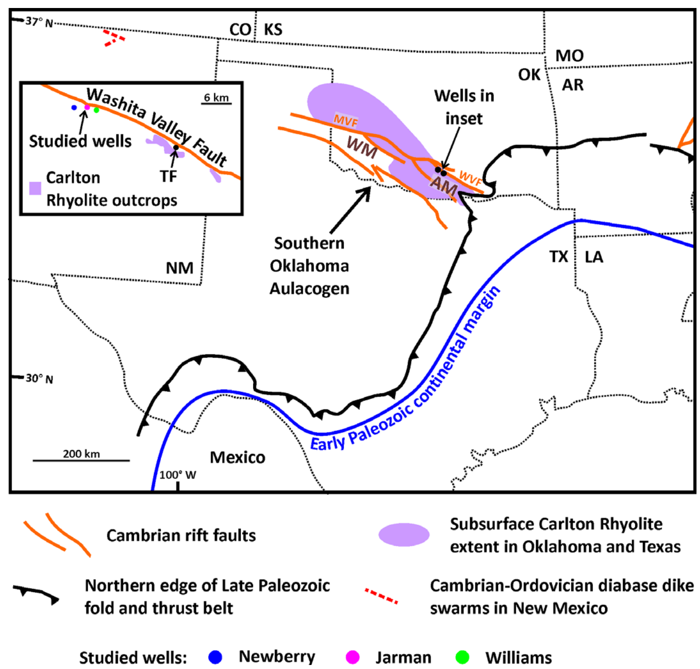

Figure 1. Map of the Southern Oklahoma Aulocogen after Hanson et al. (2012). The approximate location of Cambrian igneous rocks present in the Wichita and Arbuckle Mountains is indicated, as are major regional tectonic features and the locations of the studied wells. Well A: Pan-Am 1 Newberry; Well C: Pan-Am 1-19 Jarman; Well E: Pan-Am D-2 Williams. Well G is the Hamilton Brothers 1A-18 Turner Falls test well (Puckett, 2011) and is currently being studied by Brueseke and students). WVF: Washita Valley Fault; WM: Wichita Mountains; AM: Arbuckle Mountains.

2011; Puckett et al., this guidbeook; Fig. 1). These wells are significant because they provide clear evidence that significant and voluminous igneous activity related to the SOA extended southeast of the Wichita Mountains across other parts of southern Oklahoma, a conclusion which is also supported by geophysical studies (Keller and Stephenson, 2007). Furthermore, as discussed by Puckett (2011) and Puckett et al. (this guidebook), igneous rocks encountered in the Turner Falls test well show textures consistent with effusive origin (e.g., lavas and pyroclastic material, where the lavas range from 9 to 15 m thick based on gamma-ray logs) and, based on a limited geochemical dataset, have basaltic compositions.

In this context, the goal of this contribution is to summarize our recent work and that of Bulen (2012), which is focused on the geochemical characteristics of "mafic" cuttings from three wells in the Arbuckle Mountains region (Fig. 1). The three wells (Pan-Am 1 Newberry [NW NE NW sec. 24, T. 1 N., R. 3 W.], Pan-Am D-2 Williams [NE SE NW sec. 20, T. 1 N., R. 2 W] and Pan-Am 1-19 Jarman [NE NW NE sec. 19, T. 1 N., R. 2 W.]) are close to each other along strike and are northwest of the Turner Falls test well initially studied by Puckett (2011) (Fig. 1; see Puckett et al., this guidebook, for details about the well locations). Because these three wells are close to each other, and to an extent overlap stratigraphically at depth, geochemical analyses allow for potential groups of similar chemical types (e.g., lava-flow groups) to be identified while also providing fundamental constraints on the type of mafic magmas erupted/emplaced in this part of the SOA. Furthermore, the results discussed in this paper represent the most comprehensive geochemical dataset on mafic igneous rocks from the subsurface in the SOA. The only other geochemical results from similar subsurface rocks is a sparse dataset from the Navajoe Mountain Basalt-Spilite Group, which are subsurface basalts and spilites encountered by <350-m-deep wells drilled in the vicinity of the Wichita Mountains (Ham et al., 1964; Shapiro, 1981; Aquilar, 1988).

Cumulatively, the volume of igneous rock throughout the SOA is likely >250,000 km^3, similar to other large igneous provinces on Earth (Hanson et al., 2012). Included in this estimate are gabbros exposed in the Wichita Mountains that yield fairly precise $^{40}Ar/^{39}Ar$ ages that range between ~540 to 530 Ma (e.g., Roosevelt Gabbro) and coeval felsic intrusives and volcanic rocks across the SOA, some of which yield identical U-Pb ages (Hames et al., 1998; Hanson et al., 2012; Thomas et al., 2012). In the Wichita Mountains, these rocks are partly underlain by the 528±29 Ma Glen Mountains Layered Complex (Lambert et al., 1988) and are cut by large numbers of tholeiitic diabase dikes (e.g., late diabase dikes of Ham et al. [1964] and Gilbert [1983]) that appear to be broadly coeval with regional felsic volcanism. Diabase dikes in the Arbuckle Mountains east of our study area primarily strike N60°W and are fairly well exposed in some quarries and occasionally at the surface (Ham et al., 1964; Price et al., 1998; Lidiak et al., 2005; Stops 1, 2, and 3 in this guidebook). Some of these dikes are equivalent to the late diabase dikes in the Wichitas, but others that cut Precambrian rocks of the Eastern Arbuckle Province predate felsic volcanism in the SOA (Hanson et al., 2012). Lidiak et al. (2005) used field/petrographic data, bulk major- and trace-element geochemistry, and Sr-Nd isotope characteristics to conclude that dike emplacement occurred due to Cambrian continental rifting in the SOA and that the dikes were injected as part of a large igneous province. Similar observations focused on the chemistry and some sparse isotope data of the Glen Mountains Layered Complex resulted in similar conclusions (Lambert et al., 1988) (See Hanson et al. (2012) for a comprehensive overview of the SOA.)

