Geosphere

Ages of pre-rift basement and synrift rocks along the conjugate rift and transform margins of the Argentine Precordillera and Laurentia

William A. Thomas, Robert D. Tucker, Ricardo A. Astini and Rodger E. Denison

Geosphere 2012;8;1366-1383
doi: 10.1130/GES00800.1

Notes

Ages of pre-rift basement and synrift rocks along the conjugate rift and transform margins of the Argentine Precordillera and Laurentia

William A. Thomas[1], Robert D. Tucker[2], Ricardo A. Astini[3], and Rodger E. Denison[4]
[1]*Geological Survey of Alabama, 420 Hackberry Lane, P.O. Box 869999, Tuscaloosa, Alabama 35486-6999, USA*
[2]*U.S. Geological Survey, 12201 Sunrise Valley Drive, National Center, MS 926A, Reston, Virginia 20192, USA*
[3]*Laboratorio de Análisis de Cuencas, Universidad Nacional de Córdoba, Avenida Velez Sarsfield 1611, Oficino 7, 2° Piso, X5016GCA Córdoba, Argentina*
[4]*15141 Kingstree Drive, Dallas, Texas 75248, USA*

ABSTRACT

New geochronologic data from basement rocks support the interpretation that the Argentine Precordillera (Cuyania) terrane was rifted from the Ouachita embayment of the Iapetan margin of Laurentia. New data from the Ozark dome show a range of ages in two groups at 1466 ± 3 to 1462 ± 1 Ma and 1323 ± 2 to 1317 ± 2 Ma, consistent with existing data for the Eastern Granite-Rhyolite province and Southern Granite-Rhyolite province, respectively. Similarly, a newly determined age of 1364 ± 2 Ma for the Tishomingo Granite in the Arbuckle Mountains confirms previously published analyses for this part of the Southern Granite-Rhyolite province. Along with previously reported ages from basement olistoliths in Ordovician slope deposits in the Ouachita embayment, the data for basement ages support the interpretation that rocks of the Southern Granite-Rhyolite province form the margin of Laurentian crust around the corner of the Ouachita embayment, which is bounded by the Ouachita rift and Alabama-Oklahoma transform fault. In contrast, both west and east of the corner of the Ouachita embayment, Grenville-Llano basement (approximately 1325–1000 Ma) forms the rifted margin of Laurentia.

New U/Pb zircon data from basement rocks in the southern part of the Argentine Precordillera indicate crystallization ages of 1205 ± 1 Ma and 1204 ± 2 Ma, consistent with previously reported ages (approximately 1250–1000 Ma) of basement rocks from other parts of the Precordillera. These data document multiple events within the same time span as multiple events in the Grenville orogeny in eastern Laurentia, and are consistent with Grenville-age rocks along the conjugate margins of the Precordillera and Laurentia. Ages from one newly analyzed collection, however, are older than those from other basement rocks in the Precordillera. These ages, from granodioritic-granitic basement clasts in a conglomerate olistolith in Ordovician slope deposits, are 1370 ± 2 Ma and 1367 ± 5 Ma. These older ages from the Precordillera are consistent with indications that the Iapetan margin in the Ouachita embayment of Laurentia truncated the Grenville front and left older rocks of the Southern Granite-Rhyolite province (1390–1320 Ma) at the rifted margin.

Chronostratigraphic correlations of synrift and post-rift sedimentary deposits on the Precordillera and on the Texas promontory of Laurentia document initial rifting in the Early Cambrian. Previously published data from synrift plutonic and volcanic rocks in the Wichita and Arbuckle Mountains along the transform-parallel intracratonic Southern Oklahoma fault system inboard from the Ouachita embayment document crystallization ages of 539–530 Ma. New data from synrift volcanic rocks in the Arbuckle Mountains in the eastern part of the Southern Oklahoma fault system yield ages of 539 ± 5 Ma and 536 ± 5 Ma, confirming the age of synrift volcanism.

INTRODUCTION

The Precordillera in the Andean frontal thrust belt in northwestern Argentina is an exotic terrane, which is interpreted to have been rifted from the Ouachita embayment of southern Laurentia in Cambrian time and accreted to the western margin of Gondwana during Ordovician time (Fig. 1) (e.g., Thomas and Astini, 1996, 1999, 2003; Astini and Thomas, 1999; Ramos, 2004). The Laurentian origin of the Precordillera terrane is based on a variety of data from Precambrian basement rocks, Early Cambrian synrift deposits, and a Cambrian–Ordovician passive-margin carbonate succession (e.g., Astini et al., 1995; Astini, 1998; Astini and Thomas 1999; Thomas and Astini, 1999, 2003; Ramos, 2004). Proposed alternative interpretations include different times of rifting, different times of accretion, different palinspastic sites along the Laurentian margin, and a Gondwanan rather than Laurentian origin (e.g., Dalla Salda et al., 1992a, 1992b; Dalziel, 1997; Keller et al., 1998; Pankhurst et al., 1998; Rapela et al., 1998; Keller, 1999; Cawood et al., 2001; Aceñolaza et al., 2002; Finney, 2007). Ultimately, resolution of the tectonic history of the Precordillera is significant to interpretation of the structural style, trace, and age of the margins of Iapetus, as well as to global plate reconstructions. The purpose of this article is to integrate new data for resolution of the ages of basement and synrift rocks on both sides of the Iapetan rift.

Rifting of the Argentine Precordillera from the Ouachita embayment of Laurentia defines the conjugate margins of the Ouachita rift as the eastern rift margin of the Texas promontory of Laurentia and the western rift margin of the Precordillera (directions are present day with Precordillera palinspastically restored) (Fig. 1). Similarly, the Alabama-Oklahoma transform fault separates the northwest-trending edge of the Ouachita embayment from the Precordillera. This article has two objectives: (1) to review existing data and present new U/Pb isotopic ages of Precambrian basement rocks on opposite sides of the rift-and-transform boundary of the Precordillera and the Ouachita embayment of Laurentia, and (2) to review existing data and present new U/Pb isotopic ages that bear on the

Geosphere; December 2012; v. 8; no. 6; p. 1366–1383; doi:10.1130/GES00800.1; 11 figures; 1 table.
Received 18 February 2012 ♦ Revision received 11 June 2012 ♦ Accepted 26 June 2012 ♦ Published online 18 October 2012

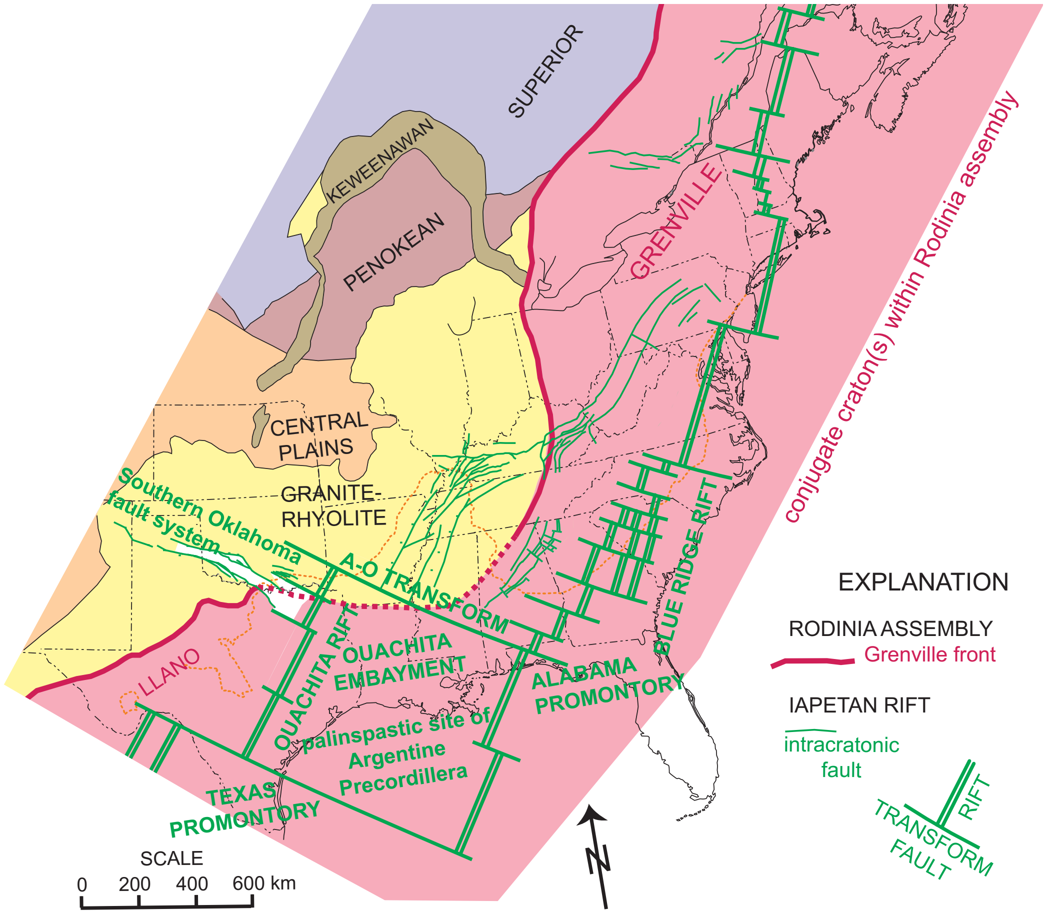

Figure 1. Regional map of Precambrian age provinces of southeastern Laurentia, showing the palinspastic location of the Precordillera in relation to the known (solid line) and inferred (dashed line) trace of the Grenville front (adapted from Thomas, 2006). Abbreviation: A-O transform—Alabama-Oklahoma transform.

age of rifting. These data provide further validation of the Laurentian origin of the Precordillera terrane and the palinspastic restoration of the Precordillera in the Ouachita embayment of Laurentia.

BACKGROUND

Along the Iapetan rifted margin of southeastern Laurentia, a large-scale transform offset of the rift outlines the Ouachita embayment between the Texas and Alabama promontories (Figs. 1 and 2). The rift margin has been covered by passive-margin strata of Cambrian–Ordovician age, by allochthons and foreland-basin sediment of the late Paleozoic Appalachian-Ouachita orogen, and by synrift and post-rift strata associated with Mesozoic rifting and opening of the Gulf of Mexico and Atlantic Ocean (Fig. 2). The Iapetan rifted margin can be palinspastically restored, however, using data from deep wells and geophysical surveys to extend the geometry of geologic structures from the outcrops (summary in Thomas, 2011). Inboard from the rift and transform margins of the Ouachita embayment, pre-Iapetan Precambrian crystalline basement rocks, as well as the base of the passive-margin cover, are exposed around the Llano uplift and Ozark dome, and in late Paleozoic fault blocks in the Arbuckle Mountains (Fig. 2). Along both the Ouachita rift and Alabama-Oklahoma transform margins of the Ouachita embayment, in the late Paleozoic Ouachita thrust belt, passive-margin Cambrian–Ordovician off-shelf deep-water mud-dominated facies were thrust over the coeval shelf-carbonate facies on Laurentian continental crust; the Precambrian crystalline basement rocks and post-rift passive-margin shelf-carbonate cover remained in the Ouachita footwall and were only mildly shortened by late Paleozoic Ouachita thrusting (summary in Thomas, 2011). The Southern Oklahoma fault system encompasses Cambrian synrift volcanic and plutonic rocks, which are exposed in late Paleozoic high-amplitude fault-bounded uplifts of the Arbuckle and Wichita Mountains (Fig. 2). In addition to the basement outcrops in the Llano, Arbuckle, and Ozark uplifts, basement data have been obtained from deep wells (Van Schmus et al., 1993; Rohs and Van Schmus, 2007). The off-shelf passive-margin succession is exposed in internal uplifts within the Ouachita thrust belt; part of the off-shelf passive-margin succession (Ordovician Blakely Sandstone) locally contains boulders of basement rocks (Fig. 2) (Stone and Haley, 1977; Bowring, 1984), providing another source of data for the age of basement rocks. Outcrops around the basement uplifts, in addition to deep wells, provide data to constrain the lithostratigraphy and chronostratigraphy of the passive-margin carbonate-shelf succession (Johnson et al., 1988).

In the Argentine Precordillera (Cuyania) microcontinent terrane (Fig. 3), Paleozoic sedimentary rocks are imbricated by frontal Andean thrust faults, including both thin-skinned east-directed thrust faults and basement-rooted west-directed Pampean (broken foreland) thrust faults (Ramos et al., 1986; Ramos, 2004, 2010). Cambrian–Ordovician passive-margin carbonate-shelf rocks and rare Cambrian synrift rocks are imbricated in the frontal Andean thrust sheets (Fig. 3), which are detached locally within the synrift succession and more commonly within the lower part of the passive-margin carbonate succession (Astini et al., 1995; Astini and Vaccari, 1996). No basement rocks are exposed in the sedimentary thrust belt of the Precordillera. The Precordillera microcontinent terrane includes the sedimentary succession in the frontal thrust sheets of the Andes (strictly the Pre-

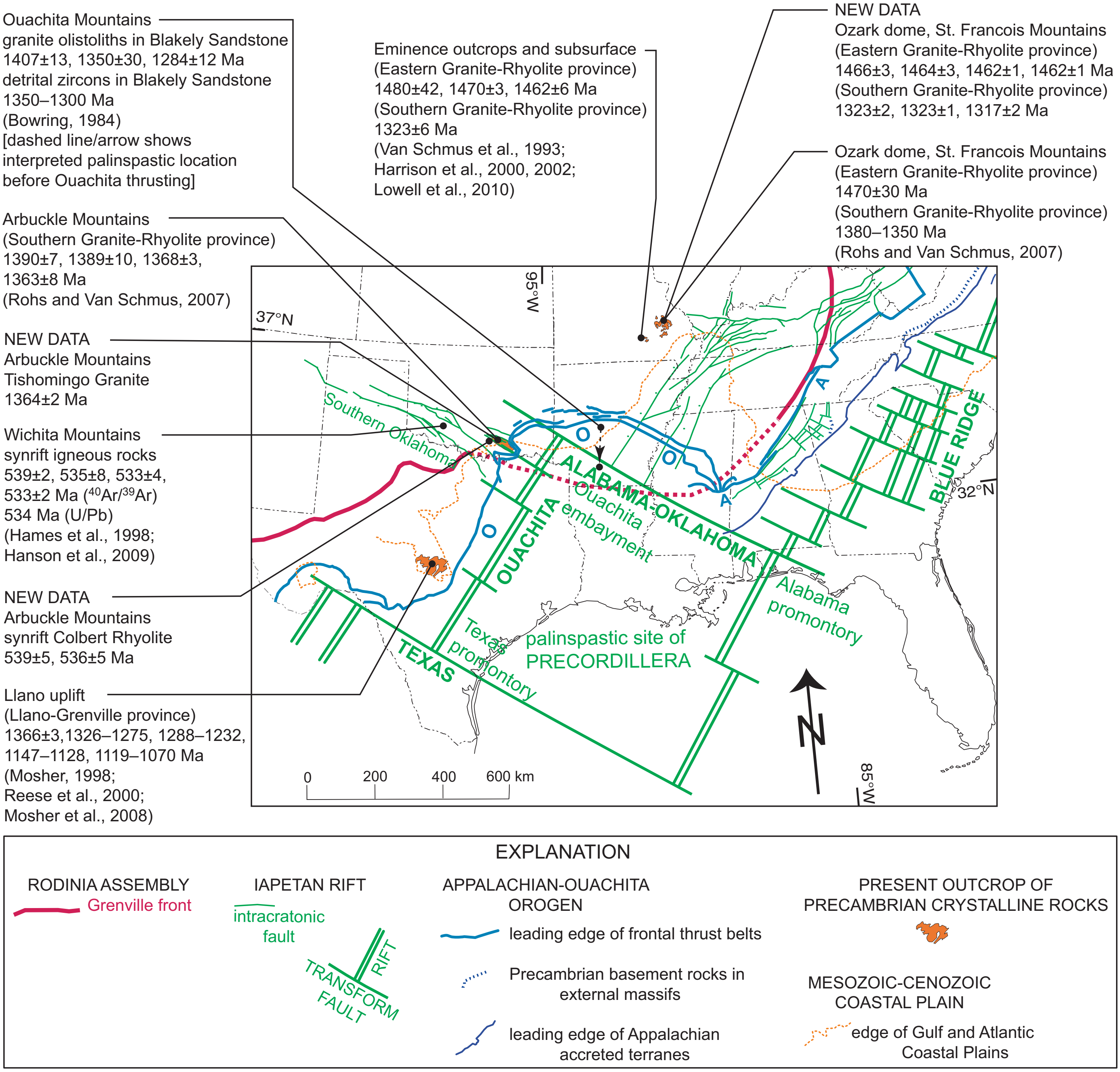

Figure 2. Map of southeastern Laurentia with locations of sample sites for new and previously published ages of Precambrian basement rocks and Cambrian synrift igneous rocks. The late Paleozoic Appalachian-Ouachita thrust belt and Mesozoic–Cenozoic Gulf Coastal Plain cover the trace of the Iapetan rifted margin of Laurentia. For the granite olistoliths in the Blakely Sandstone, the dashed line and arrow show the palinspastic location to restore shortening in the Ouachita thrust belt with respect to the present location. Abbreviations: A—Appalachian; O—Ouachita.

cordillera geologic/physiographic province), the basement rocks and metasedimentary cover in the Western Sierras Pampeanas (Sierra de Pie de Palo, Sierra de Umango, Sierra de Maz) east of the sedimentary thrust sheets, and isolated exposures of basement and sedimentary cover rocks farther south at Ponón Trehue (San Rafael block) and Cerro San Jorge (Las Matras block) (Fig. 3); this broad definition corresponds to the Cuyania terrane (Ramos et al., 1998; Ramos, 2004, 2010). In addition, Tertiary plutons within the Precordillera contain xenoliths of crystalline rocks, providing samples of the basement directly beneath the Precordillera (Kay et al., 1996).

