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Integrating zircon trace-element geochemistry and high-precision U-Pb zircon geochronology to resolve the timing and petrogenesis of the late Ediacaran–Cambrian Wichita igneous province, Southern Oklahoma Aulacogen, USA

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ABSTRACT

The bimodal Wichita igneous province (WIP) represents the only exposed Ediacaran to Cambrian anorogenic magmatic assemblage present along the buried southern margin of Laurentia and was emplaced during rifting in the Southern Oklahoma Aulacogen prior to Cambrian opening of the southern Iapetus Ocean. Here, we establish the first high-precision U-Pb zircon geochronological framework for the province. Weighted mean $^{206}Pb/^{238}U$ dates from mafic and felsic rocks in the Wichita Mountains indicate emplacement in a narrow time frame from 532.49 ± 0.12 Ma to 530.23 ± 0.14 Ma. Rhyolite lavas in the Arbuckle Mountains farther east yield weighted mean $^{206}Pb/^{238}U$ dates of 539.20 ± 0.15 Ma and 539.46 ± 0.13 Ma. These dates for the WIP indicate that magmatism in the Southern Oklahoma Aulacogen postdated the ca. 540 Ma rift-drift transition along the Appalachian margin to the east. Whole-rock trace-element and isotopic geochemistry, supplemented by trace elements in zircon, tracks the evolution of magma sources during WIP petrogenesis. These data indicate that initial melting and assimilation of subcontinental mantle lithosphere by an uprising mantle plume were followed by increasing involvement of asthenospheric melts with time. We suggest that upwelling of this plume in the area of the Southern Oklahoma Aulacogen triggered an inboard jump of the spreading center active along the eastern margin of Laurentia, which led to separation of the Precordillera terrane (now located in Argentina) from the Ouachita embayment present in the southern Laurentian margin.

INTRODUCTION

Anorogenic magmatism along craton margins provides important constraints on the timing and causes of rifting during progressive disaggregation of supercontinents to form new ocean basins. The western, northern, and eastern margins of the Laurentia craton contain a protracted record of such magmatism, which ranges in age from ca. 780 to 540 Ma, and which preceded the onset of seafloor spreading during the late Ediacaran to early Cambrian breakup of the Rodinia supercontinent (Thomas, 2014; Yonkee et al., 2014). Indications that the largely buried southern Laurentian margin may have had a similar history occur in west Texas, USA (Fig. 1A). Cryogenian to early Cambrian U-Pb zircon ages in that region have been obtained from volcanic rocks in drill cores in the subsurface Devils River uplift and from volcanic clasts with intraplate geochemical signatures in Ordovician strata in the Marathon fold-and-thrust belt (Hanson et al., 2016; Dickerson et al., 2020). The extent of this igneous activity and its relation to rifting, however, remain unclear.

The only exposed igneous assemblage within this time frame anywhere along the southern Laurentian margin is the bimodal Wichita igneous province (WIP) in southern Oklahoma and adjacent parts of Texas (Fig. 1A). Emplacement of these rocks occurred during extensional or transtensional tectonism within the Southern Oklahoma Aulacogen (SOA), which developed in relation to Cambrian opening of the southern Iapetus Ocean (e.g., Thomas, 2011). Although only a few parts of the WIP crop out at the surface (Fig. 1B), a large amount of additional information is provided by numerous wells drilled into igneous basement in the region (Ham et al., 1964; Puckett et al., 2014). One important aspect that has remained poorly constrained is the duration of the igneous activity and the temporal relations of mafic and felsic magmatism within the WIP. We used high-precision U-Pb zircon geochronology, whole-rock isotope and trace-element geochemistry, and zircon trace-element analyses from exposed igneous units within the WIP to address these questions and constrain source regions for the bimodal magmas.