Major- and trace-element bulk chemistry

Cuttings were collected from the three wells drilled in the Arbuckle Mountains region (Bulen, 2012) from the sample library housed at the Oklahoma Geological Survey in Norman, Oklahoma. Cuttings were collected from intervals in the wells that were dominated by mafic material and overall, 21 samples were collected from the Williams, 17 from the Jarman, and 23 from the Newberry wells. An additional suite of samples was collected from the Turner Falls well (well G; Fig. 1), but results are pending and not discussed here.

Primary minerals in the cuttings include olivine, clinopyroxene, plagioclase, and Fe-Ti oxides; however, as noted by Puckett (2011), and Puckett et al. (this guidebook), the cuttings are partially altered, including sericitization, carbonate replacement of plagioclase, and chloritization/epidotization of matrix/mafic minerals. Bulk samples were handpicked to remove any non-mafic contaminants (e.g., carbonates, zeolites, altered rock fragments, felsic rock fragments, etc.) and the remaining sample split was crushed and powdered in preparation for major- and trace-element analyses by x-ray fluorescence (XRF) spectroscopy and loss on ignition (LOI) determination at Franklin and Marshall College. Details of the XRF technique including analytical precision and reproducibility can be found in Mertzman (2000), Hanson et al. (2012), and at http://www.fandm.edu/earth-and-environment/x-ray-laboratory.

In addition to major element analyses, concentrations of nineteen trace elements (Rb, Sr, Y, Zr, Nb, Ni, Ga, Cu, Zn, U, Th, Co, Pb, Sc, Cr, V, La, Ce, and Ba) were determined. All reported major element data have been normalized to 100% anhydrous after adjusting the FeO/Fe_2O_3 after LeMaitre (1976). Table 1 gives the bulk-rock chemistry of representative samples.

Because of the alteration, Bulen (2012) applied a statistical "alteration filter" (Beswick and Soucie, 1978) to identify any analyzed samples where the whole-rock geochemistry may reflect low-grade metamorphism/alteration and not primary magmatic concentrations. One sample from the Jarman well (CB-PAJ-17) failed this statistical test and thus it is not considered further here. To mitigate the effect of any potential alteration not identified via the "alteration filter," and also because it is likely that even though a sample has passed this "filter" some disturbance of the igneous geochemistry has occurred given the petrographic evidence for alteration, interpretations made in this study and Bulen (2012) from the well cuttings' bulk chemistry are based primarily on immobile major- and trace-element concentrations.

Figure 2A illustrates that SOA well cuttings are classified primarily as broadly transitional, tholeiitic basalts to andesites, based on their bulk-chemical characteristics. Good agreement exits between the total alkali vs. silica diagram of Le Bas et al. (1986; Fig. 2A) and the Zr/TiO_2 diagram of Winchester and Floyd (1977; Fig. 2B), which suggests that the alkali concentrations of the cuttings have not been significantly altered, even though concentrations of these elements can be affected by low-temperature flu-

TABLE 1: REPRESENTATIVE GEOCHEMICAL ANALYSES OF SOA WELL CUTTINGS IN THE VICINITY OF THE ARBUCKLE MTS. AREA, OKLAHOMA.

Sample	CB-PAN-20	CB-PAN-16	CB-PAW-12	CB-PAW-8	CB-PAJ-10	CB-PAJ-13
SiO2	46.17	60.00	52.91	50.32	57.02	54.94
TiO2	2.90	2.18	2.26	2.15	1.73	1.67
Al2O3	14.52	13.04	12.71	13.95	13.40	13.24
Fe2O3	15.26	10.12	15.82	13.27	12.38	13.16
MnO	0.23	0.18	0.25	0.23	0.16	0.20
MgO	6.38	2.19	3.36	6.37	4.12	4.26
CaO	10.37	5.19	7.45	8.57	5.33	6.66
Na2O	2.52	3.40	3.07	3.63	2.68	3.47
K2O	0.75	2.80	1.63	1.18	2.19	1.92
P2O5	0.38	0.63	0.49	0.30	0.32	0.30
LOI	2.44	1.88	1.29	3.74	6.10	2.31
Total	99.48	99.73	99.95	99.97	99.33	99.82
Ni	75	16	24	60	41	39
Cr	111	17	19	100	42	45
Sc	40	21	37	37	31	33
V	372	137	295	325	260	288
Ba	346	639	408	402	370	419
Rb	13	52.2	28.1	15.1	37.8	28.6
Sr	438	370	332	413	218	292
Zr	119	431	237	140	293	206
Y	24.7	55.8	45.5	30.2	48.2	40.5
Nb	16.1	41.7	25.3	20.4	35.8	22.0
Ga	17.0	20.2	17.5	14.8	17.2	14.5
Cu	87	34	106	135	103	95
Co	56	25	47	49	44	45
Zn	109	126	133	103	110	105
U	1.1	2.8	<0.5	0.7	1.8	1.4
Th	4.4	6.7	4.7	2.5	7.1	2.5
La	9	33	20	11	25	22
Ce	20	67	43	32	65	47
Zr/Nb	7.4	10.3	9.4	6.9	8.2	9.4
La/Nb	0.56	0.79	0.79	0.54	0.70	1.00
K/Nb	398	570	542	499	545	743
Location	Newberry	Newberry	Williams	Williams	Jarman	Jarman
Depth range (m)	2529.84 - 2545.08	1478.28 - 1493.52	1974.52 - 1889.76	1813.56- 1828.80	1676.40 - 1691.64	2011.68 - 2026.92

Note: All major element data is reported as weight percent oxides and expressed as raw data; all other concentrations in ppm. Location corresponds to well; depth is depth range (m) of sample interval.