PRECAMBRIAN BASEMENT ROCKS AROUND THE OUACHITA EMBAYMENT OF LAURENTIA

Basement rocks around the Ouachita embayment of Laurentia are assigned to either the Granite-Rhyolite province (1500–1320 Ma) or

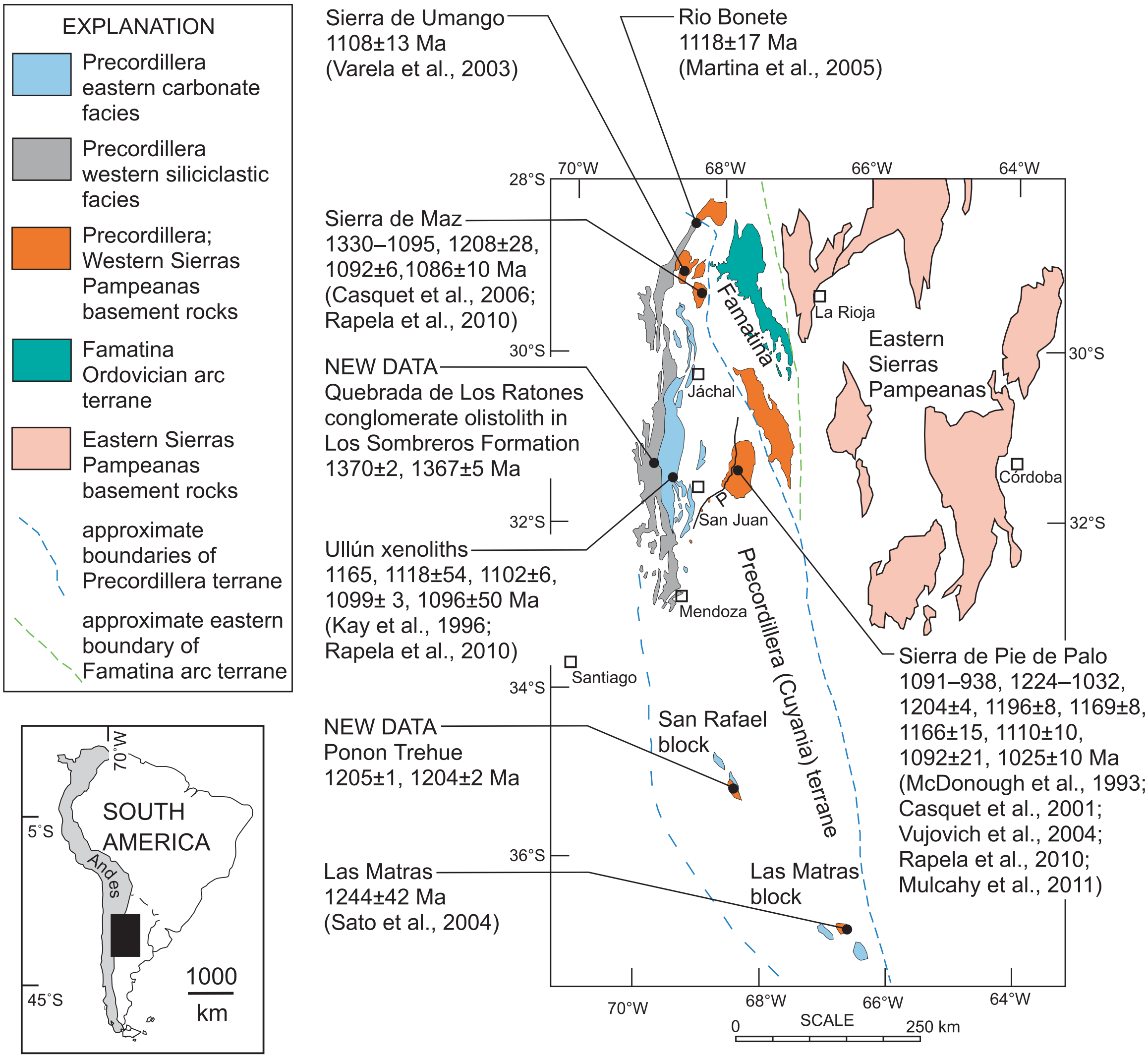

Figure 3. Map of Precordillera (adapted from Astini, 2003, and Chernicoff et al., 2009) with locations of sample sites for new and previously published zircon ages of Precambrian basement rocks. Abbreviation: P—Las Pirquitas fault.

the Grenville-Llano province (1325–1000 Ma), which are separated by the Grenville-Llano front (summary in Van Schmus et al., 1993). From outcrops in southern Canada, the Grenville province has been traced beneath the Paleozoic sedimentary cover, using geophysical surveys and samples from deep wells, southward through the eastern interior part of Laurentia (Figs. 1 and 2) (Lidiak and Heinze, *in* Rankin et al., 1993). On the basis of subsurface data (age determinations from basement rocks penetrated in wells), the Grenville front at the western margin of the Grenville province is traced with reasonable confidence as far south as northern Tennessee (Figs. 1 and 2) (Lidiak and Heinze, *in* Rankin et al., 1993; Reed, 1993). South and west from central Tennessee, few wells have penetrated Precambrian basement rocks beneath the Paleozoic cover, or farther south beneath the Mesozoic–Cenozoic Gulf Coastal Plain (summary in Thomas, 1988). The distribution and resolution of the sparse data do not clearly define the extent of the Grenville province or front; however, the Grenville front is generally inferred to intersect the Alabama-Oklahoma transform margin of Laurentian crust approximately in Mississippi (Figs. 1 and 2) (Rohs and Van Schmus, 2007). If that inference is generally correct, the southeastern part of the trace of the Alabama-Oklahoma transform fault cuts the Grenville province; whereas the northwestern part, extending into the corner of the Ouachita embayment, cuts the Granite-Rhyolite province (Figs. 1 and 2).

Rocks of the Granite-Rhyolite province are separated into two subdivisions on the basis of age differences (summary in Rohs and Van Schmus, 2007). Rocks of the Eastern Granite-Rhyolite province have ages of 1480–1460 Ma and are exposed in the St. Francois Mountains at the crest of the Ozark dome, an intracratonic uplift inboard from the Alabama-Oklahoma transform margin of Laurentia (Fig. 2). Rocks of the Southern Granite-Rhyolite province have ages of 1390–1320 Ma and are exposed principally in the Arbuckle Mountains along the eastern part of the Southern Oklahoma transform-parallel intracratonic fault system (Fig. 2). As we demonstrate later herein, these two age provinces overlap in the St. Francois Mountains of southeastern Missouri, where the older volcanic strata of the Eastern Granite-Rhyolite province are intruded by alkaline granite and syenite complexes of the

Southern Granite-Rhyolite province. In the St. Francois Mountains, rocks of the younger Southern Granite-Rhyolite province also include a significant amount of gabbro and diabase ("Skrainka diabase").

In Texas, northwest of the outcrops of the Llano (Grenville) province in the Llano uplift, subsurface data define a northeast-trending trace of the Grenville-Llano front across the Texas promontory, extending northeastward to an intersection with the intracratonic Southern Oklahoma fault system near the Ouachita rift boundary of the Ouachita embayment (Figs. 1 and 2) (Reed, 1993; summary in Van Schmus et al., 1993; Rohs and Van Schmus, 2007). The Southern Granite-Rhyolite province, with crystallization ages of approximately 1400–1340 Ma (Van Schmus et al., 1993), borders the Llano province on the northwest. South of the intersection of the Ouachita rift with the Southern Oklahoma fault system, the rift bounds the Llano (Grenville) province; north of the intersection, the rift bounds the Granite-Rhyolite province (Figs. 1 and 2).

Summary of Available Age Data

Ages of 1350–1000 Ma characterize rocks of the Grenville province in eastern Laurentia, although the province includes older protoliths and detrital zircons in metasedimentary rocks (e.g., Rankin et al., 1993; McLelland et al., 1996). The Grenville province extends along the southeast side of the easternmost Canadian Shield in eastern Canada (e.g., Cawood et al., 2001; Bartholomew and Hatcher, 2010) and is identified in outcrops in the Adirondack dome and along basement massifs of the Appalachian Mountains (e.g., Blue Ridge, Green Mountains) (Rankin et al., 1989). The initial use of the name Grenville designated the geologic-mapping province on the basis of rock types and degree of metamorphism. Since the advent of radiometric dating, the term Grenville has taken on an age connotation, generally with reference to a regional metamorphic event with an age of approximately 1000 Ma. With the growing recognition of a range of ages within rocks of the Grenville province, multiple events are considered to constitute the Grenville orogeny, including four thermal events at 1250–1200 Ma, 1200–1150 Ma, 1080–1020 Ma, and 1020–1000 Ma, along with accretion of older terranes (summary in Bartholomew and Hatcher, 2010). From northern Laurentia southward to the Alabama promontory, Grenville rocks form the eastern part of the Laurentian craton, and the Iapetan rifted margin of Laurentia is entirely within rocks of the Grenville province (Fig. 1) (e.g., Thomas, 2006).

Exposures of the Eastern Granite-Rhyolite province in the St. Francois Mountains on the Ozark dome include rhyolitic to dacitic tuff, rhyolitic flows, granitic plutons, and basaltic dikes, as well as minor inclusions of metamorphic rocks (summary in Bickford and Anderson, *in* Van Schmus et al., 1993; Rohs and Van Schmus, 2007). The U/Pb zircon ages document a primary magmatic episode at 1470 ± 30 Ma, characteristic of the Eastern Granite-Rhyolite province. Data from deep wells document the extent of the Eastern Granite-Rhyolite province north and east of the outcrops in the St. Francois Mountains (Lidiak, Bickford, and Kisvarsanyi, *in* Van Schmus et al., 1993). Other intrusive rocks exposed in the St. Francois Mountains, however, yield ages of 1380–1350 Ma, characteristic of the Southern Granite-Rhyolite province, indicating overlap of the two subdivisions of the Granite-Rhyolite province (Bickford and Anderson, *in* Van Schmus et al., 1993; Van Schmus et al., 1996; Rohs and Van Schmus, 2007; Lowell et al., 2010). In the area around the St. Francois Mountains, separate outcrops and drill samples of basement rocks yield ages of 1480 ± 42 Ma, 1470 ± 3 Ma, 1462 ± 6 Ma, and 1323 ± 6 Ma, further indicating both the Eastern and Southern Granite-Rhyolite provinces (Van Schmus, Bickford, Sims, Anderson, Shearer, and Treves, *in* Van Schmus et al., 1993; Harrison et al., 2000, 2002). In the subsurface, data from drill holes indicate the continuity of the Southern Granite-Rhyolite province across the region between the outcrops in the St. Francois Mountains and in the Arbuckle Mountains (Fig. 2) (Van Schmus et al., 1993; Rohs and Van Schmus, 2007).

Southern Granite-Rhyolite province rocks are exposed in the Arbuckle basement uplift, which extends in the subsurface southeastward to the Ouachita rifted margin of Laurentia, near the northwestern corner of the Ouachita embayment (Figs. 1 and 2) (e.g., Ham et al., 1964; Thomas et al., 1989). Mesozonal plutons of the Southern Granite-Rhyolite province exposed in the eastern Arbuckle Mountains include granite and granitic gneiss (Denison, 1973). U/Pb zircon ages of 1374 ± 15 Ma for the Tishomingo Granite, 1399 ± 95 Ma for the Troy Granite, and 1396 ± 40 Ma for the Blue River Gneiss were reported by Bickford and Lewis (1979), and 1397 ± 7 Ma for the Burch Granodiorite by Thomas et al. (1984). More recently, Rohs and Van Schmus (2007) determined ages of 1363 ± 8 Ma for the Tishomingo Granite, 1368 ± 3 Ma for the Troy Granite, 1389 ± 10 Ma for the Blue River Gneiss, and 1390 ± 7 Ma for the Burch Granodiorite (Fig. 2). In the subsurface in northeastern Oklahoma (north and east of the outcrops in the Arbuckle Mountains), drill samples are mostly rhyolite and epizonal granite plutons (Denison, 1981). The 1400–1360 Ma ages of these rocks are consistent with those characteristic of the Southern Granite-Rhyolite province (Thomas et al., 1984; Van Schmus et al., 1996). Precambrian magmatic rocks in the subsurface southwest of the Arbuckle Mountains and northwest of the Grenville-Llano front have ages of 1380–1340 Ma (Barnes et al., 2002), further indicating the original extent of the Southern Granite-Rhyolite province.

Rocks exposed in the Llano uplift, an intracratonic uplift inboard from the Ouachita rift margin on the Texas promontory of Laurentia (Fig. 2), have a tectonic history similar to that of the Grenville province of the eastern United States and Canada (Mosher, 1998). Multiply deformed igneous and sedimentary rocks indicate a collision orogen coeval with the Grenville orogeny. Accreted exotic arc-terrane rocks have U/Pb zircon ages of 1326–1275 Ma (Mosher, 1998; Mosher et al., 2008). Plutonic and supracrustal rocks have U/Pb zircon ages of 1288–1232 Ma, but include an older gneiss dated at 1366 ± 3 Ma (Reese et al., 2000; Mosher et al., 2008). Collision-related deformation and metamorphism are dated between 1147 Ma and 1128 Ma, and late syntectonic and post-tectonic plutons range in age from 1119 to 1070 Ma (Mosher, 1998; Reese et al., 2000; Mosher et al., 2008). The range of ages in the Llano uplift generally distinguishes the Grenville province from the Granite-Rhyolite province; however, the 1366 ± 3 Ma protolith age suggests a pre-Grenville basement of Laurentia, coeval with parts of the Southern Granite-Rhyolite province (Reese et al., 2000).

In the Ouachita thrust belt in Arkansas and Oklahoma, disharmonically thrust-imbricated and ductilely deformed shale-dominated off-shelf Cambrian–Mississippian passive-margin facies are thrust over the Laurentian continental margin and shelf facies (Fig. 2) (summary in Arbenz, 2008; Thomas, 2011). The Cambrian–Lower Ordovician off-shelf passive-margin succession is characterized by black shale, and includes sandstone, calcareous mudstone, chert, and carbonate-clast conglomerates (summary in Arbenz, 1989; Viele and Thomas, 1989). One sandstone unit (Middle Ordovician Blakely Sandstone) contains scattered boulders of granite and meta-arkose, indicating a supply of clasts from steep scarps that exposed basement rocks along the Laurentian continental margin (Stone and Haley, 1977). Separate granite boulders have U/Pb zircon ages of 1407 ± 13 Ma, 1350 ± 30 Ma, and 1284 ± 12 Ma; detrital zircons from arkosic sandstone in the Blakely Sandstone have ages of 1350–1300 Ma (Bowring, 1984). The ages of the granite boulders suggest that