WICHITA IGNEOUS PROVINCE

Outcrops of the WIP occur in the Wichita and Arbuckle Mountains in southern Oklahoma (Fig. 1), which were uplifted when the SOA underwent late Paleozoic compressional to transpressional deformation (McConnell, 1989; Perry, 1989). The oldest igneous unit exposed in the Wichita Mountains, the Glen Mountains Layered Complex (GMLC; Fig. 1C), extends for ~7000 km² in the subsurface in the western part

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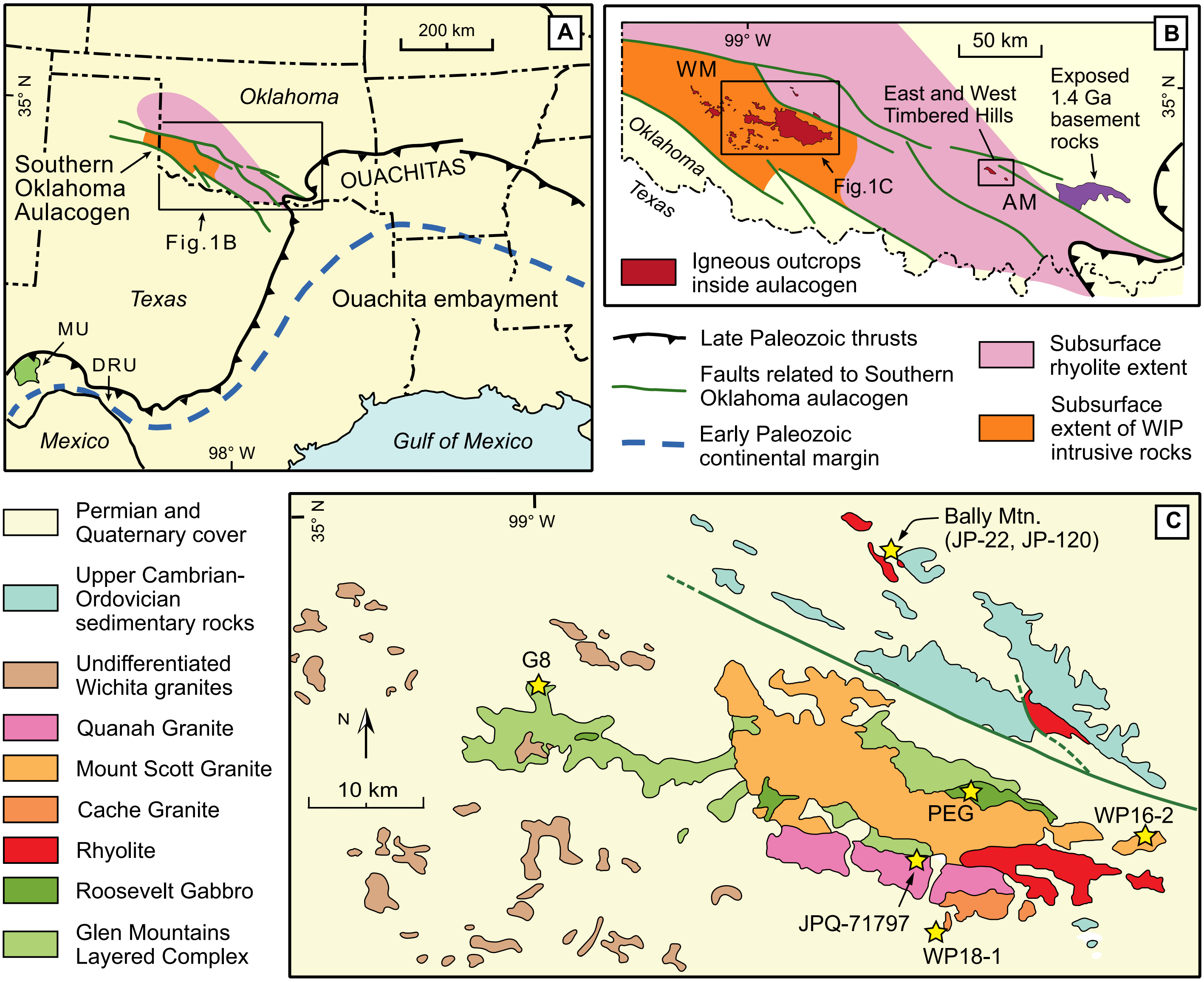