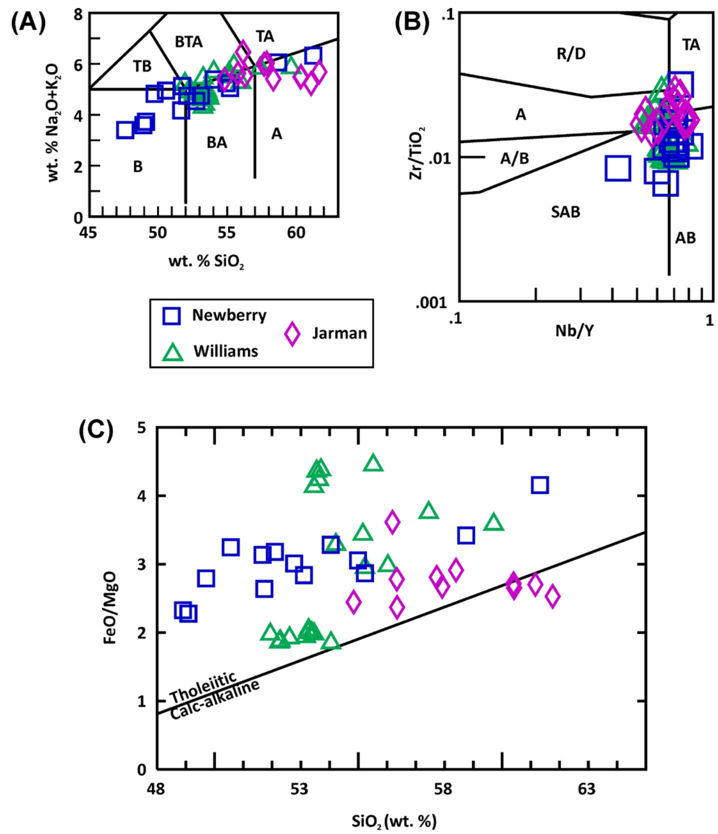

Figure 2. (A) Volcanic rock classification based on total alkalies vs. silica (Le Bas et al., 1986). Notice the range of compositions from basalt through andesite. (B) Discrimination diagram of Winchester and Floyd (1977). Notice the agreement with Figure 2A classifications for the well cuttings. R/D: rhyodacite/dacite; TA: trachyandesite; A: andesite; A/B: andesite/basalt; SAB: subalkaline basalt; AB: alkaline basalt; TB: trachybasalt; BTA: basaltic trachyandesite; B: basalt; BA: basaltic andesite. (C) Tholeiitic vs. calc-alkaline discrimination diagram of Miyashiro (1974) illustrating the tholeiitic nature of the well cuttings.