TABLE 1. U-Pb ISOTOPE DILUTION DATA: ST. FRANCOIS AND ARBUCKLE MOUNTAINS (USA), AND PRECORDILLERA OF ARGENTINA

Fractions			Concentrations			Atomic ratios								Age (Ma)	
No.	Properties*	Wt.† (µg)	Pb† rad (ppm)	U† (ppm)	Pb§ com (pg)	Th#/U	^{206}Pb/^{204}Pb**	^{207}Pb/^{206}Pb**	±	^{207}Pb/^{235}U††	±	^{206}Pb/^{238}U††	±	^{207}Pb/^{206}Pb††	±
ST. FRANCOIS MOUNTAINS, MISSOURI, EASTERN GRANITE-RHYOLITE PROVINCE (Fig. 4)															
Cope Hollow Rhyolite, upper ash-flow tuff [field number CH-9293; map location 37°32.517′N, 90°50.504′W]															
1	1, cl,c,eu,s-p	1	13.9	120	2.10	0.56	2460	0.09119	3	3.2107	31	0.25385	26	1461.8	0.7
2	2, cl,c,s-p	2	14.4	151	1.50	0.67	2601	0.09117	8	3.1942	90	0.25289	76	1459.6	2.7
3	2, cl,c,s-p	2	23.4	166	1.90	0.89	2119	0.09200	8	3.1721	60	0.25069	44	1462.7	2.8
4	10, cl,c,eu,s-p	16	20.3	119	0.80	0.76	10,852	0.09119	6	3.1428	40	0.24850	22	1462.2	1.0
Johnson's Shut-Ins Rhyolite, lower ash-flow tuff [field number JR-9292; map location 37°32.295′N, 90°50.249′W]															
5	1, cl,c,s-p	2	21.9	91.3	2.00	1.70	1235	0.09118	9	3.1875	38	0.25223	30	1461.2	1.9
6	2, cl,c,s-p	3	20.7	99.4	1.40	1.10	2166	0.09200	5	3.1976	33	0.25262	22	1462.9	0.9
7	1, cl,c,s-p	1	19.9	111	0.90	1.60	488.2	0.09201	8	3.1698	43	0.25003	32	1463.3	1.8
8	5, cl,c,s-p	12	19.8	105	3.10	1.50	1240	0.09205	12	2.9009	49	0.22866	25	1467.7	2.9
Taum Sauk Rhyolite, upper ash-flow tuff [map location 37°31.950′N, 90°50.407′W]															
9	3, cl,c,eu,s-p	5	17.9	197	0.88	0.57	4387	0.09203	3	3.2168	28	0.25379	19	1465.4	0.8
10	2, cl,c,eu,s-p	2	20.8	189	0.90	0.36	2036	0.09204	7	3.1656	41	0.24989	25	1466.7	1.3
11	1, cl,c,eu,s-p	1	12.4	190	0.95	0.61	1136	0.09119	10	2.8708	53	0.22690	38	1462.3	2.5
Hawn State Park Gneiss [field number HSP-1; map location 37°49.990′N, 90°14.038′W]															
12	4, cl,c,t,l-p	11	18.2	180	1.10	0.75	867.9	0.09201	8	3.2197	44	0.25441	35	1463.0	1.9
13	5, cl,c,t,l-p	15	16.2	150	1.30	0.65	29,418	0.09119	4	3.2157	38	0.25418	27	1462.3	1.3
14	3, cl,c,t,l-p	9	14.8	135	1.60	0.59	12,611	0.09200	3	3.2134	35	0.25398	23	1462.6	1.6
15	5, cl,c,t,l-p	18	18.3	188	2.00	1.10	32,176	0.09119	4	3.2167	31	0.25429	22	1462.1	0.9
ST. FRANCOIS MOUNTAINS, MISSOURI, SOUTHERN GRANITE-RHYOLITE PROVINCE (Fig. 5)															
Devil's Tollgate Gabbro [map location 37°33.324′N, 90°44.840′W]															
16	3, B, br,p,fr	8	120	561	8.90	0.02	7572	0.08531	5	2.6766	42	0.22755	36	1322.6	1.0
17	4, B, pb,p,fr	11	137	637	2.90	0.03	33,644	0.08529	4	2.6873	31	0.22853	26	1322.0	0.9
18	5, B, pb,p,fr	13	120	552	4.60	0.04	23,027	0.08533	12	2.7014	90	0.22961	76	1323.1	2.7
19	9, B, pb,p,fr	17	124	581	7.50	0.03	19,365	0.08536	4	2.6707	53	0.22692	45	1323.7	0.9
20	4, B, db,p,fr	10	177	822	4.30	0.02	29,491	0.08541	4	2.6967	59	0.22899	50	1324.8	0.9
Graniteville Granite [map location 37°39.719′N, 90°40.889′W]															
21	1, cl,c,s-p	2	13.5	58.1	1.80	0.34	1372	0.08502	13	2.6576	62	0.22672	46	1315.9	3.0
22	2, cl,c,s-p	3	16.4	70.5	1.80	0.43	1750	0.08498	26	2.6107	105	0.22282	62	1315.0	6.0
23	7, cl,c,s-p	15	22.3	96.3	2.00	0.43	9344	0.08510	6	2.5907	33	0.22079	25	1317.8	1.3
24	4, cl,c,s-p	9	26.4	116	3.90	0.41	3592	0.08505	11	2.5606	49	0.21837	43	1316.6	2.5
Munger Granite Porphyry [field number MGP-1; map location 37°31.209′N, 90°49.743′W]															
25	2, cl,c,s-p	5	17.9	75.3	2.00	0.41	2920	0.08534	9	2.6828	45	0.22800	33	1323.3	2.0
26	1, cl,c,s-p	2	18.8	80.1	1.30	0.38	2069	0.08538	16	2.6649	58	0.22691	26	1324.2	3.6
27	4, cl,c,s-p	9	14.4	61.8	1.90	0.38	4458	0.08537	6	2.6636	36	0.22629	27	1323.9	1.4
28	5, cl,c,s-p	11	20.7	88.8	3.40	0.37	4149	0.08531	8	2.6514	43	0.22540	32	1322.7	1.8
29	2, cl,c,s-p	5	22.7	102	2.20	0.40	3078	0.08525	8	2.5114	38	0.21365	30	1321.2	1.8
ARBUCKLE MOUNTAINS, OKLAHOMA, SOUTHERN GRANITE-RHYOLITE PROVINCE (Fig. 6)															
Tishomingo Granite [field number BT-98-106A; map location 34.260°N, 96.697°W]															
30	10, cl,c,l-p	26	6.64	25.5	2.90	0.65	3465	0.08705	11	2.8191	48	0.23489	33	1361.5	2.5
31	10, cl,c,l-p	27	22.7	86.9	2.90	0.67	12,326	0.08714	4	2.8170	32	0.23446	25	1363.6	0.9
32	20, cl,c,l-p	48	6.75	25.9	2.90	0.71	6294	0.08719	7	2.7820	120	0.23142	100	1364.7	1.6

(*continued*)

rocks of the Southern Granite-Rhyolite province formed this segment of the Laurentian margin along the Alabama-Oklahoma transform (e.g., Bickford and Anderson, *in* Van Schmus et al., 1993). Although rocks of the Grenville orogen (1350–1000 Ma) extend along most of the Laurentian rifted margin both northeast and southwest of the Ouachita embayment, the ages of these boulders show that, locally at least, the Alabama-Oklahoma transform fault cut across the trace of the Grenville front into the Southern Granite-Rhyolite province (Fig. 2).

New Data

In this article, we report previously unpublished U/Pb zircon and baddeleyite data from igneous basement rocks in the St. Francois Mountains (Ozark dome) and in the Arbuckle Mountains (Southern Oklahoma fault system). Analytical methods are described in the Appendix, and results are listed in Table 1.

New isotopic ages from the St. Francois Mountains (Fig. 2) further refine the dominant magmatic event at 1470–1460 Ma and a later event at 1325–1315 Ma, characteristic of the Eastern Granite-Rhyolite province and Southern Granite-Rhyolite province, respectively. Our new isotopic ages include three U/Pb zircon ages from the well-known but previously undated volcanic succession of the St. Francois Mountains exposed in the East Fork of the Black River at Johnson's Shut-Ins State Park, Missouri. These are, in descending stratigraphic order (Fig. 4): 1462 ± 1 Ma for the upper ash-flow tuff of the Cope Hollow Rhyolite, 1464 ± 3 Ma for the lower ash-flow tuff of the Johnson's Shut-Ins Rhyolite, and 1466 ± 3 Ma for the upper ash-flow tuff of the Taum Sauk Rhyolite, the lowest of the volcanic formations exposed in the East Fork of the Black River (Kisvarsanyi et al., 1981). The isotopic ages for the three volcanic rocks agree well with the relative stratigraphic positions; thus, the entire volcanic succession, which is ~650 m thick, was erupted in ~4–8 m.y. (at 95% confidence limits). Coeval with the pyroclastic eruptives of the western St. Francois Mountains, intrusive igneous rocks were emplaced into the Butler Hill volcanic-plutonic complex of eastern St. Francois County and western Ste. Genevieve County (Bickford and Mose, 1975; Lowell, 1976). Well-known among these plutonic rocks are the small isolated intrusions of biotite granite porphyry with xenoliths of weakly foliated

TABLE 1. U-Pb ISOTOPE DILUTION DATA: ST. FRANCOIS AND ARBUCKLE MOUNTAINS (USA), AND PRECORDILLERA OF ARGENTINA (*continued*)

Fractions			Concentrations			Atomic ratios								Age (Ma)	
No.	Properties*	Wt.† (μg)	Pb† rad (ppm)	U† (ppm)	Pb§ com (pg)	Th#/U	$^{206}Pb/^{204}Pb$**	$^{207}Pb/^{206}Pb$**	±	$^{207}Pb/^{235}U$††	±	$^{206}Pb/^{238}U$††	±	$^{207}Pb/^{206}Pb$††	±
PRECORDILLERA BASEMENT (Fig. 7)															
Ponon Trehue Granite [field number BT-128-2; map location 35.169°S, 68.282°W]															
33	10, cl,c,t-p	26	20.3	96.8	9.20	0.41	3601	0.08034	6	2.2409	30	0.20229	26	1205.4	1.4
34	10, cl,c,t-p	21	40.9	192	3.40	0.41	15,634	0.08033	4	2.2672	33	0.20470	29	1205.0	1.0
35	9, cl,p,t-p	17	39.9	188	2.60	0.41	16,020	0.08020	7	2.2591	49	0.20430	46	1201.9	1.7
Ponon Trehue Granite [field number BT-130-3, map location 35.169°S, 68.282°W]															
36	5, cl,pp,fr	10	27.9	133	1.80	0.34	9685	0.08037	7	2.2824	65	0.20598	57	1206.0	1.6
37	8, cl,pp,fr	17	31.7	153	4.20	0.31	8110	0.08028	5	2.2686	33	0.20496	29	1203.8	1.3
38	10, cl,pp,fr	21	24.1	113	10.00	0.41	3184	0.08021	6	2.2576	33	0.20413	30	1202.2	1.6
39	12, cl,pp,fr	25	9.8	48.8	6.70	0.42	2299	0.08029	9	2.1263	33	0.19207	25	1204.2	2.3
PRECORDILLERA BASEMENT CLASTS IN CONGLOMERATE OLISTOLITH (Fig. 10)															
Clast in conglomerate olistolith in Ordovician Los Sombreros Formation [field number BT-146-2; map location 31.306°S, 69.126°W]															
40	14, cl,c,s-p	32	35.8	152	2.40	0.25	29,537	0.08718	5	2.8345	38	0.23579	32	1364.6	1.1
41	28, cl,c,s-p	64	26.3	112	7.40	0.27	14,417	0.08733	7	2.8049	33	0.23295	31	1367.8	1.4
42	16, cl,c,s-p	36	12.9	56.6	5.90	0.24	4993	0.08743	16	2.7552	44	0.22855	41	1370.1	3.6
Clast in conglomerate olistolith in Ordovician Los Sombreros Formation [field number BT-146-3, map location 31.306°S, 69.126°W]															
43	8, cl,c,t-p	17	34.6	139	1.80	0.49	19,612	0.08740	8	2.8177	37	0.23382	35	1369.3	1.7
44	9, cl,c,t-p	18	29.9	118	1.80	0.58	17,624	0.08746	6	2.8200	34	0.23385	28	1370.7	1.2
45	9, cl,c,t-p	20	35.2	141	2.10	0.54	19,707	0.08740	8	2.7889	37	0.23142	35	1369.4	1.7
ARBUCKLE MOUNTAINS, OKLAHOMA, SYNRIFT RHYOLITES (Fig. 11)															
Colbert Rhyolite [field number BT-98-107; map location 34.239°N, 96.718°W]															
46	8, cl,c,eu,s-p	16	5.41	50.3	3.20	1.17	1382	0.05818	8	0.6995	12	0.08719	12	536.7	2.9
47	12, cl,c,eu,s-p	24	4.29	48.1	10.10	1.08	571	0.05817	22	0.5875	29	0.07326	32	536.1	8.1
Colbert Rhyolite [field number BT-98-112B; map location 34.419°N, 97.150°W]															
48	3, cl,c,eq,f,s-p	7	6.32	68	2.10	0.57	1177	0.05817	10	0.6989	15	0.08714	11	536.2	3.8
49	9, cl,c,eq,f,s-p	18	1.56	17.9	2.40	0.36	781	0.05822	13	0.6952	18	0.08661	14	537.9	4.9
50	6, cl,c,eq,f,s-p	14	3.81	42.2	2.20	0.61	1396	0.05831	10	0.6723	38	0.08361	46	541.6	3.5

*B—baddeleyite; all other analyses are of zircon. Cardinal number indicates the number of grains analyzed (e.g., 2 grains). Zircon and baddeleyite were selected from nonparamagnetic separates at 0° tilt at full magnetic field in Frantz magnetic separator. br—brown; c—colorless; cl—clear; eq—equant; db—dark brown; eu—euhedral; f—faceted; fr—fragment; l-p—long-prismatic; p—prismatic; pb—pale brown; pp—pale pink; s-p—short-prismatic; t—tips from prisms. Zircon was air-abraded following Krogh (1982) prior to acid digestion; baddeleyite was not.

†Concentrations are known to ± 30% for sample weights of about 30 μg and ± 50% for samples <3 μg.

§Corrected for 0.0125 mole fraction common-Pb in the ^{205}Pb-^{235}U spike.

#Calculated Th/U ratio assuming that all ^{208}Pb in excess of blank, common-Pb, and spike is radiogenic (λ ^{232}Th = 4.9475×10^{-11} yr^{-1}).

**Measured, uncorrected ratio.

††Ratio corrected for fractionation, spike, blank, and initial common-Pb (at the determined age from Stacey and Kramers, 1975). Pb fractionation correction = 0.094% / amu (± 0.025%, 1σ); U fractionation correction = 0.111% / amu (± 0.02% 1σ). U blank = 0.2 pg; Pb blank ≤ 10 pg. Absolute uncertainties (1σ) in the Pb/U and $^{207}Pb/^{206}Pb$ ratios calculated following Ludwig (2001, 2003). U and Pb half-lives and isotopic abundance ratios from Jaffey et al. (1971).

granodiorite gneiss along Pickle Creek in Hawn State Park (Lowell, 1976). Our sample of the granodiorite gneiss xenolith yielded a crystallization age of 1462 ± 1 Ma (Fig. 4), which is in close agreement with the U/Pb determination of 1500 ± 30 Ma for the same rock by Bickford and Mose (1975).

The younger magmatic event of the St. Francois Mountains is documented by new U/Pb ages for two small granitic stocks of the central and western St. Francois Mountains, as well as a microgabbro dike of the "Skrainka diabase" (Kisvarsanyi et al., 1981). Our new isotopic ages (Fig. 5) include a U/Pb baddeleyite age for the Devil's Tollgate Gabbro (1323 ± 1 Ma; "Skrainka diabase"), and U/Pb zircon ages for the Graniteville Granite (1317 ± 2 Ma) and the Munger Granite Porphyry (1323 ± 2 Ma), the latter of which intrudes the aforementioned volcanic succession at Johnson's Shut-Ins State Park. The isotopic ages of this younger magmatic event also overlap the range of ages of basement boulders in the Blakely Sandstone in the Ouachita Mountains (Bowring, 1984), further indicating the probable source of the boulders from rocks of the Southern Granite-Rhyolite province.

A newly dated sample of the Tishomingo Granite in the Arbuckle Mountains (Fig. 2) has a U/Pb zircon age of 1364 ± 2 Ma (Fig. 6), which is in good agreement with the previously published ages of 1374 ± 15 Ma (Bickford and Lewis, 1979) and 1363 ± 8 Ma (Rohs and Van Schmus, 2007). These ages and rock types are consistent with those of the Southern Granite-Rhyolite province.

BASEMENT ROCKS IN AND AROUND THE ARGENTINE PRECORDILLERA TERRANE

Characterization of basement rocks in the Precordillera comes from basement massifs in the Western Sierras Pampeanas around the eastern side of the belt of sedimentary thrust sheets, isolated exposures of basement and Precordillera cover strata south of the primary outcrops of the sedimentary thrust sheets, and xenoliths of basement rocks in Tertiary plutons within the Paleozoic strata of the Precordillera (Fig. 3). In addition, olistoliths in slope facies in the western Precordillera include basement rocks.

Summary of Available Age Data

Basement rocks are exposed along an alignment of massifs north and east of the Precordillera sedimentary outcrops (Sierra de Maz, Sierra de Umango, and Sierra de Pie de Palo, Fig. 3). Ages of rocks from these massifs have led to alternative interpretations of the tectonic history and affinities of the basement rocks.

In the Sierra de Maz (Fig. 3), a complex history of zircon overgrowths in metasedimentary garnet schist gives U/Pb ages (sensitive high-resolution ion microprobe [SHRIMP]) of 1880–1700 Ma for zircon cores, and a range of overgrowth ages of 1230–1180 Ma (weighted mean 1208 ± 28 Ma) (Casquet et al., 2006).