Figure 1. Regional geology of the Wichita igneous province (WIP), southern Oklahoma, USA. (A) Geological setting of province. MU—Marathon uplift; DRU—Devils River uplift. Map is modified from Hanson et al. (2013); subsurface extent of the WIP is modified from Ham et al. (1964); early Paleozoic continental margin is from Keller and Stephenson (2007). (B) Closer view of the WIP in southern Oklahoma showing exposed parts of the province (from Miser, 1954). WM—Wichita Mountains, AM—Arbuckle Mountains. (C) Simplified geology of the main part of the Wichita Mountains, modified from Powell et al. (1980). Yellow stars indicate locations of geochronological samples.

of the SOA (Ham et al., 1964). The GMLC consists of anorthositic and gabbroic rocks considered to represent the middle portion of a tholeiitic layered mafic intrusion (Powell and Phelps, 1977; Powell, 1986). An angular unconformity of 10°–20° between the igneous layering in the GMLC and the overlying A-type rhyolites records tilting of the complex followed by a period of erosion. Wichita granite sills compositionally similar to the rhyolites intruded along this surface (Fig. 2). Biotite-bearing Roosevelt Gabbro plutons also intrude the GMLC but are petrogenetically unrelated to the layered complex (Powell, 1986). Although these biotite-bearing gabbros form relatively limited exposures in the Wichita Mountains (Fig. 1C), they are more abundant in the subsurface (Powell et al., 1980). Diabase dikes and sills cut all the other igneous units (McConnell and Gilbert, 1990; Hogan et al., 2000). Smaller outcrops of the WIP in the Arbuckle Mountains consist primarily of rhyolite lavas and felsic and diabasic intrusions (Fig. S1 in the Supplemental Material[1]). Basalt lavas are not exposed at the surface but occur in large amounts in the subsurface, where they are interbedded with rhyolites and intruded by Wichita granite plutons (Puckett et al., 2014).

Geophysical studies indicate that those parts of the WIP exposed at the surface represent the uppermost portion of a mass of mafic igneous rock that extends along the axis of the SOA, reaches depths of at least 10 km in the crust, and has a volume of ~210,000 km³ (Hanson et al., 2013). It is unknown how much of this mafic mass consists of basaltic lavas versus intrusive rocks. The total volume of felsic rock is estimated to be at least 40,000 km³ (Hanson and Eschberger, 2014).

Published geochronology for the WIP includes a Sm-Nd isochron date of 528 ± 29 Ma from the GMLC (Lambert et al., 1988) and U-Pb zircon dates of ca. 539 and ca. 536 Ma from two rhyolite units in the Arbuckle Mountains (Thomas et al., 2012). Additional U-Pb zircon and titanite and $^{40}Ar/^{39}Ar$ hornblende and biotite dates of ca. 577–530 Ma from rhyolites, granites, and Roosevelt Gabbro exposed in the

[1]Supplemental Material. Section S1 (geological setting of Arbuckle rhyolite samples), Section S2 (analytical methods), Section S3 (CL images), Section S4 (data tables), and Section S5 (Concordia diagrams). Please visit https://doi.org/10.1130/GEOL.S.13020647 to access the supplemental material, and contact editing@geosociety.org with any questions.