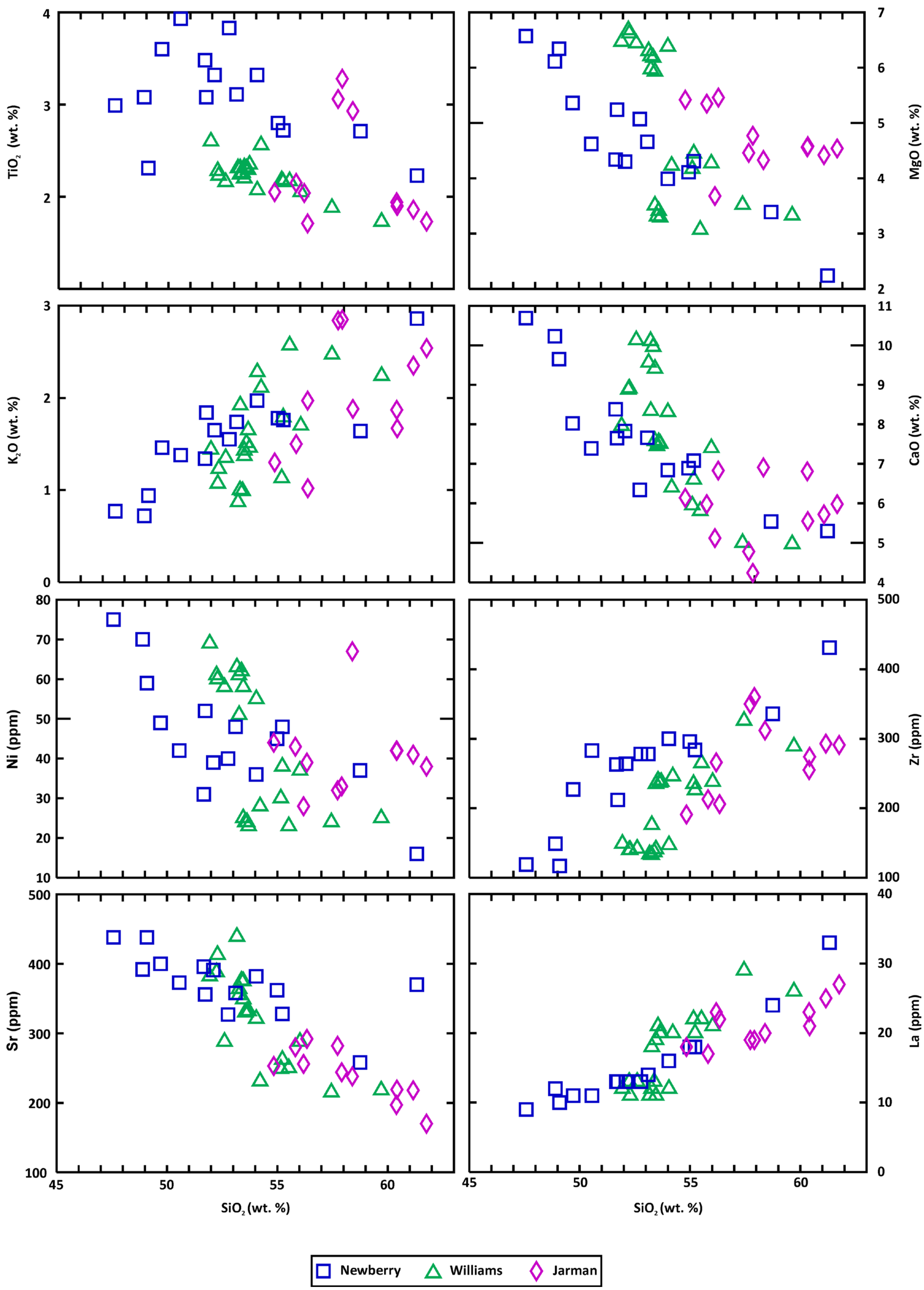

Figure 3. Harker diagrams illustrating representative major- and trace-element variations of the well cuttings.

ids. Figure 3 illustrates select Harker diagrams for the well cuttings. The arrays exhibited by most samples on these diagrams and general relationships with silica (e.g., decrease in MgO, CaO, TiO_2, Ni, Sr and increase in K_2O, Zr, La with increasing SiO2) suggest that more evolved magma compositions (e.g., high SiO_2, low MgO andesites) are related to less evolved magmas through fractional crystallization. It is also apparent that samples from individual wells overlap in some of the Harker diagrms (e.g., Sr), but in other cases are characterized by slightly different compositions (e.g., TiO_2 at a given SiO_2). This type of relationship is consistent with the observation by Bulen (2012) that separate lava flow "groups" (petrogenetically related lavas sourced from the same magmatic system; Hughes et al., 2002) occur at similar depth intervals in each of the three wells. Furthermore, these slight chemical differences among samples from different wells also suggest that even though the wells are close to each other, the volcanic stratigraphy each encountered records the presence of multiple, in some cases overlapping, eruptive systems (Bulen, 2012). For the mafic rocks of this study, two analogies are the ~17 to 14 Ma flood-basalt volcanism in Oregon (e.g., Steens Basalt [Brueseke et al., 2007]) and the <10 Ma basaltic volcanism of the Snake River Plain, Idaho. Both provinces are characterized by basalt eruptions from overlapping shield volcanoes and fissures via "plains-style" volcanism (Greeley, 1982; Hughes et al., 1999, 2002; Brueseke et al., 2007; Bondre and Hart, 2008; Bulen, 2012).

Other geochemical characteristics of the cuttings shed light on petrogenetic processes that affected the magmas, help constrain their mantle source(s), and provide critical tectonic constraints on the SOA. Figure 4 illustrates select trace-element concentrations of the samples normalized to primitive mantle. All samples show the same general enrichments and depletions and the overall patterns (e.g., incompatible-element enrichments of 10 to 100x primitive mantle) are more similar to continental flood basalts and ocean-island basalts than mid-ocean ridge basalts, which generally have incompatible-element enrichments of <10x primitive mantle. Figure 5 illustrates the Zr/Nb and K/P values of the samples vs. wt.% SiO_2. Incompatible-element ratios such as these in mafic magmas can be used to infer the type of mantle involved in magma production. The Zr/Nb values of the samples range from 6.8 to 11.1 (avg. = 8.7) and are similar to enriched mantle 1 (EMI) ocean-island basalt (OIB) type mantle. Other incompatible trace-element ratios (e.g., K/Nb, Ba/Nb, La/Nb) show similar results (Bulen, 2012). K/P ratios for the samples increase with increasing SiO2; this relationship is consistent with contamination by K-rich upper