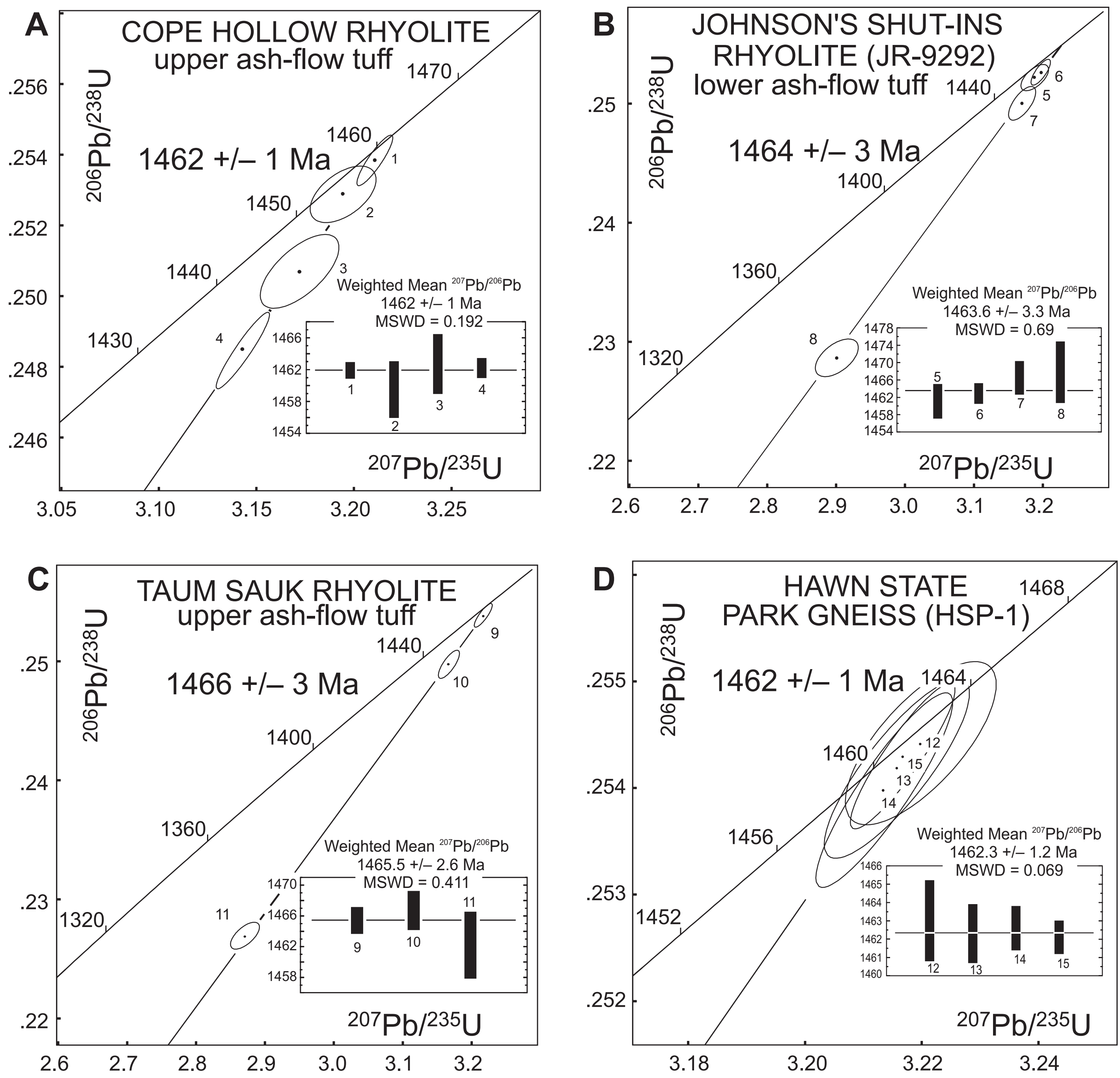

Figure 4. Concordia plots of U/Pb zircon analyses of the older (Geon 14) rocks in the Eastern Granite-Rhyolite province in the St. Francois Mountains on the Ozark dome. MSWD—mean square of weighted deviates.

These ages are interpreted to reflect a Paleoproterozoic provenance of the metasedimentary rocks, and high-grade metamorphism during an orogenic event coeval with the Grenville orogeny (Casquet et al., 2006). Other orthogneisses in the Sierra de Maz have crystallization ages of 1092 ± 6 to 1086 ± 10 Ma (Rapela et al., 2010). For complex zircons from orthogneiss, ages (SHRIMP) of 1330–1260 Ma are interpreted to represent crystallization of the igneous protolith, and ages of 1175–1095 Ma are interpreted to record metamorphism (Rapela et al., 2010). A granitic orthogneiss in the nearby Sierra de Umango (Fig. 3) has a U/Pb zircon magmatic-crystallization age of 1108 ± 13 Ma (Varela et al., 2003).

In a regional context, the Sierras de Maz and Umango have been interpreted to be part of a continental crustal block, extending northwest to Arequipa-Antofalla and perhaps southeast to the Sierra de Pie de Palo, and representing a Mesoproterozoic mobile belt autochthonous to Gondwana (Casquet et al., 2006, 2010). The Arequipa-Antofalla terrane was accreted to Amazonia during the Sunsas orogeny at 1200–1000 Ma, but it includes orthogneisses with ages of 1900–1800 Ma (Loewy et al., 2004), similar

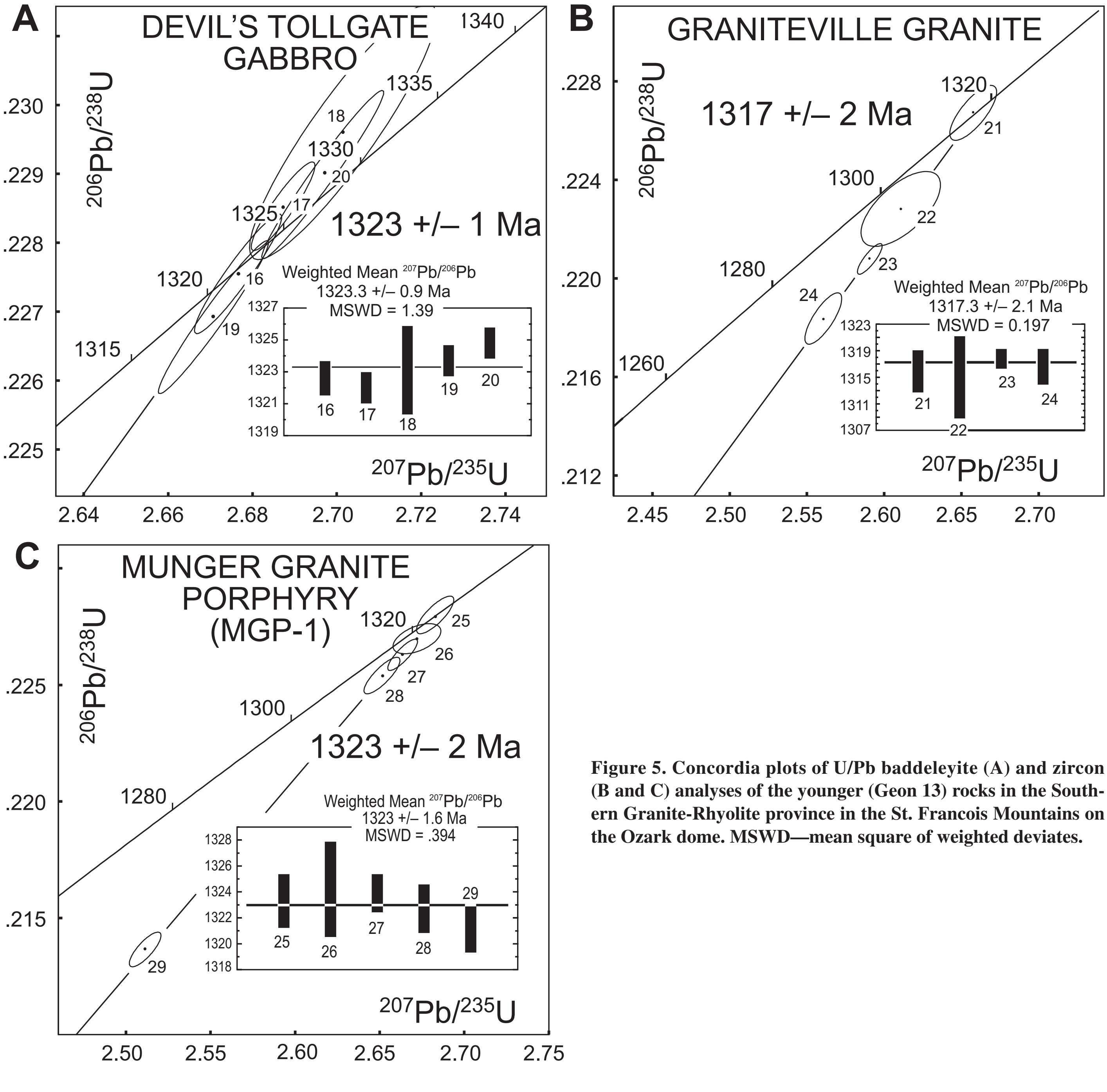

Figure 5. Concordia plots of U/Pb baddeleyite (A) and zircon (B and C) analyses of the younger (Geon 13) rocks in the Southern Granite-Rhyolite province in the St. Francois Mountains on the Ozark dome. MSWD—mean square of weighted deviates.

to the ages of zircon cores in the Sierra de Maz (Casquet et al., 2006, 2010). Comparable ages of basement rocks in the Sierras de Maz, Umango, and Pie de Palo, as well as Arequipa-Antofalla, are consistent with a common history of Grenville-age continental accretion and assembly of Rodinia. The Arequipa-Antofalla and related terranes have been interpreted to have formed a ribbon continent, first rifted from Amazonia to open the Puncoviscana Ocean in latest Precambrian time, then re-accreted by subduction beneath the Pampean arc, and finally rifted from Laurentia to open the Iapetus Ocean (Escayola et al., 2011). Such a tectonic scenario indicates that the Mesoproterozoic basement terrane was accreted before the Precordillera arrived at the western Gondwanan margin, and that the basement rocks represent the continental margin to which the Precordillera was accreted.

The Sierra de Pie de Palo (Fig. 3), east of the Precordillera sedimentary cover, includes the Pie de Palo Complex of orthogneisses, high-grade metasedimentary rocks, and a mafic-ultramafic arc complex (Vujovich and Kay, 1998; Vujovich et al., 2004; Chernicoff et al., 2009). The earliest reported Pb/Pb zircon ages from the gneisses of 1091–938 Ma (McDonough et al., 1993) are similar to more recently reported U/Pb zircon ages of 1224–1032 Ma (Casquet et al., 2001) and 1204 ± 4 Ma, 1196 ± 8 Ma, 1169 ± 8 Ma, 1166 ± 15 Ma, 1110 ± 10 Ma, 1092 ± 21 Ma, and 1025 ± 10 Ma (Vujovich et al., 2004; Rapela et al., 2010; Mulcahy et al., 2011). Zircon ages

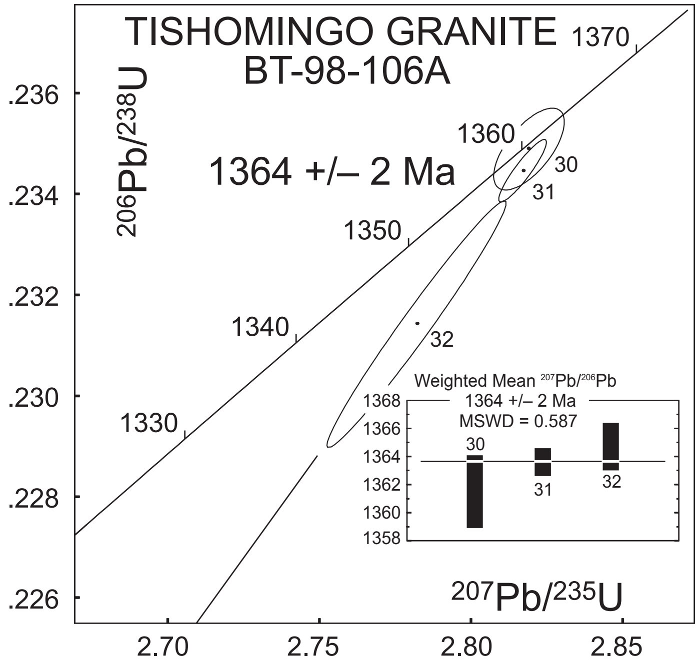

Figure 6. Concordia plot of U/Pb zircon analyses of Tishomingo Granite in the Southern Granite-Rhyolite province in the eastern Arbuckle Mountains along the Southern Oklahoma fault system. MSWD—mean square of weighted deviates.

of 1224–938 Ma for orogenic events recorded in the Pie de Palo basement are consistent with the ages of basement rocks in the Sierras de Maz and Umango, as well as with the Grenville orogeny of Laurentia.

Along the western side of the Sierra de Pie de Palo, the west-directed Las Pirquitas fault (Fig. 3) separates the higher grade gneisses of the Pie de Palo Complex on the east from metasedimentary rocks of the Caucete Group on the west. Detrital-zircon populations in metasedimentary quartzite (part of Caucete Group) in the footwall of the Las Pirquitas fault on the western side of the Pie de Palo are similar to detrital-zircon populations in the Lower Cambrian synrift Cerro Totora Formation, the oldest part of the Precordillera sedimentary succession (Naipauer et al., 2005, 2010). These relationships suggest that the Caucete Group in the Las Pirquitas footwall was originally part of the Cambrian sedimentary cover of the Precordillera terrane and was near the leading edge at the time of collision during the Ordovician (Naipauer et al., 2005, 2010; Chernicoff et al., 2009; van Staal et al., 2011).

Although the Caucete Group is documented to be part of the Precordillera (Cuyania) terrane, alternative interpretations consider the Pie de Palo Complex either to represent the basement of the Precordillera terrane (e.g., Ramos et al., 1998; Vujovich and Kay, 1998) or to be a separate microcontinental fragment. The mafic-ultramafic belt in the Pie de Palo may represent a Mesoproterozoic suture between the orthogneisses in the sierra and a separate basement terrane (the Precordillera) on the west; the Grenville-age suture may have been reactivated as the Las Pirquitas fault during the Ordovician collision of the Precordillera terrane (Chernicoff et al., 2009). Mylonites (ca. 515 Ma) in the hanging wall of the Las Pirquitas fault have been interpreted to indicate that the Pie de Palo Complex was within an active convergent margin along western Gondwana before the arrival of the separate Precordillera terrane (Mulcahy et al., 2007, 2011). In contrast, comprehensive structural models show that the mylonites could be a result of extension during opening of Iapetus along the margin of a Precordillera terrane that included the Pie de Palo Complex (van Staal et al., 2011).

Along the Rio Bonete, the northwest-trending Jagüé shear zone, which is the probable northern boundary of the Precordillera terrane (Martina and Astini, 2009), includes mylonitic granite and marble (Fig. 3). The granite is interpreted to be part of the Precordillera basement, and the associated calcitic and dolomitic marbles suggest protoliths of the Precordillera carbonate cover (Martina et al., 2005; Martina and Astini, 2009). The association of the sheared granite and the marble is consistent with a passive-margin transgression similar to that documented for the characteristic succession in the Precordillera (Astini et al., 1995). The structural position of the basement rocks at Rio Bonete suggests a location along the original margin of the Precordillera at the Alabama-Oklahoma transform fault (Fig. 1). Twenty zircons from the mylonitic granite yielded a weighted mean age (U/Pb laser ablation–inductively coupled plasma–mass spectrometry [LA-ICP-MS]) of 1118 ± 17 Ma (Martina et al., 2005).

More than 150 km south of the primary outcrops of the Precordillera platform rocks and basement, isolated exposures in the San Rafael block (Fig. 3) are surrounded by Cenozoic outwash from the Andes and include basement granite and Paleozoic sedimentary cover at Ponón Trehue (Bordonaro et al., 1996; Astini, 2002, 2003; Cingolani et al., 2003). The granite has a previously reported Rb-Sr isochron age of 1063 ± 106 Ma (Cingolani and Varela, 1999).

Basement rocks and metasedimentary carbonates exposed locally farther south in the Cerro San Jorge and Limay Mahuida area, the Las Matras block (Fig. 3), are evidently part of the Precordillera terrane (Astini et al., 1995; Ramos, 2004, 2010; Sato et al., 2004). The basement rocks have a Rb-Sr age of 1212 ± 47 Ma and a Sm-Nd age of 1178 ± 47 Ma (Sato et al., 1998, 1999, 2004). More recently, a U/Pb zircon age of 1244 ± 42 Ma has been reported (Sato et al., 2004).

In part of the Precordillera, Tertiary dacitic to andesitic plutons intrude the sedimentary succession, rising from the basement beneath the sedimentary thrust sheets. Basement xenoliths in Tertiary plutons at Ullún (Fig. 3) yield zircon ages of 1102 ± 6 Ma (U/Pb) and 1099 ± 3 Ma (Pb/Pb) for mafic gneisses and 1096 ± 50 Ma and 1118 ± 54 Ma for acidic gneisses (Kay et al., 1996). Additional U/Pb zircon data yielded a crystallization age of ca. 1165 Ma and a metamorphic overprint at ca. 1060 Ma (Rapela et al., 2010). Common Pb ratios indicate geochemical similarity of these rocks to the basement rocks of the Llano uplift on the Texas promontory of Laurentia (Kay et al., 1996).

In summary, previously reported U/Pb zircon ages of basement rocks from basement massifs around the Argentine Precordillera, as well as from xenoliths, are mostly within the range of 1244 ± 42 to 1025 ± 10 Ma. Some, or all, of the basement rocks north and east of the Precordillera sedimentary thrust belt (in the Sierras de Maz, Umango, and Pie de Palo, Fig. 3) may represent a separate terrane or terranes, but alternatively may be part of a greater Precordillera (Cuyania) terrane (e.g., Ramos et al., 1986; Ramos, 2004, 2010). Regardless of whether these massifs represent the basement of a singular Precordillera terrane or a constellation of separate small terranes along the leading edge of a composite Precordillera, the counterparts on the Laurentian conjugate margins are the Grenville and Llano provinces, which have similar ages, as well as a history of multiple events. The basement massifs south of the Precordillera have cover stratigraphy correlative with the Precordillera sedimentary succession and, thus, represent the Precordillera basement, as do the xenoliths from Tertiary plutons. Omitting the ages of the debatable basement massifs, the range of securely Precordillera basement ages is 1244 ± 42 to 1099 ± 3 Ma, within the age range of the Grenville orogeny of eastern Laurentia.

New Data

In this article, we report previously unpublished isotopic ages for basement rocks at Ponón Trehue in the San Rafael block south of the primary outcrops of the Precordillera and for basement clasts in a conglomerate olistolith in slope deposits of the western Precordillera (Fig. 3). Analytical results are listed in Table 1.