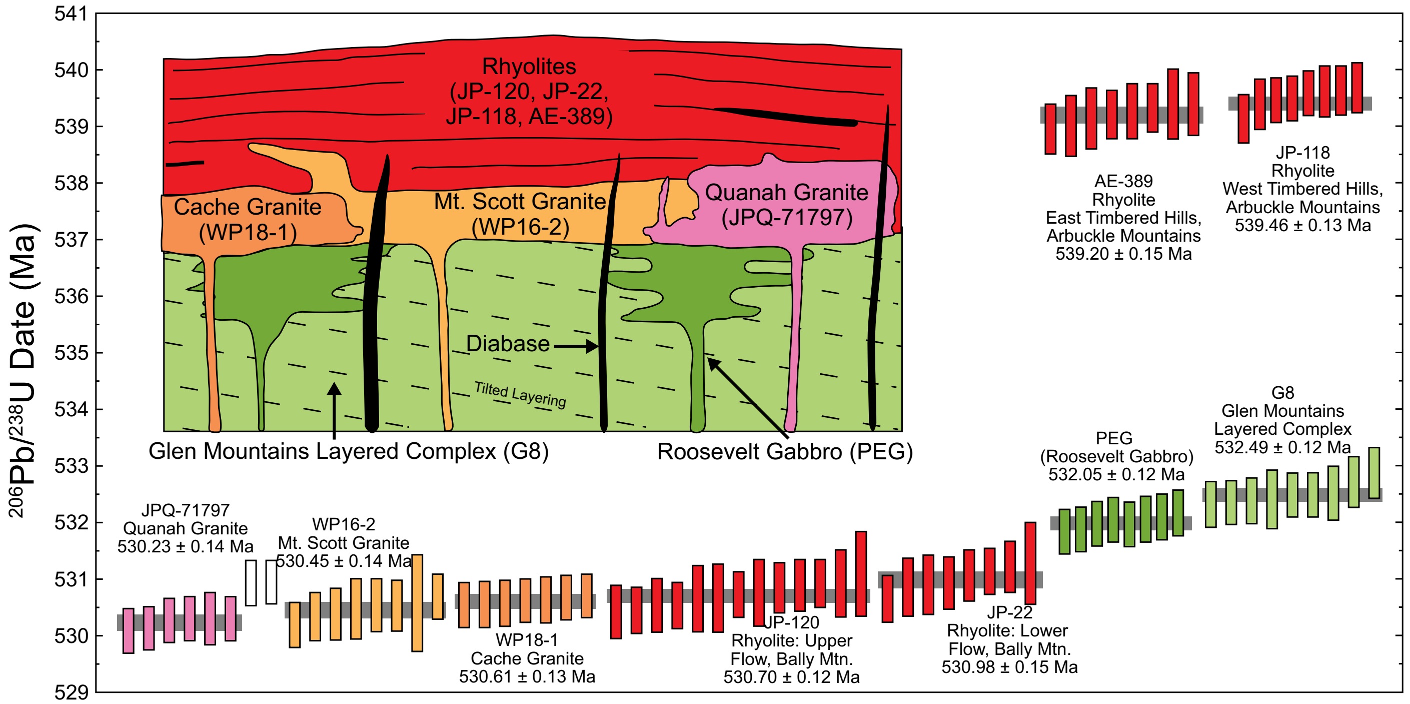

Figure 2. Cross section of igneous rocks exposed in the Wichita Mountains (Oklahoma, USA), modified from Hogan et al. (2000), with geochronological samples indicated. Note that samples AE-389 and JP-118 come from rhyolites in the Arbuckle Mountains. Ranked $^{206}Pb/^{238}U$ dates from all samples dated from the Wichita igneous province are also shown. Bars represent single-zircon analyses at 2σ uncertainty and are color coded based on geologic unit. Bars with no color fill are zircon fractions not included in the $^{206}Pb/^{238}U$ weighted mean. Horizontal gray bands represent uncertainty in $^{206}Pb/^{238}U$ weighted mean.

Wichita Mountains have only been published in conference abstracts (e.g., Wright et al., 1996; Hames et al., 1998; Hogan and Amato, 2015).