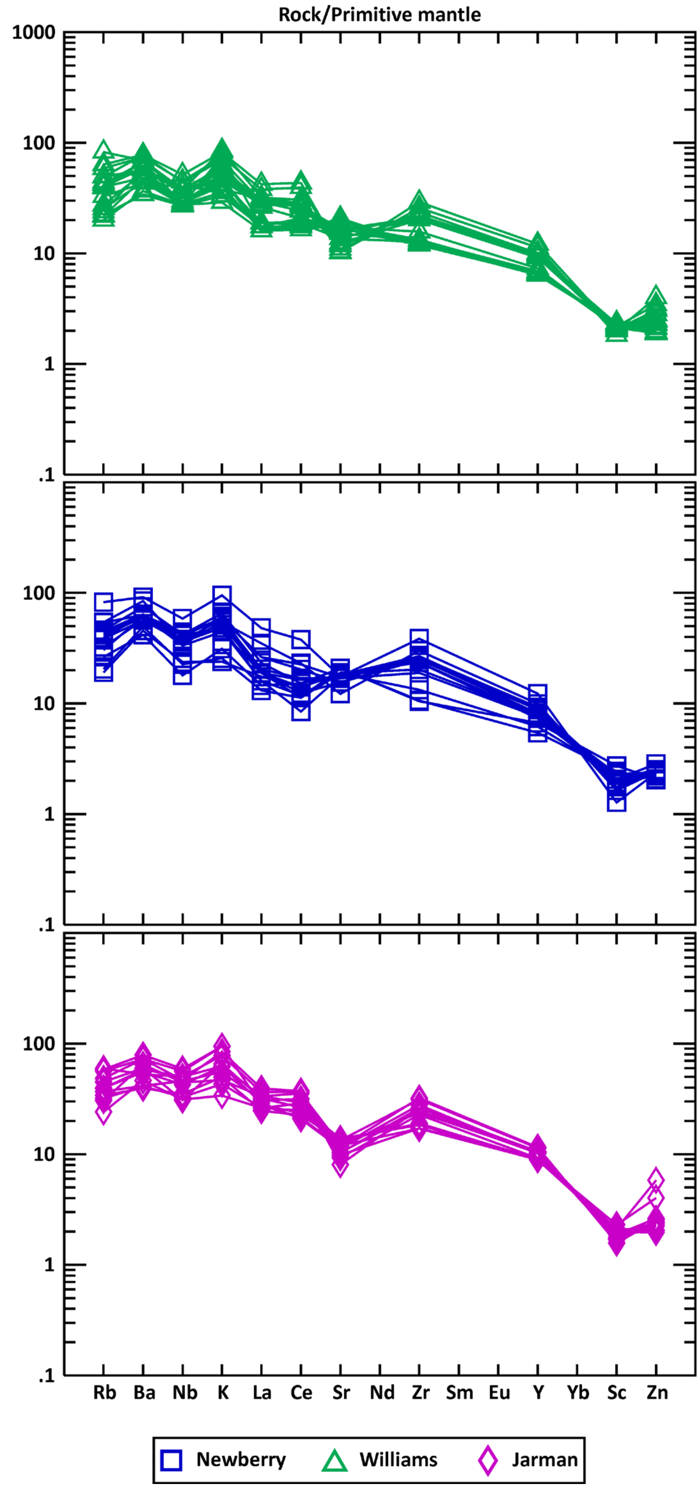

Figure 4. Primitive mantle normalized trace element variations of the well cuttings modified after Sun and McDonough (1989).

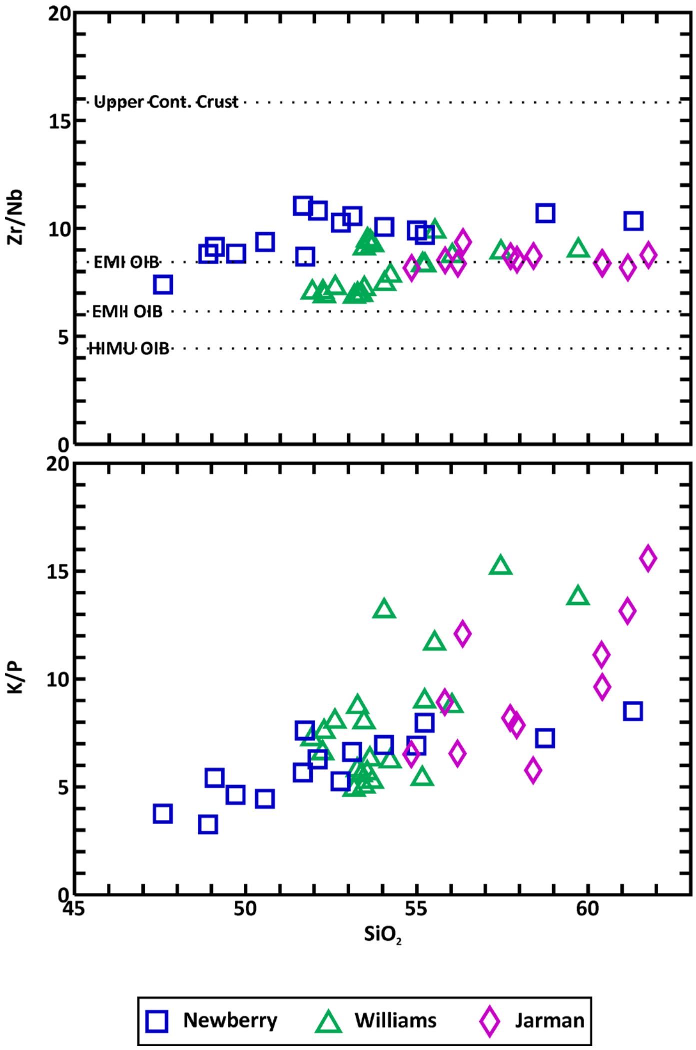

Figure 5. Plots of Zr/Nb and K/P vs. wt.% SiO_2 illustrating important trace-element ratio characteristics of the well cuttings. Upper continental crust, EMI (Enriched mantle 1) OIB (ocean-island basalt), EMII (enriched mantle 2) OIB, and HIMU (high [U+Th]/Pb mantle) OIB values are average values calculated from Weaver (1991); average MORB Zr/Nb = ~30 (not shown on Figure). Note [1] how sample Zr/Nb ratios are fairly constant with increasing wt.% SiO_2 and are most similar to EMI OIB mantle; [2] how all samples together define an array of increasing K/P with increasing wt.% SiO_2.

crust (Carlson and Hart, 1987) and/or apatite fractionation in the most evolved samples. It is significant that the least evolved samples (e.g., Newberry well) have the lowest K/P ratios (Fig. 5) and highest MgO (Fig. 3) and thus represent the most "primitive" igneous rocks sampled by the wells, with little or no upper-crustal input. Ultimately, radiogenic isotope data from the cuttings are needed to fully identify mantle and crustal sources involved in magma production and modification.