Basement granite at Ponón Trehue underlies a structurally and stratigraphically complex succession of basal conglomerate and overlying carbonate (Astini et al., 1995; Bordonaro et al., 1996; Cingolani and Varela, 1999; Cingolani et al., 2003). We report new U/Pb zircon ages for two granite samples (Fig. 7): one, BT-128-2, has a weighted mean $^{207}Pb/^{206}Pb$ age of 1205 ± 1 Ma, and the other, BT-130-3, has a weighted mean $^{207}Pb/^{206}Pb$ age of 1204 ± 2 Ma. The dates record the age of crystallization of the granites, and both are similar to previously reported ages of basement in other parts of the Precordillera (Fig. 3). These new data provide further evidence that the age of Precordillera basement is coeval with the Grenville orogeny of eastern Laurentia.

Unique "samples" of Precordillera basement were collected as clasts from a conglomerate olistolith in the Middle Ordovician Los Sombreros Formation along the Quebrada de Los Ratones, a tributary of the Rio San Juan, in the western Precordillera (Fig. 3). The Los Sombreros Formation, a deep-water and mud-dominated succession, records deposition on the continental slope and rise west of the Precordillera carbonate platform (Astini et al., 1995; Thomas and Astini, 2003). The western shelf edge of the Precordillera carbonate platform, now concealed beneath Andean thrust sheets, evidently marks the western rifted margin of Precordillera continental crust. The Los Sombreros muddy slope facies contains olistoliths of rocks from the platform, slope, and basement (Astini et al., 1995; Keller, 1999). The olistoliths include (1) Middle Cambrian to Lower Ordovician platform-carbonate rocks, Lower to Middle Cambrian limestone-shale strata, and Ordovician shales, which represent parts of the exposed stratigraphy of the Precordillera platform; (2) Middle Cambrian deep-water carbonates, which define the minimum age of the western Precordillera slope; (3) lithic-clast conglomerate, quartz-pebble conglomerate, arkosic sandstone, and red beds, interpreted to represent the basal part of the platform succession and older synrift deposits (Astini and Thomas, 1999); and (4) basement granites, indicating that the source of the olistoliths cut down through the entire cover succession. The composition and position of the conglomerate olistoliths in the muddy slope deposits suggest slope-collapse faults and/or submarine canyons that fragmented the outer edge of the carbonate platform along with the underlying synrift deposits and basement (Fig. 8). Ultimately, the conglomerate olistolith within a muddy turbidite succession (Los Sombreros Formation) on the western slope of the Precordillera was imbricated by Andean thrusting and exposed by erosion on the present surface (Thomas and Astini, 2003).

In exposures of the Los Sombreros Formation along the Quebrada de Los Ratones, one large (several meters across) olistolith of polymictic conglomerate contains rounded clasts, ~25 cm in diameter, of granodiorite, granitic gneiss, and granodioritic gneiss in a coarse sandstone matrix (Fig. 9). Some of the rocks are highly sheared and recrystallized, but a primary igneous texture is largely intact. The lithology of the clasts suggests derivation from a variably deformed mesozonal pluton. Some alteration evidently occurred during surface weathering and transportation. The lithology and texture of the conglomerate suggest synrift deposition

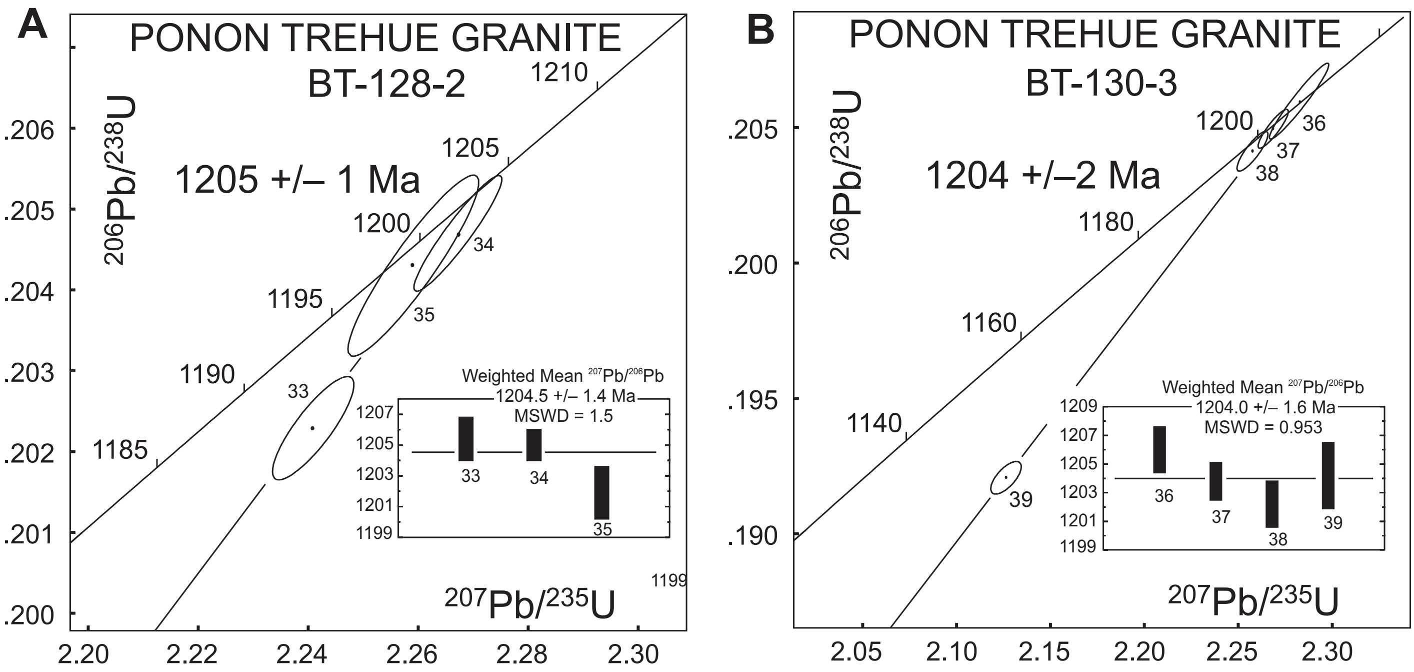

Figure 7. Concordia plots of U/Pb zircon analyses of granite from Ponón Trehue in the San Rafael block south of the principal outcrops of the Precordillera sedimentary thrust belt. MSWD—mean square of weighted deviates.

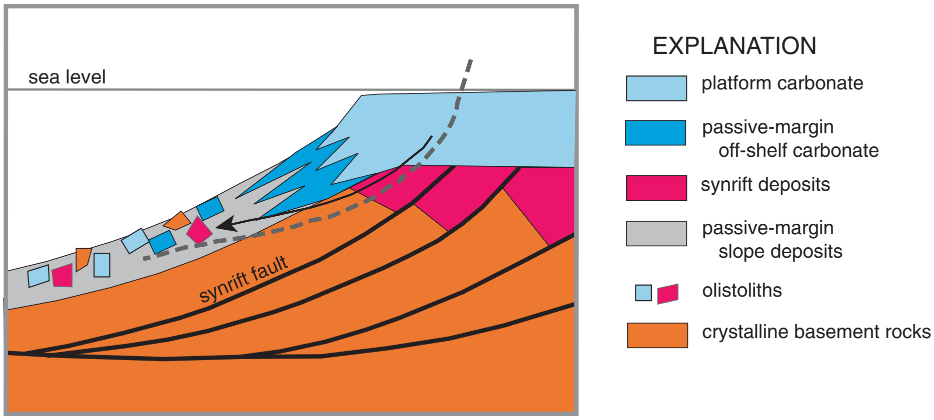

Figure 8. Schematic conceptual cross section of the mechanism of emplacement and the source of olistoliths in the Ordovician Los Sombreros Formation in the western siliciclastic facies of the Precordillera. The olistoliths are contained within dark-colored mudstones of the deeper slope facies and include fragments of the platform carbonate, deeper water off-shelf carbonate of the passive margin, synrift red beds and conglomerates, and crystalline basement rocks. The depositional setting of synrift sediment indicates a lower-plate rifted margin (Thomas and Astini, 1999). The olistoliths are interpreted to have been supplied to the outer slope as a result of submarine-canyon erosion and/or slope-collapse faults along the passive margin; the dashed line shows the depth of the interpreted submarine canyon(s) and/or slope-collapse fault(s). A similar setting, but along a transform margin, is appropriate for the boulders in the Blakely Sandstone in the Ouachita thrust belt in southern Laurentia (Thomas, 2010, 2011).

in alluvial fans along fault scarps in an extensional graben system on rifted continental crust, consistent with synrift graben-fill deposits that underlie the passive-margin platform-carbonate succession of the Precordillera (Thomas and Astini, 1999, 2003). The provenance of the large clasts in the conglomerate must have been the local continental basement exposed on proximal fault scarps.

We report two new U/Pb zircon ages of 1370 ± 2 Ma and 1367 ± 5 Ma (Fig. 10) for separate basement clasts within the single conglomerate olistolith. Both ages are best interpreted as the date of emplacement and crystallization of the plutonic protoliths. Both ages are significantly older than the oldest known basement rocks in the Precordillera, although they are near the ages of an early event (1330–1260 Ma) in the Sierra de Maz (Rapela et al., 2010). Moreover, the ages of these unusual samples show that this part of the Precordillera contains basement rocks that are similar in age to the Southern Granite-Rhyolite province of southern Laurentia but different from most of the Grenville province near the Laurentian margin (Figs. 1 and 2) (e.g., Van Schmus et al., 1993; Mosher, 1998), and also similar to the 1366 ± 3 Ma gneiss in the Llano uplift (Reese et al., 2000). Although the Granite-Rhyolite province generally lacks granodioritic phases, basement rocks exposed in the Arbuckle uplift include the Burch Granodiorite and granodioritic gneisses in the Blue River Gneiss (Lidiak and Denison, 1999); drill penetrations of subsurface basement rocks in the Arbuckle region include local diorites (Ham et al., 1964). The granodiorites in the Arbuckle uplift are near the rifted conjugate margin of Laurentia and the Precordillera, suggesting lithologic and temporal counterparts for the granodiorite and granodioritic gneiss clasts in the olistolith along the rifted margin of the Precordillera, and further supporting the interpretation of rifting of the Precordillera from the Ouachita embayment of Laurentia.

SYNRIFT ROCKS AND AGE OF RIFTING

The age of rifting and opening of the Ouachita segment of the Iapetus Ocean between the Precordillera terrane and Laurentia has been based primarily on the synrift and passive-margin successions on the conjugate margins of the Texas promontory of Laurentia and the Precordillera (Figs. 1 and 2) (e.g., Thomas and Astini, 1999). A bimodal igneous suite along the Southern Oklahoma fault system (Ham et al., 1964; Gilbert, 1983; Hogan and Gilbert, 1998) provides geochronological constraints for the transform-parallel synrift intracratonic fault system.

Figure 9. Photograph of conglomerate olistolith in the Los Sombreros Formation along the Quebrada de Los Ratones tributary of the Rio San Juan. Samples for U/Pb analyses were taken from the rounded clasts of granodioritic-granitic basement rocks seen here in the conglomerate. The block of conglomerate is surrounded by dark-colored mudstones, which constitute the slope in the background.

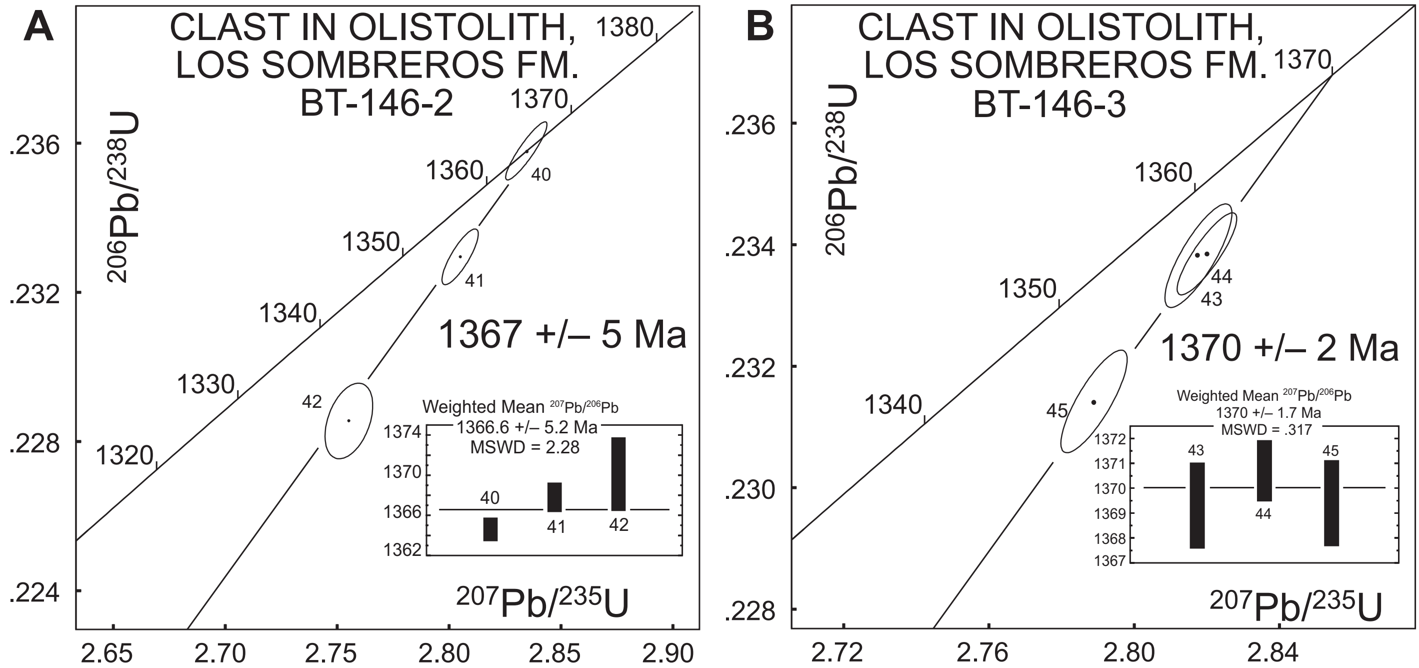

Figure 10. Concordia plots of U/Pb zircon analyses of basement clasts from the conglomerate olistolith in the Los Sombreros Formation along the Quebrada de Los Ratones in the western siliciclastic facies in the Precordillera. MSWD—mean square of weighted deviates.

Sedimentary Record of Rift History

The passive-margin succession exposed around the Llano uplift and drilled in the subsurface on the Texas promontory of Laurentia has a basal sandstone of latest Middle Cambrian age, and an overlying carbonate succession generally less than 1000 m thick (summary in Thomas and Astini, 1999). The basal sandstone overlaps a paleotopographic surface with more than 200 m of relief on the Precambrian basement (Barnes et al., 1972). The age of thermal subsidence and passive-margin transgression onto the Laurentian margin along the Ouachita rift is consistent with rifting during the Early Cambrian (Thomas and Astini, 1999).

Paleozoic rocks in the Precordillera are in the hanging walls of Andean thrust faults, and the contact with basement rocks is not exposed. The oldest Paleozoic rocks exposed in the Precordillera are a synrift succession of red beds, evaporites, and carbonates of the Lower Cambrian Cerro Totora Formation (Astini and Vaccari, 1996). The Cerro Totora Formation has an olenellid and *Salterella* fauna, indicating an Early Cambrian age (Astini et al., 1995, 2004), and strontium isotopes from Cerro Totora evaporites are consistent with that age (Thomas et al., 2001). The Cerro Totora Formation is similar lithologically, stratigraphically, paleontologically, and isotopically to the coeval Rome Formation in a basement graben on the Alabama promontory of Laurentia, indicating a similar tectonic framework of sedimentation on opposite sides of the Alabama-Oklahoma transform (Fig. 1) (Thomas et al., 2001). A passive-margin carbonate succession above the Cerro Totora clastic-evaporite facies ranges in age from Early Cambrian through Early Ordovician (Astini et al., 1995). The Precordillera carbonate succession is much thicker than the partly coeval carbonate-shelf succession on the Texas promontory of Laurentia, where no synrift deposits are preserved; the base of the carbonate succession in the Precordillera is older than that on the Texas promontory (Thomas and Astini, 1999). Stratigraphic comparisons show that passive-margin subsidence and transgression began earlier on the Precordillera than on the Texas promontory, and that the magnitude of subsidence was greater on the Precordillera. This seeming paradox is explained by observations of complementary asymmetry of post-rift thermal subsidence on the conjugate rift margins of a simple-shear low-angle-detachment rift system (Thomas and Astini, 1999, fig. 5). The lack of synrift sedimentary accumulations, as well as the paleotopographic relief beneath the basal transgressive sandstone, indicates an upper-plate margin in Texas; whereas the preserved synrift graben-fill sediment, as well as earlier thermal subsidence and post-rift transgression, indicates a lower-plate margin on the Precordillera (Thomas and Astini, 1999). The ages of synrift rocks in the Precordillera and the diachronous ages of initial passive-margin deposition are consistent with rifting of the Precordillera from Laurentia in the Early Cambrian, the age of the Cerro Totora synrift red beds and evaporites (Astini et al., 1995; Thomas and Astini, 1996, 1999). Initial rifting in the earliest Cambrian led to opening of an Ouachita ocean floor and migration of the Precordillera microcontinent along the Alabama-Oklahoma transform fault (Thomas, 1991; Thomas and Astini, 1996). Movement along the transform fault is consistent with episodic reactivation of the basement faults of the Mississippi Valley and Birmingham grabens until the Ouachita mid-ocean ridge migrated past the corner of Laurentian crust on the Alabama promontory (Thomas, 1991). The end of active extension on the basement faults marks the time of separation of the Precordillera microplate from Laurentia in the Late Cambrian.