METHODS AND RESULTS

We present chemical abrasion–isotope dilution–thermal ionization mass spectrometry (CA-ID-TIMS) U-Pb isotopic and laser ablation–inductively coupled plasma–mass spectrometry (LA-ICP-MS) trace-element data for zircon from a number of the main units exposed within the WIP. Two samples (AE389 and JP-118) came from the Arbuckle Mountains, from rhyolite lavas located in the East and West Timbered Hills, respectively (Fig. 1B; Fig. S1). Other samples came from the well-exposed eastern part of the Wichita Mountains and include samples from rhyolite lavas at the base (JP-22) and top (JP-120) of a sequence of felsic volcanic rocks ≥2 km thick exposed at Bally Mountain (Fig. 1C). Intrusive rocks sampled include typical anorthositic gabbro from the GMLC (G8) and the three main granites exposed in the eastern Wichita Mountains. We also collected a felsic pegmatitic segregation (PEG) from an internally differentiated Roosevelt Gabbro, which intrudes the GMLC.

Based on results from 477 laser-ablation spots, 77 grains that showed no sign of inclusions and yielded consistent U-Pb laser dates were plucked from their respective grain mounts for high-precision CA-ID-TIMS geochronology (see Supplemental Material S2 for methods and analytical results). The CA-ID-TIMS U-Pb data for zircon from the nine samples yielded weighted mean $^{206}Pb/^{238}U$ dates in the range of 539–531 Ma (Fig. 2; Fig. S5). The two rhyolite lavas from the Arbuckle Mountains (AE-389 and JP-118) yielded weighted mean $^{206}Pb/^{238}U$ dates of 539.20 ± 0.15 Ma and 539.46 ± 0.13 Ma, respectively. These dates are older than the currently accepted age bracket of 538.6–538.8 Ma for the base of the Cambrian (Linnemann et al., 2019) and indicate a late Ediacaran age for some WIP magmatism. In contrast, our new age results from the Wichita Mountains fall entirely into the early Cambrian. Anorthosite from the GMLC (G-8) yielded a weighted mean $^{206}Pb/^{238}U$ date of 532.49 ± 0.12 Ma (Fig. 2), and zircon trace-element ratios from this sample are dispersed into continental arc fields on zircon trace-element discrimination diagrams (Fig. 3A; Grimes et al., 2015). The Roosevelt Gabbro (PEG) yielded a weighted mean $^{206}Pb/^{238}U$ date of 532.05 ± 0.12 Ma, constraining intrusion and cooling of the GMLC to have occurred within a narrow time frame of <500 k.y. The two rhyolite samples from the Wichita Mountains (JP-22 and JP-120) yielded weighted mean $^{206}Pb/^{238}U$ dates of 530.98 ± 0.15 Ma and 530.70 ± 0.12 Ma. The Cache Granite (WP18–1), Mt. Scott Granite (WP16–2), and Quanah Granite (JPQ-71797) yielded weighted mean $^{206}Pb/^{238}U$ dates of 530.61 ± 0.13 Ma, 530.45 ± 0.14 Ma, and 530.23 ± 0.14 Ma, respectively. Trace-element ratios for zircon from the Roosevelt Gabbro and the felsic samples indicate asthenospheric sources, and the felsic data cluster near or within the field for plume-influenced ocean-island basalt (OIB)–type settings (Fig. 3A).

DISCUSSION

Our new dates for rhyolite lavas in the Arbuckle Mountains overlap within uncertainty with the less-precise U-Pb zircon dates of 539 ± 5 and 536 ± 5 Ma obtained by Thomas et al. (2012) for two other rhyolite units in that area (Fig. S1). The new dates from the Wichita Mountains show that voluminous felsic magmatism occurred at 531–530 Ma in that part of the SOA and was preceded by intrusion of the GMLC and slightly younger Roosevelt Gabbro at 532 Ma. Erosional removal of higher parts of the GMLC and an unknown amount of overburden occurred during and/or after these rocks were tilted northward, which is ascribed to block rotation along south-dipping normal faults during extensional tectonism (McConnell and Gilbert, 1990).