Figure 6 illustrates select tectonic discrimination diagrams based on the bulk major and trace-element geochemistry of the well cuttings. Figures 6A and B both show that the cuttings overlap and primarily lie in fields characterized by intraplate, tholeiitic to transitional (Fig. basalts. This characteristic is also clear on Figure 6C (Pearce and Cann, 1973) and on the diagram of Pearce and Norry (1979; Zr/Y vs. Zr), where the cuttings fall within the within plate field. In summary, these discriminant diagrams yield similar observations to the incompatible trace-element and bulk-chemical characteristics of the cuttings; sampled magmas have mafic to intermediate compositions, are dominantly tholeiitic or transitional ? to slightly alkalic, and are characterized by bulk chemistry consistent with a strong petrogenetic link to an enriched mantle source similar to that associated with ocean-island basalts. These are all traits similar to basaltic rocks in other continental large igneous provinces and are consistent with an origin in an intracontinenal rift zone (Bulen, 2012; Hanson et al., 2012).

Geochemical relationship to Cambrian mafic rocks in other parts of the Wichita Province

While the exact stratigraphic and temporal relationship of the subsurface mafic and intermediate lavas in the Arbuckle region to some of the gabbros exposed in the Wichita Mountains (specifically the Glen Mountains Layered Complex) is unclear and needs refinement, our working hypothesis is that the well cuttings studied here represent volcanic rocks that are temporally equivalent at least to the Roosevelt gabbros, thus reflecting the occurrence of voluminous mafic magmatism across the SOA. Figure 7 depicts select geochemical characteristics of the samples from this study, as well as the Roosevelt Gabbro from the Wichita Province and late diabase dikes from the Wichita and Arbuckle Mountains (Aquilar, 1988; Diez de Medina, 1988; DeGroat et al., 1995; Price et al., 1998; Eschberger, 2012: Eschberger and Hanson paper, this guidebook; Eschberger et al. paper, this guidebook) for comparative purposes. The major- and trace-element arrays are consistent with fractional crystallization of a