Synrift Igneous Rocks along the Southern Oklahoma Fault System

In the context of Iapetan rifting, the Southern Oklahoma fault system is parallel with transform faults and extends >500 km northwesterly into the Laurentian continental crust from the Ouachita embayment in the rifted margin (Fig. 1); however, the Southern Oklahoma fault system intersects the Ouachita rift margin

~150 km south of the corner of the embayment at the intersection of the rift with the Alabama-Oklahoma transform fault (summaries in Thomas, 2010, 2011). The Southern Oklahoma fault system encompasses a suite of bimodal plutonic and volcanic rocks, including gabbro, basalt, granite, and rhyolite (Hogan and Gilbert, 1998), the composition of which indicates deep sources in the upper mantle. High-amplitude, short-wavelength gravity and magnetic anomalies indicate dense mafic rocks with steep boundaries in the shallow continental crust (Keller and Stephenson, 2007). Identity of specific synrift basement faults is obscured by the large volume of igneous rocks, as well as by overprint of late Paleozoic large-magnitude basement faults (Denison, *in* Johnson et al., 1988). Faults within volcanic rocks, as well as angular discordances between different units within the layered complex, suggest rift-bounding faults with >1 km of vertical separation and cumulative extension across the system of 17–21 km (McConnell and Gilbert, 1986). The geometry and composition of the igneous rocks indicate crust-penetrating near-vertical fractures as magma conduits, consistent with a leaky transform fault.

The entire bimodal suite of igneous rocks is extensively exposed in the Wichita Mountains, where the oldest exposed unit is layered gabbro and anorthositic rocks of the Glen Mountains Layered Complex. Only the younger rhyolite is exposed in the Arbuckle Mountains. Diabase dikes cut all of the other igneous rocks and mark the end of igneous activity. Geochronologic analyses, using a variety of techniques, have documented ages that center at 540–530 Ma (Tilton et al., 1962; Ham et al., 1964; Bowring and Hoppe, 1982; Lambert and Unruh, 1986; Lambert et al., 1988; Wright et al., 1996; Hogan and Gilbert, 1998); the ages of the younger rhyolites are within error of the ages of the older gabbros, even though they are clearly separated by a time of uplift and erosion (Ham et al., 1964). For example, for the Mount Sheridan Gabbro, $^{40}Ar/^{39}Ar$ analyses of amphibole yielded ages of 535 ± 8 Ma and 533 ± 2 Ma, and of biotite an age of 533 ± 4 Ma; amphibole yielded an age of 539 ± 2 Ma for the Mount Scott Granite sheet (Hames et al., 1998). U/Pb zircon ages of ca. 534 Ma for rhyolite in the Wichita Mountains confirm the limited age range (Hanson et al., 2009). Taken together, the available ages indicate a short time span for emplacement of the entire igneous complex.

A transgressive passive-margin succession of basal sandstone and overlying shallow-marine carbonates overlaps the Early Cambrian igneous rocks, and the age of the base of the transgressive succession is middle Late Cambrian (Denison, *in* Johnson et al., 1988). Above the basal sandstone along the Southern Oklahoma fault system, the overlying carbonate succession is exceptionally thick, consistent with large-magnitude synrift thermal uplift followed by post-rift cooling and deep subsidence of the shallow igneous rocks (Thomas and Astini, 1999).

Rift History of the Eastern Precordillera and Western Gondwana

An A-type granite orthogneiss within the Pie de Palo Complex in the Sierra de Pie de Palo has a U/Pb zircon age of 774 ± 6 Ma and is interpreted to represent an early phase of Iapetan rifting (Baldo et al., 2006). By comparison, ages of synrift igneous rocks along the Blue Ridge rift in eastern Laurentia include older phases at 765–680 Ma (Tollo et al., 2004). The times of continental breakup and opening of Iapetus along the Blue Ridge rift are indicated by U/Pb ages of synrift igneous rocks at 572 ± 5 to 564 ± 9 Ma (Aleinikoff et al., 1995). The similarity of ages of synrift rocks suggests that the Blue Ridge rift may have extended southward across the eastern margin of the Precordillera terrane before it was rifted from the Ouachita embayment some 30 m.y. later (Fig. 2) (Thomas, 1991). This setting places the basement rocks of the Sierra de Pie de Palo as the basement of the leading part of the Precordillera.

East of the alignment of basement massifs (Sierras de Maz, Umango, and Pie de Palo), the Ordovician Famatina volcanic arc marks the suture of the accreted Precordillera (Cuyania) terrane with Gondwana (e.g., Astini et al., 1995; Thomas and Astini, 2003; Ramos, 2004). Famatina is a continental-margin arc on the western margin of Gondwana, beneath which the Precordillera was subducted (Astini and Dávila, 2004). The rocks of the western part of Gondwana, in the vicinity of Famatina, record a tectonic history quite distinct from those of Mesoproterozoic mobile belts west of Famatina, as well as of the Grenville province of eastern Laurentia. A comprehensive interpretation of the setting of Famatina on the western margin of Gondwana yields the following: 700–640 Ma, Brasiliano orogeny imprinted on Mesoproterozoic basement; 640–600 Ma, rifting and opening of the Puncoviscana basin, contemporaneous with opening of Iapetus; 550–520 Ma, Pampean orogeny, including deformation of Puncoviscana sedimentary rocks; and 500–460 Ma, Famatina subduction of the Precordillera terrane and initiation of the Ocloyic orogeny (Collo et al., 2009). This succession of events, in contrast to the rift and passive-margin history of eastern Laurentia, further suggests that the Precordillera terrane had been separated from western Gondwana, beginning with early rifting and opening of Iapetus no later than approximately 600 Ma. The Mesoproterozoic basement of the Precordillera, as well as the Sierras de Maz, Umango, and Pie de Palo (whether or not the latter elements remained part of the Precordillera terrane), indicates a history similar to that of the Grenville-Llano province of eastern Laurentia, including multiple accretionary events in the time span of approximately 1250–1000 Ma, as well as incorporation of some older accreted terranes.

New Data from Synrift Igneous Rocks along the Southern Oklahoma Fault System

We present two new U/Pb zircon ages for the Colbert Rhyolite, a synrift volcanic unit in the Arbuckle Mountains (Fig. 2). Our results were previously reported in an abstract (Thomas et al., 2000), and the data are fully documented here (Fig. 11; Table 1). Two samples of fine-grained quartz-phyric rhyolite yielded a small amount of short-prismatic, equant zircon. Two small fractions of zircon from one sample, BT-98-107 (rhyolite dike in Tishomingo Granite), yielded one concordant and one discordant analysis with a weighted mean $^{207}Pb/^{206}Pb$ age of 536 ± 5 Ma (Fig. 11). We interpret this date to be the crystallization age of the rhyolite. Three small fractions of zircon from another rhyolite sample, BT-98-112B (hypabyssal rhyolite intrusion), yielded two concordant analyses and one discordant analysis. The three analyses have a weighted mean $^{207}Pb/^{206}Pb$ age of 539 ± 5 Ma (Fig. 11), which we also interpret as the crystallization age of the rhyolite. The U/Pb zircon ages overlap at 95% confidence limits, and both are similar to previously reported ages for other components of the Southern Oklahoma igneous suite (Fig. 2). Thus, we consider the age of the synrift volcanism in this part of the Arbuckle Mountains to be well established. Combining all of the recent data, an age range of 539 to 530 Ma spans the synrift igneous rocks along the Southern Oklahoma fault system and is consistent with the Early Cambrian age of rifting of the Precordillera from Laurentia as indicated by the stratigraphically documented synrift and post-rift subsidence history.

CONCLUSIONS

A growing body of geochronological data has documented a succession of accretionary events that together constitute what has come to be called the Grenville orogeny. Similar multicomponent metamorphic-plutonic events of Mesoproterozoic age are recognized in both western Gondwana-Amazonia and eastern Laurentia. Events associated with the Sunsas belt along

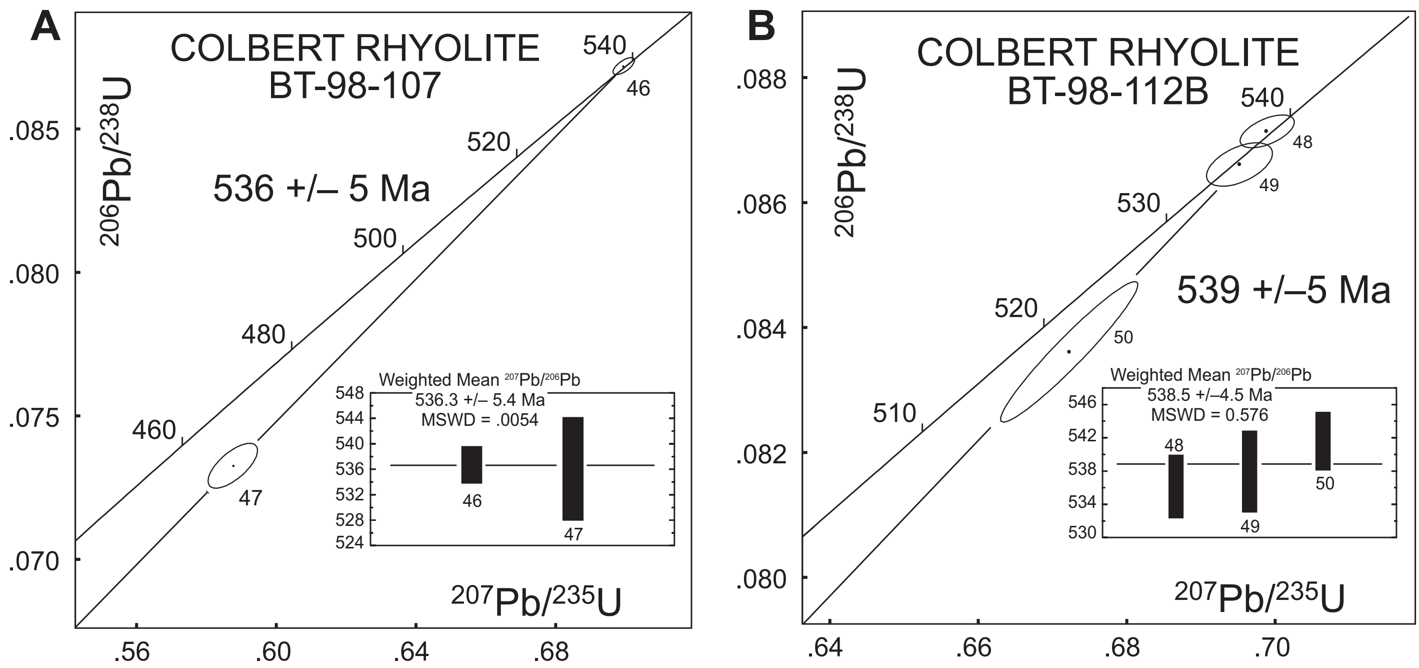

Figure 11. Concordia plots of U/Pb zircon analyses of the synrift Colbert Rhyolite in the Arbuckle Mountains along the Southern Oklahoma fault system. MSWD—mean square of weighted deviates.

southwestern Amazonia are paralleled by events in Arequipa-Antofalla, Sierra de Umango, Sierra de Maz, and Sierra de Pie de Palo. Together, these events span the time of 1250–1000 Ma. Similarly, along eastern Laurentia, successive components of the Grenville orogen span a range of 1250–1000 Ma. New data from the San Rafael block at Ponón Trehue in the Precordillera yield ages of 1205 ± 1 Ma and 1204 ± 2 Ma, which are within the age range of other Mesoproterozoic events. In contrast, ages of granodioritic-granitic basement clasts in a conglomerate olistolith in the northern western Precordillera are 1370 ± 2 Ma and 1367 ± 5 Ma, which are distinctly older than other basement rocks of the Precordillera. These samples indicate the inclusion in the Precordillera microplate of rocks older than the Grenville orogeny as defined in Laurentia. Although data are limited for the subsurface in eastern Laurentia, mapping the Grenville front (the western boundary of the Grenville orogen) suggests that the rift and transform outline of the Ouachita embayment of the Iapetan margin truncated the Grenville front, leaving older rocks of the Southern Granite-Rhyolite province at the Laurentian Iapetan margin in the corner of the embayment. New data from the Arbuckle and St. Francois Mountains confirm ages of 1364 ± 2 to 1317 ± 2 Ma for the Southern Granite-Rhyolite province, in contrast to ages of 1466 ± 3 to 1462 ± 1 Ma for the Eastern Granite-Rhyolite province. The palinspastic location of the Precordillera in the Ouachita embayment is consistent with rocks of the Southern Granite-Rhyolite province along the rifted Laurentian margin as temporal and lithologic counterparts of the part of the Precordillera terrane that includes anomalously old basement rocks.

The age of rifting of the Precordillera from Laurentia has been documented by the approximately 520 Ma age of Early Cambrian synrift sedimentary rocks (red beds and evaporites) in the Precordillera, the approximately 510 Ma age of the transition from synrift to post-rift passive-margin carbonates in late Early to early Middle Cambrian in the Precordillera, and complementary asymmetry of upper-plate subsidence on the Texas promontory with respect to lower-plate subsidence on the Precordillera. Synrift igneous rocks along the transform-parallel intracratonic Southern Oklahoma fault system have ages of 539 to 530 Ma, consistent with synrift magmatism and volcanism in the early stage of rifting along the Ouachita rift and Alabama-Oklahoma transform at the boundaries of the Precordillera microplate in the Ouachita embayment of Laurentia. New data from the Arbuckle Mountains in the eastern part of the Southern Oklahoma fault system yield ages of 539 ± 5 Ma and 536 ± 5 Ma, confirming the age of synrift volcanism.

The range of predominantly Mesoproterozoic ages (1250–1000 Ma) between the Sunsas orogen along the southwest margin of Amazonia and the front of the Grenville orogen in eastern Laurentia suggests a protracted process of terrane accretion and mobilization during the assembly of Rodinia. A similarly protracted process of supercontinent breakup and opening of Iapetus began with initial rifting and synrift magmatism at approximately 780 Ma, culminated in opening of Iapetus at approximately 565 Ma, and concluded with late-stage rifting of microcontinents such as the Precordillera until approximately 530 Ma. After the beginning of Cambrian time, as biostratigraphically dated (541 Ma), much of the Laurentian margin of Iapetus remained as a passive margin, from which microcontinents were shed until approximately 530 Ma. Meanwhile, a complex interplay of microplates extended through a diachronous succession of extension and contraction of Brasiliano, Puncoviscana, and Pampean elements along the Amazonian (Gondwanan) margin of Iapetus prior to accretion of the Laurentian Precordillera terrane by subduction beneath western Gondwana and magmatism of the Famatina continental-margin arc during the Ocloyic orogeny in the Ordovician.

APPENDIX: SAMPLES, ANALYTICAL METHODS, AND DATA TABULATION

Our samples include rocks from the St. Francois Mountains of Missouri and the Arbuckle Mountains of Oklahoma inboard from the Ouachita embayment of southern Laurentia, and from outcrops of basement rocks at Ponón Trehue and from basement clasts in an olistolith at Quebrada de Los Ratones in the Argentine Precordillera (Table 1). The samples from the St. Francois Mountains include three ash-flow tuffs from the well-known and previously undated section of volcanic strata at Johnson's Shut-Ins State Park, three granitoid igneous rocks (Graniteville Granite, Munger Granite Porphyry, and a granodiorite gneiss xenolith at Hawn State Park), and a microgabbro of the "Skrainka diabase" suite (Devil's Tollgate Gabbro). The samples from the Arbuckle Mountains include basement granite (Tishomingo Granite) and synrift rhyolite (Colbert Rhyolite). From the Argentine Precordillera, the Ponón Trehue Granite is part of the basement of the San Rafael block, and the clasts are from a conglomerate olistolith in the western slope deposits in the Ordovician Los Sombreros Formation. All whole-rock samples ranged in mass from 0.5 to 10 kg, and zircon and baddeleyite concentrates were obtained by standard techniques of crushing, Wilfley table concentration, and separation by heavy liquid and magnetic susceptibility methods. Following concentration of zircon, and in one sample baddeleyite, individual grains or small fractions of these minerals were picked, abraded, and cleaned, as is standard treatment for isotope dilution analysis. Table 1 lists the age for each sample and provides clarifying remarks.

All samples were analyzed by isotope-dilution thermal ionization mass spectrometry (ID-TIMS) in 1999 using the procedures outlined by Krogh (1973, 1982) with slight modifications described by Tucker et al. (2001). Our mass spectrometry procedures were as follows. Lead fractions smaller than 1 ng and all uranium fractions were analyzed in a VG Sector 54 mass spectrometer using a single-collector procedure with a Daly-type photomultiplier detector operating in pulse-counting mode. Daly bias and nonlinearity were periodically monitored with NIST (National Institute of Standards and Technology) and CBNM (Central Bureau for Nuclear Measurements) isotopic reference materials, and correction factors for Daly gain were used in data reduction. Mass dependent fractionation of Pb and U was monitored regularly since 1994, and a discrimination factor for Pb (0.094 ± 0.04 percent amu^{-1}; 2σ) and U (0.111 ± 0.04 percent amu^{-1}; 2σ) was applied to the measured ratios. Lead fractions larger than 1 ng were analyzed using a two-step, quasi-static procedure with a collector assembly of three Faraday cups and the Daly photomultiplier detector. The ^{204}Pb was measured in the Daly channel only, whereas the ^{205}Pb was measured in the H1 Faraday channel at position 1 and in the Daly channel at field position 2. Other lead isotopes were measured in Faraday channels H1 to H3. Isotope ratios involving ^{205}Pb, ^{206}Pb, ^{207}Pb, and ^{208}Pb were calculated using a static multicollector algorithm. This procedure allowed for internal gain calibration of the Daly channel relative to the H1 Faraday channel in each scan and eliminated biases related to Daly gain and ion beam instability.