Previous workers considered the unconformity separating the main mafic units and the felsic rocks in the Wichita Mountains to represent a significant break in time (e.g., Ham et al., 1964; Hogan and Amato, 2015), a view which was plausible based on the existing isotopic dates for these units. Our new data indicate that intrusion and block rotation of the GMLC and some Roosevelt Gabbro plutons, extensive erosion, and extrusion of a thick sequence of rhyolites on

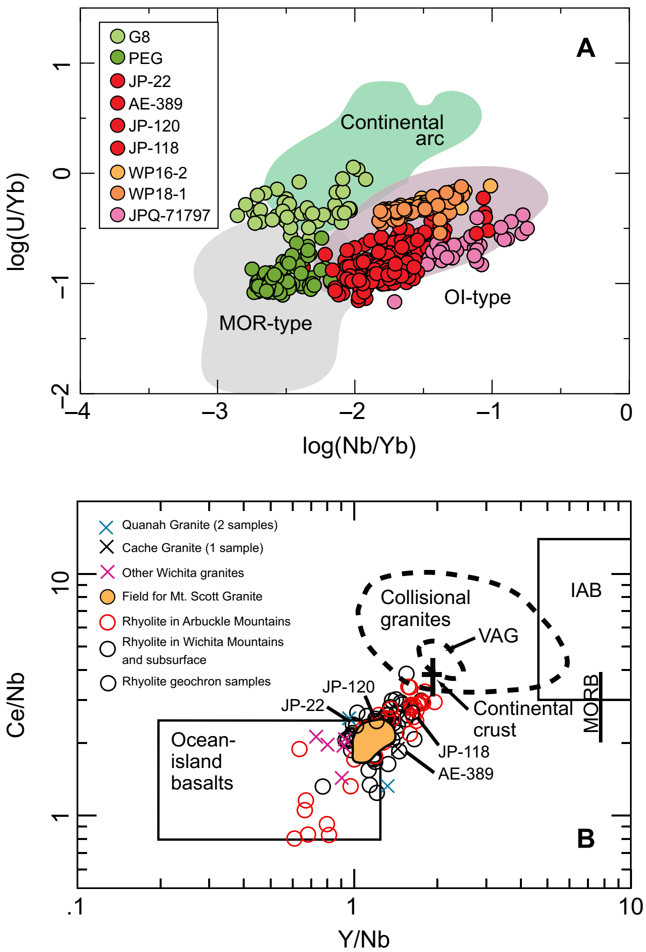

Figure 3. Trace-element distribution diagrams for zircon and whole rocks from the Wichita igneous province (Oklahoma, USA). (A) Log_{10}(U/Yb) versus log_{10}(Nb/Yb). Shaded fields represent distributions based on compiled data sets of zircon from mid-ocean ridges (MOR type), plume-influenced settings of Iceland and Hawaii (ocean island [OI] type), and continental arcs from Grimes et al. (2015). Points are color coded to correspond to colors of the appropriate unit from which they are derived (Figs. 1C and 2). (B) Ce/Nb versus Y/Nb data for whole-rock analyses from Price (1998), Boro (2015), Toews (2015), Hanson and Eschberger (2014). No equivalent data are available for the Glen Mountains Layered Complex or dated Roosevelt Gabbro pluton. Diagram is from Eby (1990). IAB—island-arc basalts, VAG—volcanic-arc granites, MORB—mid-oceanic ridge basalts.

the resulting angular unconformity, along with intrusion of slightly younger granite sills (Fig. 2, inset), occurred in this part of the SOA within a time frame of only ~2 m.y.