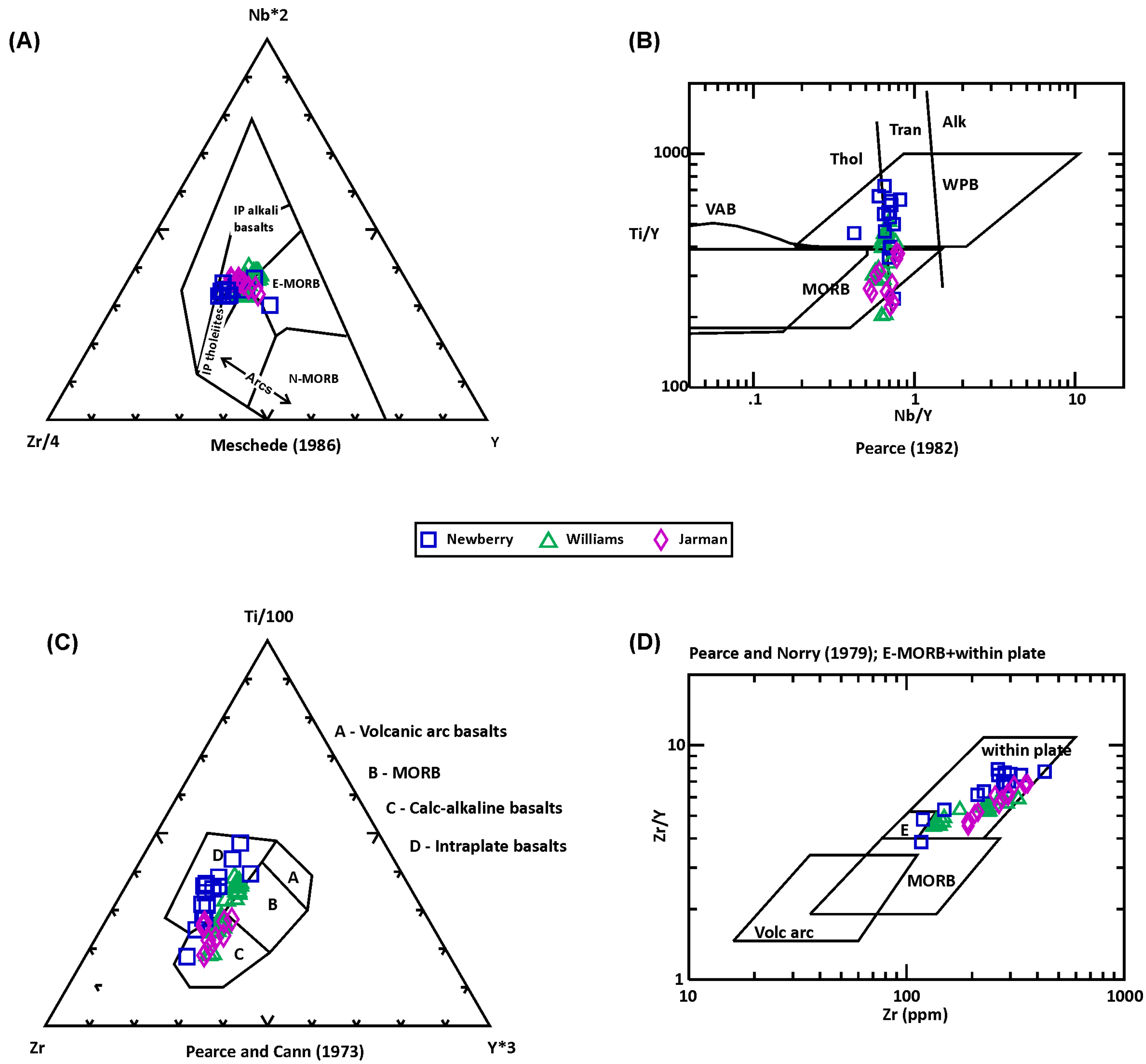

Figure 6. Discriminant diagrams showing well cuttings relative to basalts erupted in different tectonic settings. Diagrams after (A) Meschede (1986); IP tholeites: intraplate tholeiitic basalts. (B) Pearce (1982); VAB: volcanic arc basalt, MORB: mid-ocean ridge basalt, WPB: within plate basalt; Thol: tholeiitic, Tran: transitional, Alk: alkaline; (C) Pearce and Cann (1973); (D) Pearce and Norry (1979); E-MORB; enriched mid-ocean ridge basalt (MORB). (D) Shervais (1982); CFB: continental flood basalt, OIB: ocean-island basalt.

typical mafic mineral assemblage (e.g., olivine, plagioclase feldspar, clinopyroxene, Fe-Ti oxides). It is also interesting to note how the cuttings extend in a different direction from the gabbro field relative to the Wichita/Arbuckle dikes at high wt.% SiO2 and La concentrations, but both converge on the gabbros at low wt.% SiO_2 and low La (Fig. 7A); a similar relationship exists when wt.% SiO_2 is plotted vs. Y (Fig. 7A), Zr, Ce, and Sr (not shown). This divergent relationship likely reflects that magma compositions similar to those of the Roosevelt Gabbro represent an important, perhaps parental "primary" mafic magma type across the SOA. The divergence may reflect that the dikes and the lavas sampled by the subsurface cuttings underwent different evolutionary paths and/or interacted with different crustal types or other