Total-procedure blanks over the period of analysis averaged between 2 pg for Pb and 0.5 pg for U; total common-Pb contents for each analysis are reported in Table 1. Common-Pb corrections were made by first correcting the measured ratio for mass-dependent fractionation and introduced spike, and then subtracting Pb equal in amount and composition to the laboratory blank. Any remaining ^{204}Pb is assumed to represent a model lead composition given by Stacey and Kramers (1975) at the estimated age of the rock. For all of our samples, the uncertainty in the amount and composition of common-Pb represents an insignificant contribution to the uncertainty of the isotopic ages (Table 1). Error propagation is similar to that described by Ludwig (2001, 2003), and analytical reproducibility of the mineral fractions confirms that the parameters used in data reduction and the errors have been evaluated correctly.

Because of the slight discordance of some analyses, and the apparent absence of inherited zircon or ancient Pb-loss in any sample, our cited ages are based on the average ^{207}Pb/^{206}Pb age weighted according to the inverse variance of the individual analyses (Ludwig, 2001, 2003). The validity of this approach is confirmed by the reproducibility of the ^{207}Pb/^{206}Pb ages, which is portrayed graphically in Figures 4–7 and 10–11 and quantified by the mean square of the weighted deviates (MSWD). For all samples, the MSWD is less than 2.28, indicating that errors assigned to individual ^{207}Pb/^{206}Pb ages (commonly less than ±2 m.y.) may be somewhat overestimated. Age uncertainties are quoted (Table 1) and shown in concordia diagrams (Figs. 4–7 and 10–11) at 95% confidence limits.

ACKNOWLEDGMENTS

Parts of this research were supported by a grant from the U.S. National Science Foundation (EAR-9706735) to Thomas and a grant from the National Geographic Society (6090-97) to Thomas and Astini. This research was initiated while Thomas was on sabbatical leave from the University of Kentucky and Astini held a Fulbright Research Award, supporting our work together as visitors at the Geological Survey of Alabama. Astini acknowledges research support from Consejo Nacional de Investigaciones Cientificas y Técnicas (112-200801-03265) and from Agencia Nacional de Promoción Científica y Tecnológica (07-33630) (Argentina). We acknowledge constructive comments during the preparation of this article from Rich Harrison, Sharon Mosher, Ed Osborne, and Doug Rankin. Reviews of the manuscript for *Geosphere* by Richard Hanson and Bob Hatcher are gratefully acknowledged. We especially thank Bill Dickinson for the invitation to prepare this paper for the special issue of *Geosphere*, as well as for his comments on the manuscript.

REFERENCES CITED

Aceñolaza, F.G., Miller, H., and Toselli, A.J., 2002, Proterozoic–early Paleozoic evolution in western South America—A discussion: Tectonophysics, v. 354, p. 121–137, doi:10.1016/S0040-1951(02)00295-0.

Aleinikoff, J.N., Zartman, R.E., Walter, M., Rankin, D.W., Lyttle, P.T., and Burton, W.C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, central and southern Appalachians: Evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428–454, doi:10.2475/ajs.295.4.428.

Arbenz, J.K., 1989, Ouachita thrust belt and Arkoma basin, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 621–634.

Arbenz, J.K., 2008, Structural framework of the Ouachita Mountains, *in* Suneson, N.H., ed., Stratigraphic and Structural Evolution of the Ouachita Mountains and Arkoma Basin, Southeastern Oklahoma and West-Central Arkansas: Applications to Petroleum Exploration: 2004 Field Symposium: Oklahoma Geological Survey Circular 112A, p. 1–40.

Astini, R.A., 1998, Stratigraphical evidence supporting the rifting, drifting and collision of the Laurentian Precordillera terrane of western Argentina, *in* Pankhurst, R.J., and Rapela, C.W., eds., The Proto-Andean Margin of Gondwana: Geological Society [London] Special Publication 142, p. 11–33.

Astini, R.A., 2002, Los conglomerados basales del Ordovícico de Ponón Trehue (Mendoza) y su significado en la historia sedimentaria del terreno exótico de Precordillera: Revista de la Asociación Geológica Argentina, v. 57, p. 19–34.

Astini, R.A., 2003, The Ordovician proto-Andean basins, *in* Benedetto, J.L., ed., Ordovician Fossils of Argentina: Córdoba, Argentina, Secretaría de Ciencia y Tecnología, Universidad Nacional de Córdoba, p. 1–74.

Astini, R.A., and Dávila, F.M., 2004, Ordovician back arc foreland and Ocloyic thrust belt development on the western Gondwana margin as a response to Precordillera terrane accretion: Tectonics, v. 23, TC4008, doi:10.1029/2003TC001620.

Astini, R.A., and Thomas, W.A., 1999, Origin and evolution of the Precordillera terrane of western Argentina: A drifted Laurentian orphan, *in* Ramos, V.A., and Keppie, J.D., eds., Laurentia-Gondwana Connections before Pangea: Geological Society of America Special Paper 336, p. 1–20.

Astini, R.A., and Vaccari, N.E., 1996, Sucesión evaporítica del Cámbrico Inferior de la Precordillera: Significado geológico: Revista de la Asociación Geológica Argentina, v. 51, p. 97–106.

Astini, R.A., Benedetto, J.L., and Vaccari, N.E., 1995, The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted, and collided terrane: A geodynamic model: Geological Society of America Bulletin, v. 107, p. 253–273, doi:10.1130/0016-7606(1995)107<0253:TEPEOT>2.3.CO;2.

Astini, R.A., Thomas, W.A., and Yochelson, E.L., 2004, *Salterella* in the Argentine Precordillera: An Early Cambrian palaeobiogeographic indicator of Laurentian affinity: Palaeogeography, Palaeoclimatology, Palaeoecology, v. 213, p. 125–132.

Baldo, E., Casquet, C., Pankhurst, R.J., Galindo, C., Rapela, C.W., Fanning, C.M., Dahlquist, J., and Murra, J., 2006, Neoproterozoic A-type magmatism in the Western Sierras Pampeanas (Argentina): Evidence for Rodinia break-up along a proto-Iapetus rift?: Terra Nova, v. 18, p. 388–394, doi:10.1111/j.1365-3121.2006.00703.x.

Barnes, M.A., Anthony, E.Y., Williams, I., and Asquith, G.B., 2002, Architecture of a 1.38–1.34 Ga granite-rhyolite complex as revealed by geochronology and isotopic and elemental geochemistry of subsurface samples from west Texas, USA: Precambrian Research, v. 119, p. 9–43, doi:10.1016/S0301-9268(02)00116-X.

Barnes, V.E., Bell, W.C., Clabaugh, S.E., Cloud, P.E., Jr., McGehee, R.V., Rodda, P.U., and Young, K., 1972, Geology of the Llano Region and Austin Area, Field Excursion: Texas Bureau of Economic Geology, University of Texas, Guidebook 13, 154 p.

Bartholomew, M.J., and Hatcher, R.D., Jr., 2010, The Grenville orogenic cycle of southern Laurentia: Unraveling sutures, rifts, and shear zones as potential piercing points for Amazonia: Journal of South American Earth Sciences, v. 29, p. 4–20, doi:10.1016/j.jsames.2009.08.007.

Bickford, M.E., and Lewis, R.D., 1979, U-Pb geochronology of exposed basement rocks in Oklahoma: Geological Society of America Bulletin, v. 90, p. 540–544, doi:10.1130/0016-7606(1979)90<540:UGOEBR>2.0.CO;2.

Bickford, M.E., and Mose, D.G., 1975, Geochronology of Precambrian Rocks in the St. Francois Mountains, Southeast Missouri: Geological Society of America Special Paper 165, 48 p.

Bordonaro, O., Keller, M., and Lehnert, O., 1996, El Ordovícico de Ponón Trehue en la Provincia de Mendoza (Argentina): Redefiniciones estratigráficas: 13th Congreso Geológico Argentino y 3rd Congreso de Exploración de Hidrocarburos, Actas 1, p. 541–550.

Bowring, S., 1984, U-Pb zircon ages of granitic boulders in the Ordovician Blakely Sandstone, Arkansas, and implications for their provenance, *in* Stone, C.G., and Haley, B.R., A Guidebook to the Geology of the Central and Southern Ouachita Mountains, Arkansas: Arkansas Geological Commission Guidebook 84–2, p. 123.

Bowring, S.A., and Hoppe, W.J., 1982, U/Pb zircon ages from Mount Sheridan Gabbro, Wichita Mountains, *in* Gilbert, M.C., and Donovan, R.N., eds., Geology of the Eastern Wichita Mountains Southwestern Oklahoma: Oklahoma Geological Survey Guidebook 21, p. 54–59.

Casquet, C., Baldo, E., Pankhurst, R.J., Rapela, C.W., Galindo, C., Fanning, C.M., and Saavedra, J., 2001, Involvement of the Argentine Precordillera terrane in the Famatina mobile belt: U-Pb SHRIMP and metamorphic evidence from the Sierra de Pie de Palo: Geology, v. 29, p. 703–706, doi:10.1130/0091-7613(2001)029<0703:IOTAPT>2.0.CO;2.

Casquet, C., Pankhurst, R.J., Fanning, C.M., Baldo, E., Galindo, C., Rapela, C.W., González-Casado, J.M., and Dahlquist, J.A., 2006, U-Pb SHRIMP zircon dating of Grenvillian metamorphism in Western Sierras Pampeanas (Argentina): Correlation with the Arequipa-Antofalla craton and constraints on the extent of the Precordillera terrane: Gondwana Research, v. 9, p. 524–529, doi:10.1016/j.gr.2005.12.004.

Casquet, C., Fanning, C.M., Galindo, C., Pankhurst, R.J., Rapela, C.W., and Torres, P., 2010, The Arequipa massif of Peru: New SHRIMP and isotope constraints on a Paleoproterozoic inlier in the Grenvillian orogen: Journal of South American Earth Sciences, v. 29, p. 128–142, doi:10.1016/j.jsames.2009.08.009.

Cawood, P.A., McCausland, P.J.A., and Dunning, G.R., 2001, Opening Iapetus: Constraints from the Laurentian margin in Newfoundland: Geological Society of America Bulletin, v. 113, p. 443–453, doi:10.1130/0016-7606(2001)113<0443:OICFTL>2.0.CO;2.

Chernicoff, C.J., Vujovich, G.I., and van Staal, C.R., 2009, Geophysical evidence for an extensive Pie de Palo Complex mafic-ultramafic belt, San Juan, Argentina: Journal of South American Earth Sciences, v. 28, p. 325–332, doi:10.1016/j.jsames.2009.04.014.

Cingolani, C.A., and Varela, R., 1999, The San Rafael block, Mendoza (Argentina): Rb-Sr isotopic age of basement rocks: 2nd South American Symposium on Isotope Geology, Actas, p. 23–26.

Cingolani, C.A., Manassero, M., and Abre, P., 2003, Composition, provenance, and tectonic setting of Ordovician siliciclastic rocks in the San Rafael block: Southern extension of the Precordillera crustal fragment, Argentina: Journal of South American Earth Sciences, v. 16, p. 91–106, doi:10.1016/S0895-9811(03)00021-X.

Collo, G., Astini, R.A., Cawood, P.A., Buchan, C., and Pimentel, M., 2009, U-Pb detrital zircon ages and Sm-Nd isotopic features in low-grade metasedimentary rocks of the Famatina belt: Implications for late Neoproterozoic–early Palaeozoic evolution of the proto-Andean margin of Gondwana: Journal of the Geological Society [London], v. 166, p. 303–319, doi:10.1144/0016-76492008-051.

Dalla Salda, L., Cingolani, C.A., and Varela, R., 1992a, Early Paleozoic orogenic belt of the Andes in southwestern South America: Result of Laurentia-Gondwana collision?: Geology, v. 20, p. 617–620, doi:10.1130/0091-7613(1992)020<1059:DTTACI>2.3.CO;2.

Dalla Salda, L.H., Dalziel, I.W.D., Cingolani, C.A., and Varela, R., 1992b, Did the Taconic Appalachians continue into southern South America?: Geology, v. 20, p. 1059–1062.

Dalziel, I.W.D., 1997, Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16–42, doi:10.1130/0016-7606(1997)109<0016:ONPGAT>2.3.CO;2.

Denison, R.E., 1973, Basement rocks in the Arbuckle Mountains, *in* Ham, W.E., Regional Geology of the Arbuckle Mountains, Oklahoma: Geological Society of America Annual Meeting 1973, Guidebook for Field Trip 5, and Oklahoma Geological Survey Special Publication 73–3, p. 43–49.

Denison, R.E., 1981, Basement Rocks in Northeastern Oklahoma: Oklahoma Geological Survey Circular 84, 84 p.

Escayola, M.P., van Staal, C.R., and Davis, W.J., 2011, The age and tectonic setting of the Puncoviscana Formation in northwestern Argentina: An accretionary complex related to Early Cambrian closure of the Puncoviscana Ocean and accretion of the Arequipa-Antofalla block: Journal of South American Earth Sciences, v. 32, p. 438–459, doi:10.1016/j.jsames.2011.04.013.

Finney, S.C., 2007, The parautochthonous Gondwanan origin of Cuyania (greater Precordillera) terrane of Argentina: A re-evaluation of evidence used to support an allochthonous Laurentian origin: Geologica Acta, v. 5, p. 127–158.

Gilbert, M.C., 1983, Timing and chemistry of igneous events associated with the Southern Oklahoma aulacogen: Tectonophysics, v. 94, p. 439–455, doi:10.1016/0040-1951(83)90028-8.

Ham, W.E., Denison, R.E., and Merritt, C.A., 1964, Basement Rocks and Structural Evolution of Southern Oklahoma: Oklahoma Geological Survey Bulletin 95, 302 p.

Hames, W.E., Hogan, J.P., and Gilbert, M.C., 1998, Revised granite-gabbro age relationships, Southern Oklahoma aulacogen U.S.A., *in* Hogan, J.P., and Gilbert, M.C., eds., Basement Tectonics 12: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 247–249.

Hanson, R.E., McCleery, D.A., Crowley, J.L., Bowring, S.A., Burkholder, B.K., Finegan, S.A., Philips, C.M., and Pollard, J.B., 2009, Large-scale Cambrian rhyolitic volcanism in southern Oklahoma related to opening of Iapetus: Geological Society of America Abstracts with Programs, v. 41, no. 2, p. 14.

Harrison, R.W., Lowell, G.R., and Unruh, D.M., 2000, Geology, geochemistry, and age of Mesoproterozoic igneous rocks in the Eminence–Van Buren area: A major structural outlier of the St. Francois terrane, south-central Missouri: Geological Society of America Abstracts with Programs, v. 32, no. 3, p. A-14.

Harrison, R.W., Orndorff, R.C., and Weary, D.J., 2002, Geology of the Stegall Mountain 7.5-Minute Quadrangle, Shannon and Carter Counties, South-Central Missouri: U.S. Geological Survey Geologic Investigations Series Map I-2767, scale 1:24,000, 1 sheet.

Hogan, J.P., and Gilbert, M.C., 1998, The Southern Oklahoma aulacogen: A Cambrian analog for Mid-Proterozoic AMCG (anorthosite-mangerite-charnockite-granite) complexes?, *in* Hogan, J.P., and Gilbert, M.C., eds., Basement Tectonics 12: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 39–78.

Jaffey, A.H., Flynn, K.F., Glendenin, L.E., Bentley, W.C., and Essling, A.M., 1971, Precision measurement of half-lives and specific activities of ^{235}U and ^{238}U: Nuclear Physics, v. 4, p. 1889–1906.

Johnson, K.S., Amsden, T.W., Denison, R.E., Dutton, S.P., Goldstein, A.G., Rascoe, B., Jr., Sutherland, P.K., and Thompson, D.M., 1988, Southern Midcontinent region, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 307–359.

Kay, S.M., Orrell, S., and Abbruzzi, J.M., 1996, Zircon and whole rock Nd-Pb isotopic evidence for a Grenville age and a Laurentian origin for the basement of the Precordilleran terrane in Argentina: The Journal of Geology, v. 104, p. 637–648, doi:10.1086/629859.

Keller, G.R., and Stephenson, R.A., 2007, The Southern Oklahoma and Dniepr-Donets aulacogens: A comparative analysis, *in* Hatcher, R.D., Jr., Carlson, M.P., McBride, J.H., and Martínez Catalán, J.R., eds., 4-D Framework of Continental Crust: Geological Society of America Memoir 200, p. 127–143.

Keller, M., 1999, Argentine Precordillera: Sedimentary and Plate Tectonic History of a Laurentian Crustal Fragment in South America: Geological Society of America Special Paper 341, 131 p.

Keller, M., Buggish, W., and Lehnert, O., 1998, The stratigraphical record of the Argentine Precordillera and its plate-tectonic background, *in* Pankhurst, R.J., and Rapela, C.W., eds., The Proto-Andean Margin of Gondwana: Geological Society [London] Special Publication 142, p. 35–56.

Kisvarsanyi, E.B., Hebrank, A.W., and Ryan, R.F., 1981, Guidebook to the Geology and Ore Deposits of the St. Francois Mountains, Missouri: Missouri Department of Natural Resources Report of Investigations 67, and Contribution to Precambrian Geology 9, 119 p.