The narrow time frame of magmatism within the WIP and its restriction to one specific area along the southern Laurentian margin suggest that it was generated from a focused mantle thermal anomaly such as an uprising plume. The SOA is inferred to have developed either as the failed arm of a rift-rift-rift triple junction along the southern Laurentian margin (Hoffman et al., 1974) or as a transtensional fault system linked to a transform plate boundary along the northern margin of the Ouachita embayment (Thomas, 2011, 2014). Either model is consistent with formation of voluminous late Ediacaran–early Cambrian magmas in the SOA if it is assumed that rifting or transtensional basin formation interacted with, or was triggered by, an underlying mantle thermal anomaly.

Mafic rocks in the WIP have Sr and Nd isotopic ratios reflecting derivation from subcontinental lithospheric mantle as well as OIB-type asthenosphere (Supplemental Material S6; Hogan et al., 1995; Brueseke et al., 2016). WIP felsic rocks have similar Nd and Sr ratios to the mafic rocks (see the Supplemental Material; Hogan et al., 1995), suggesting an origin for the felsic magmas either from partial melting of underplated basalt or by fractionation from mafic parental magmas. The role of asthenospheric partial melting in the generation of the WIP is supported by zircon trace-element geochemistry from the felsic rocks and the Roosevelt Gabbro. We interpret these data to reflect an OIB-type component in the mantle source for the basaltic magmas that were parental to the felsic units (Fig. 3A). Zircon trace-element evidence from the older GMLC suggests that it was derived largely from continental lithosphere previously modified by subduction. The contrast in zircon chemistry between the GMLC and the younger rocks can be explained by a process in which a mantle thermal anomaly initially caused melting and assimilation of subcontinental mantle lithosphere, which gave way to increased involvement of asthenospheric melts with time. This is consistent with whole-rock trace-element data from a much larger sample set of WIP rhyolites and granites. As shown in Figure 3B, the data define a trend extending from average continental crust well into the OIB field, pointing to varying contributions from lithospheric and asthenospheric sources during petrogenesis of the felsic rocks.

Results of the present study support inclusion of the WIP within the widespread Central Iapetus magmatic province (CIMP), as proposed by Ernst and Bell (2010) and Youbi et al. (2020). CIMP developed prior to and during opening of the central Iapetus Ocean and is represented in Laurentia by Ediacaran intraplate magmatic rocks preserved along the eastern Laurentian margin in the Appalachians. Other parts of the CIMP include voluminous intraplate igneous assemblages with U-Pb zircon or baddeleyite ages of 620–520 Ma in Baltica, the West African craton, and other cratons or microcontinental blocks. CIMP igneous activity occurred in pulses, likely included several different large igneous provinces, and recorded the ascent of multiple mantle plumes (e.g., Tegner et al., 2019; Youbi et al., 2020).

Magmatism at 539–530 Ma in the SOA, with a major pulse at 532–530 Ma in the Wichita Mountains area, contrasts markedly with the Ediacaran intraplate magmatic record preserved in the Appalachians. Rift-related igneous rocks there have yielded U-Pb zircon dates as young as 550 Ma (Thomas, 2014), predating early Cambrian establishment of the passive margin in that region (Smoot and Southworth, 2014; Thomas, 2014). The passive margin did not begin to develop until the late middle Cambrian along that part of the Ouachita embayment proximal to the SOA (Thomas, 2011, 2014). In a widely accepted model, the Precordillera terrane, which has Laurentian affinities and is now located in western Argentina, originally occupied the Ouachita embayment (e.g., Thomas and Astini, 1996). According to this model, the Iapetus Ocean had already started opening along the eastern Laurentian margin before the Precordillera terrane began to separate from the margin farther southwest (present coordinates). Detachment of the terrane from Laurentia required a large inboard jump of the spreading center, but the cause of this event has remained unclear. We suggest that, during progressive evolution of the CIMP, ascent of a mantle plume near the location of what was to become the SOA resulted in thermal weakening of the lithosphere in that region. This plume-driven thermal weakening triggered or facilitated the change in plate kinematics that led to drift of the Precordillera terrane away from Laurentia.

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