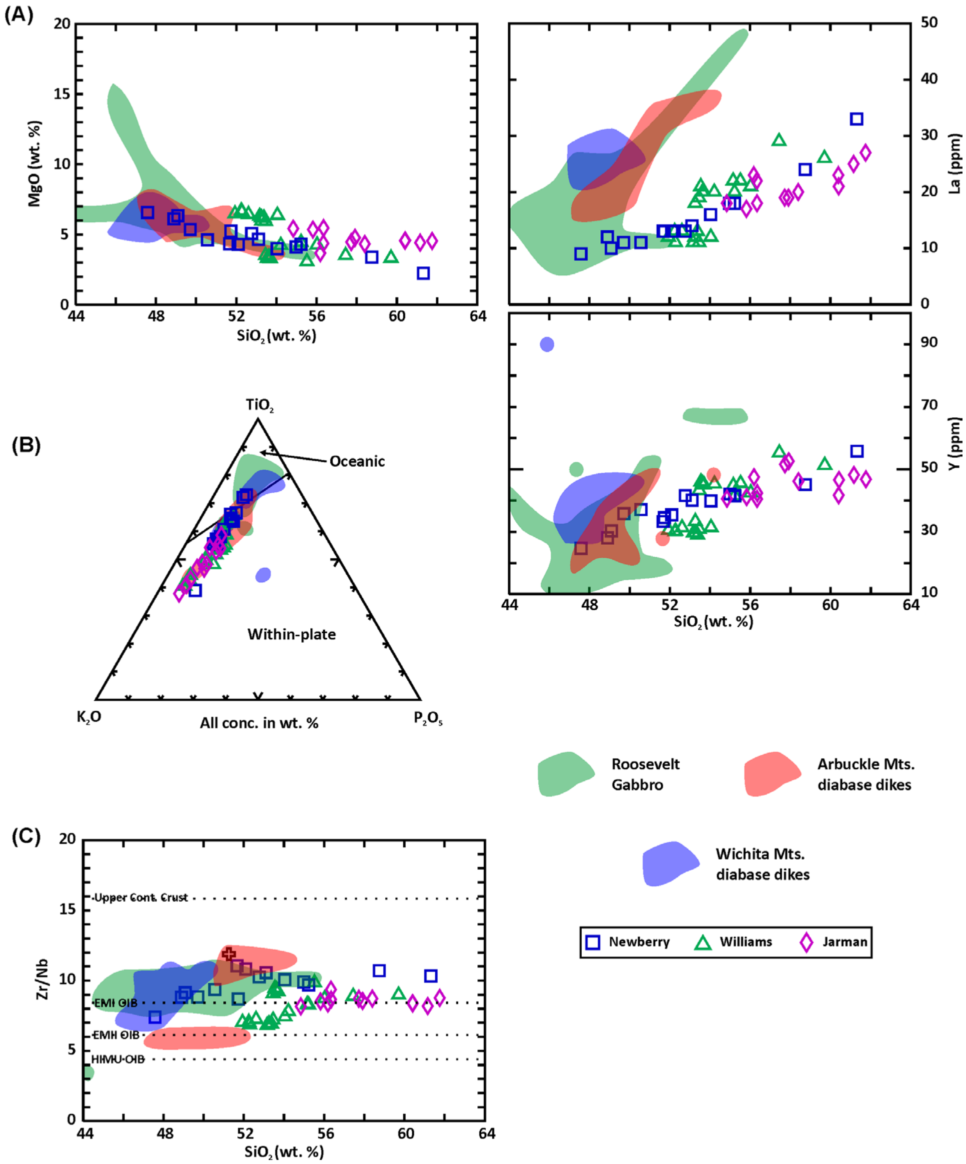

Figure 7. (A) Wt.% MgO, La (ppm), and Y (ppm) vs. wt.% SiO2 comparing samples from this study to other mafic igneous rocks from the SOA. (B) K2O-TiO2-P2O5 discriminant diagram (Pearce et al., 1975) comparing same samples as in A and B. Wichita Mts. gabbro samples from Aquilar (1988) and Diez de Medina (1988). Arbuckle diabase dikes from Price et al. (1998), Eschberger and Hanson paper, this guidebook; Eschberger et al. paper, this guidebook). Wichita diabase dikes from Aquilar (1988), and dikes and Kimbell Gabbro from DeGroat et al. (1995). Oceanic: oceanic basalts, Within-plate: within-plate basalts. (C) Zr/Nb vs. vs. wt.% SiO2 comparison; other Zr/Nb values on this diagram are same as in Figure 5. Upper continental crust, EMI (Enriched mantle 1) OIB (ocean-island basalt), EMII (enriched mantle 2) OIB, and HIMU (high [U+Th]/Pb mantle) OIB values are average values calculated from Weaver (1991).

magmas (e.g., open-system processes such as assimilation-fractional crystallization and magma-mixing). Figure 7B is a K_2O-TiO_2-P_2O_5 ternary discriminant diagram after Pearce et al (1975) that depicts the compositions of the cuttings, gabbros, and dikes and can be used to discriminate between oceanic and continental basalts. Cameron et al. (1986) used this diagram to show that samples of Roosevelt Gabbro plot in the oceanic field overlapping with mafic rocks from the Keweenawan Province (Minnesota/Wisconsin), consistent with a tectonic regime characterized by failed continental rifting. In contrast, the cuttings and Arbuckle dikes extend to higher K_2O values and fall in the within-plate field. Figure 7C illustrates that the generally similar Zr/Nb compositions of the cuttings, diabase dikes, and Roosevelt Gabbro are consistent with an enriched mantle source similar to that found in ocean-island basalts and characteristic of mantle plume-related magmatism. In summary, the well cuttings are geochemically similar to other mafic rocks exposed along the SOA (including the Navajoe Mountain Basalt-Spilite Group; which appear to be more primitive based on their limited dataset; Bulen, 2012) and link mafic magmatism in different parts of the Wichita provinces of the SOA.

Implications for mafic magmatism in the SOA and regional tectonomagmatic models

The major and trace-element results discussed in Bulen (2012) and in this contribution provide critical geochemical information on the insufficiently documented and partly inaccessible mafic components of the large igneous province within the SOA. The recent work of Puckett (2011), Hanson et al. (2012), and Puckett et al. (this guidebook), coupled with our results, indicate that within-plate basalt volcanism occurred throughout the aulacogen in the Cambrian. These results support the hypothesis that the SOA represents the failed arm of a continental rift associated with the opening of the Iapetus Ocean and are inconsistent with the small-volume, dominantly alkalic magmatism that would be expected if the SOA was a "leaky" transform boundary (e.g. Skulski et al, 1991; 1992; Thomas, 2011, and this guidebook). Supporting the rift hypothesis are the numerous rhyolites and felsic intrusives penetrated by the SOA wells and Carlton Rhyolite and Wichita Granite exposures at the surface; all exhibit A-type chemistry and petrogenetic histories consistent with derivation via partial melting and/or fractional crystallization of OIB-like mafic materials (Hogan et al., 1995; Hanson et al., 2012). Furthermore, syn-rift sedimentary strata have been identified in some wells and have been modeled in regional seismic velocity studies (Keller and Stephenson, 2007; Puckett et al., this guidebook).

At the surface, Cambrian igneous rocks in the SOA are dominated by compositionally bimodal, basalt-rhyolite bulk chemistries and a paucity of volcanic rocks exists aside from sporadic Carlton Rhyolite exposures. In the subsurface, our results coupled with recent work by Puckett (2011), Puckett et al. (this guidebook), and Bulen (2012) document a >4.8-km-thick pile of mafic to intermediate lavas, intrusives, and felsic igneous rocks in the vicinity of the Arbuckle Mountains. Furthermore, the results of Bulen (2012) suggest that some of the cuttings likely represent lava-flow groups that can be traced through the subsurface and were penetrated by multiple wells. The magmas represented by the cuttings are compositionally similar and likely related to the Roosevelt Gabbro that crops out in the Wichita Mountains and the lavas of the Navajoe Mountain Basalt-Spilite Group present in the subsurface near the Wichita Mountains. These cuttings also appear to be unrelated to the late diabase dikes, which regionally are the youngest phase of mafic magmatism in the SOA and apparently much less voluminous than the main phase of basalt volcanism represented by the samples studied here.

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