Krogh, T.E., 1973, A low contamination method for the hydrothermal decomposition of zircon and extraction of U and Pb for isotopic age determinations: Geochimica et Cosmochimica Acta, v. 37, p. 485–494, doi:10.1016/0016-7037(73)90213-5.

Krogh, T.E., 1982, Improved accuracy of U-Pb zircon ages by the creation of more concordant systems using an air abrasion technique: Geochimica et Cosmochimica Acta, v. 46, p. 637–649, doi:10.1016/0016-7037(82)90165-X.

Lambert, D.D., and Unruh, D.M., 1986, Isotopic constraints on the age and source history of the Glen Mountains Layered Complex, Wichita Mountains, *in* Gilbert, M.C., ed., Petrology of the Cambrian Wichita Mountains Igneous Suite: Oklahoma Geological Survey Guidebook 23, p. 53–59.

Lambert, D.D., Unruh, D.M., and Gilbert, M.C., 1988, Rb-Sr and Sm-Nd isotopic study of the Glen Mountains layered complex: Initiation of rifting within the southern Oklahoma aulacogen: Geology, v. 16, p. 13–17, doi:10.1130/0091-7613(1988)016<0013:RSASNI>2.3.CO;2.

Lidiak, E.G., and Denison, R.E., 1999, Geology of the Blue River Gneiss, eastern Arbuckle Mountains, Oklahoma, *in* Sinha, A.K., ed., Basement Tectonics 13: Dordrecht, Netherlands, Kluwer Academic Publishers, p. 139–153.

Loewy, S.L., Connelly, J.N., and Dalziel, I.W.D., 2004, An orphaned basement block: The Arequipa-Antofalla basement of the central Andean margin of South America: Geological Society of America Bulletin, v. 116, p. 171–187, doi:10.1130/B25226.1.

Lowell, G.R., 1976, Petrography of Precambrian rocks in the Hawn State Park area, Ste. Genevieve County, Missouri, *in* Kisvarsanyi, E.B., ed., Studies in Precambrian Geology with a Guide to Selected Parts of the St. Francois Mountains, Missouri: Missouri Department of Natural Resources Report of Investigations 61, and Contribution to Precambrian Geology 6, p. 140–148.

Lowell, G.R., Harrison, R.W., Weary, D.J., Orndorff, R.C., Repetski, J.E., and Pierce, H.A., 2010, Rift-related volcanism and karst geohydrology of the southern Ozark dome, *in* Evans, K.R., and Aber, J.S., eds., Precambrian Rift Volcanoes to the Mississippian Shelf Margin: Geological Field Excursions in the Ozark Mountains: Geological Society of America Field Guide 17, p. 99–158.

Ludwig, K.R., 2001, Squid 1.02 User's Manual: Berkeley Geochronology Center Special Publication 2, 19 p.

Ludwig, K.R., 2003, Isoplot 3.00 User's Manual: A Geochronological Toolkit for Microsoft Excel: Berkeley Geochronology Center Special Publication 4, 70 p.

Martina, F., and Astini, R.A., 2009, Geología de la región Del Rio Bonete en el antepaís Andino (27°30′LS): Extremo norte del terreno de Precordillera: Revista de la Asociación Geológica Argentina, v. 64, p. 311–327.

Martina, F., Astini, R.A., Becker, T.P., and Thomas, W.A., 2005, Granitos grenvilianos milonitizadas en la faja de deformación de Jagüé, noroeste de La Rioja: 16th Congreso Geológico Argentino, Actas, v. 4, p. 591–594.

McConnell, D.A., and Gilbert, M.C., 1986, Calculations for Cambrian extension of the southern Oklahoma aulacogen, *in* Gilbert, M.C., ed., Petrology of the Cambrian Wichita Mountains Igneous Suite: Oklahoma Geological Survey Guidebook 23, p. 11–20.

McDonough, M.R., Ramos, V.A., Isachsen, C.E., Bowring, S.A., and Vujovich, G.I., 1993, Edades preliminares de circones del basemento de La Sierra de Pie de Palo, Sierras Pampeanas Occidentales de San Juan: Sus implicancias para el supercontinente Proterozoico de Rodinia: 12th Congreso Geológico Argentino y 2nd Congreso de Exploración de Hidrocarburos, Actas 3, p. 340–342.

McLelland, J., Daly, J.S., and McLelland, J.M., 1996, The Grenville orogenic cycle (ca. 1350–1000 Ma): An Adirondack perspective: Tectonophysics, v. 265, p. 1–28, doi:10.1016/S0040-1951(96)00144-8.

Mosher, S., 1998, Tectonic evolution of the southern Laurentian Grenville orogenic belt: Geological Society of America Bulletin, v. 110, p. 1357–1375, doi:10.1130/0016-7606(1998)110<1357:TEOTSL>2.3.CO;2.

Mosher, S., Levine, J.S.F., and Carlson, W.D., 2008, Mesoproterozoic plate tectonics: A collisional model for the Grenville-aged orogenic belt in the Llano uplift, central Texas: Geology, v. 36, p. 55–58, doi:10.1130/G24049A.1.

Mulcahy, S.R., Roeske, S.M., McClelland, W.C., Nomade, S., and Renne, P.R., 2007, Cambrian initiation of the Las Pirquitas thrust of the western Sierras Pampeanas, Argentina: Implications for the tectonic evolution of the proto-Andean margin of South America: Geology, v. 35, p. 443–446, doi:10.1130/G23436A.1.

Mulcahy, S.R., Roeske, S.M., McClelland, W.C., Jourdan, F., Iriondo, A., Renne, P.R., Vervoort, J.D., and Vujovich, G.I., 2011, Structural evolution of a composite middle- to lower-crustal section: The Sierra de Pie de Palo, northwest Argentina: Tectonics, v. 30, TC1005, doi:10.1029/2009TC002656.

Naipauer, M., McClelland, W.C., Vujovich, G.I., Cingolani, C.A., and Ellis, J.R., 2005, U/Pb and ^{207}Pb/^{206}Pb ages on detrital zircons from El Quemado Quartzite (Caucete Group), Sierra de Pie de Palo, San Juan Province: 16th Congreso Geológico Argentino, Actas, v. 1, p. 19–26.

Naipauer, M., Vujovich, G.I., Cingolani, C.A., and McClelland, W.C., 2010, Detrital zircon analysis from the Neoproterozoic–Cambrian sedimentary cover (Cuyania terrane), Sierra de Pie de Palo, Argentina: Evidence of a rift and passive margin system?: Journal of South American Earth Sciences, v. 29, p. 306–326, doi:10.1016/j.jsames.2009.10.001.

Pankhurst, R.J., Rapela, C.W., Saavedra, J., Baldo, E., Dahlquist, J., Pascua, I., and Fanning, C.M., 1998, The Famatinian magmatic arc in the central Sierras Pampeanas: An Early to Mid-Ordovician continental arc on the Gondwana margin, *in* Pankhurst, R.J., and Rapela, C.W., eds., The Proto-Andean Margin of Gondwana: Geological Society [London] Special Publication 142, p. 343–367.

Ramos, V.A., 2004, Cuyania, an exotic block to Gondwana: Historical success and present problems: Gondwana Research, v. 7, p. 1009–1026, doi:10.1016/S1342-937X(05)71081-9.

Ramos, V.A., 2010, The Grenville-age basement of the Andes: Journal of South American Earth Sciences, v. 29, p. 77–91, doi:10.1016/j.jsames.2009.09.004.

Ramos, V.A., Jordan, T.E., Allmendinger, R.W., Mpodozis, C., Kay, S.M., Cortés, J.M., and Palma, M., 1986, Paleozoic terranes of the central Argentine-Chilean Andes: Tectonics, v. 5, p. 855–880, doi:10.1029/TC005i006p00855.

Ramos, V.A., Dallmeyer, D., and Vujovich, G., 1998, Time constraints on the early Palaeozoic docking of the Precordillera, central Argentina, *in* Pankhurst, R.J., and Rapela, C.W., eds., The Proto-Andean Margin of Gondwana: Geological Society [London] Special Publication 142, p. 143–158.

Rankin, D.W., Drake, A.A., Jr., Glover, L., III, Goldsmith, R., Hall, L.M., Murray, D.P., Ratcliffe, N.M., Read, J.F., Secor, D.T., Jr., and Stanley, R.S., 1989, Pre-orogenic terranes, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 7–100.

Rankin, D.W., and 12 others, 1993, Proterozoic rocks east and southeast of the Grenville front, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 335–461.

Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Saavedra, J., and Galindo, C., 1998, Early evolution of the proto-Andean margin of South America: Geology, v. 26, p. 707–710, doi:10.1130/0091-7613(1998)026<0707:EEOTPA>2.3.CO;2.

Rapela, C.W., Pankhurst, R.J., Casquet, C., Baldo, E., Galindo, C., Fanning, C.M., and Dahlquist, J.M., 2010, The Western Sierras Pampeanas: Protracted Grenville-age history (1330–1030 Ma) of intra-oceanic arcs, subduction-accretion at continental edge and AMCG intraplate magmatism: Journal of South American Earth Sciences, v. 29, p. 105–127, doi:10.1016/j.jsames.2009.08.004.

Reed, J.C., Jr., compiler, 1993, Map of the Precambrian rocks of the conterminous United States and some adjacent parts of Canada, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, Plate 1, scale 1:5,000,000.

Reese, J.F., Mosher, S., Connelly, J., and Roback, R., 2000, Mesoproterozoic chronostratigraphy of the southeastern Llano uplift, central Texas: Geological Society of America Bulletin, v. 112, p. 278–291, doi:10.1130/0016-7606(2000)112<278:MCOTSL>2.0.CO;2.

Rohs, C.R., and Van Schmus, W.R., 2007, Isotopic connections between basement rocks exposed in the St. Francois Mountains and the Arbuckle Mountains, southern mid-continent, North America: International Journal of Earth Sciences (Geologische Rundschau), v. 96, p. 599–611, doi:10.1007/s00531-006-0123-5.

Sato, A.M., Tickyj, H., and Llambías, E.J., 1998, Rb-Sr Grenvillian age from the Las Matras Diorite, La Pampa province, Argentina: 10th Congreso Latinoamericano de Geología y 6th Congreso Nacional de Geología Económica, Actas, v. 2, p. 418.

Sato, A.M., Tickyj, H., Llambías, E.J., and Sato, K., 1999, Rb-Sr, Sm-Nd and K-Ar age constraints of the Grenvillian Las Matras pluton, central Argentina: 2nd South American Symposium on Isotope Geology, Actas, p. 122–126.

Sato, A.M., Tickyj, H., Llambías, E.J., Basei, M.A.S., and González, P.D., 2004, Las Matras block, central Argentina (37°S–67°W): The southernmost Cuyania terrane and its relationship with the Famatinian orogeny: Gondwana Research, v. 7, p. 1077–1087, doi:10.1016/S1342-937X(05)71085-6.

Stacey, J.S., and Kramers, J.D., 1975, Approximation of terrestrial lead isotope evolution by a two-stage model: Earth and Planetary Science Letters, v. 26, p. 207–221, doi:10.1016/0012-821X(75)90088-6.

Stone, C.G., and Haley, B.R., 1977, The occurrence and origin of the granite–meta-arkose erratics in the Ordovician Blakely Sandstone, Arkansas, *in* Stone, C.G., ed., Symposium on the Geology of the Ouachita Mountains: Little Rock, Arkansas Geological Commission, v. 1, p. 107–111.

Thomas, J.J., Shuster, R.D., and Bickford, M.E., 1984, A terrane of 1350- to 1400-m.y.-old silicic volcanic and plutonic rocks in the buried Proterozoic of the mid-continent and in the Wet Mountains, Colorado: Geological Society of America Bulletin, v. 95, p. 1150–1157, doi:10.1130/0016-7606(1984)95<1150:ATOTMS>2.0.CO;2.

Thomas, W.A., 1988, The Black Warrior basin, *in* Sloss, L.L., ed., Sedimentary Cover—North American Craton: U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. D-2, p. 471–492, Plate 8.

Thomas, W.A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415–431, doi:10.1130/0016-7606(1991)103<0415:TAORMO>2.3.CO;2.

Thomas, W.A., 2006, Tectonic inheritance at a continental margin: GSA Today, v. 16, no. 2, p. 4–11, doi:10.1130/1052-5173(2006)016[4:TIAACM]2.0.CO;2.

Thomas, W.A., 2010, Interactions between the southern Appalachian–Ouachita orogenic belt and basement faults in the orogenic footwall and foreland, *in* Tollo, R.P., Bartholomew, M.J., Hibbard, J.P., and Karabinos, P.M., eds., From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region: Geological Society of America Memoir 206, p. 897–916.

Thomas, W.A., 2011, The Iapetan rifted margin of southern Laurentia: Geosphere, v. 7, p. 97–120, doi:10.1130/GES00574.1.

Thomas, W.A., and Astini, R.A., 1996, The Argentine Precordillera: A traveler from the Ouachita embayment of North American Laurentia: Science, v. 273, p. 752–757, doi:10.1126/science.273.5276.752.

Thomas, W.A., and Astini, R.A., 1999, Simple-shear conjugate rift margins of the Argentine Precordillera and the Ouachita embayment of Laurentia: Geological Society of America Bulletin, v. 111, p. 1069–1079, doi:10.1130/0016-7606(1999)111<1069:SSCRMO>2.3.CO;2.

Thomas, W.A., and Astini, R.A., 2003, Ordovician accretion of the Argentine Precordillera terrane to Gondwana: A review: Journal of South American Earth Sciences, v. 16, p. 67–79, doi:10.1016/S0895-9811(03)00019-1.

Thomas, W.A., Viele, G.W., Arbenz, J.K., Nicholas, R.L., Denison, R.E., Muehlberger, W.R., and Tauvers, P.R., 1989, Tectonic map of the Ouachita orogen, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, Plate 9.

Thomas, W.A., Tucker, R.D., and Astini, R.A., 2000, Rifting of the Argentine Precordillera from southern Laurentia: Palinspastic restoration of basement provinces: Geological Society of America Abstracts with Programs, v. 32, no. 7, p. A-505.

Thomas, W.A., Astini, R.A., and Denison, R.E., 2001, Strontium isotopes, age, and tectonic setting of Cambrian salinas along the rift and transform margins of the Argentine Precordillera and southern Laurentia: The Journal of Geology, v. 109, p. 231–246, doi:10.1086/319241.

Tilton, G.R., Wetherill, G.W., and Davis, G.L., 1962, Mineral ages from the Wichita and Arbuckle Mountains, Oklahoma, and the St. Francois Mountains, Missouri: Journal of Geophysical Research, v. 67, p. 4011–4019, doi:10.1029/JZ067i010p04011.

Tollo, R.P., Aleinikoff, J.N., Bartholomew, M.J., and Rankin, D.W., 2004, Neoproterozoic A-type granitoids of the central and southern Appalachians: Intraplate magmatism associated with episodic rifting of the Rodinian supercontinent: Precambrian Research, v. 128, p. 3–38, doi:10.1016/j.precamres.2003.08.007.

Tucker, R.D., Osberg, P.H., and Berry, H.N., IV, 2001, The geology of a part of Acadia and the nature of the Acadian orogeny across central and eastern Maine: American Journal of Science, v. 301, p. 205–260, doi:10.2475/ajs.301.3.205.

Van Schmus, W.R., and 24 others, 1993, Transcontinental Proterozoic provinces, *in* Reed, J.C., Jr., Bickford, M.E., Houston, R.S., Link, P.K., Rankin, D.W., Sims, P.K., and Van Schmus, W.R., eds., Precambrian: Conterminous U.S.: Boulder, Colorado, Geological Society of America, The Geology of North America, v. C-2, p. 171–334.

Van Schmus, W.R., Bickford, M.E., and Turek, A., 1996, Proterozoic geology of the east-central Midcontinent basement, *in* van der Pluijm, B.A., and Catacosinos, P.A., eds., Basement and Basins of Eastern North America: Geological Society of America Special Paper 308, p. 7–32.

van Staal, C.R., Vujovich, G.I., Currie, K.L., and Naipauer, M., 2011, An Alpine-style Ordovician collision complex in the Sierra de Pie de Palo, Argentina: Record of subduction of Cuyania beneath the Famatina arc: Journal of Structural Geology, v. 33, p. 343–361, doi:10.1016/j.jsg.2010.10.011.

Varela, R., Sato, A.M., Basei, M.A.S., and Siga, O., Jr., 2003, Proterozoico medio y Paleozoico inferior de la sierra de Umango, antepaís andino (29°S), Argentina: Edades U-Pb y caracterizaciones isotópicas: Revista Geológica de Chile, v. 30, p. 265–284.

Viele, G.W., and Thomas, W.A., 1989, Tectonic synthesis of the Ouachita orogenic belt, *in* Hatcher, R.D., Jr., Thomas, W.A., and Viele, G.W., eds., The Appalachian-Ouachita Orogen in the United States: Boulder, Colorado, Geological Society of America, The Geology of North America, v. F-2, p. 695–728.

Vujovich, G.I., and Kay, S.M., 1998, A Laurentian? Grenville-age oceanic arc/back-arc terrane in the Sierra de Pie de Palo, Western Sierras Pampeanas, Argentina, *in* Pankhurst, R.J., and Rapela, C.W., eds., The Proto-Andean Margin of Gondwana: Geological Society [London] Special Publication 142, p. 159–179.

Vujovich, G.I., van Staal, C.R., and Davis, W., 2004, Age constraints on the tectonic evolution and provenance of the Pie de Palo Complex, Cuyania composite terrane, and the Famatinian orogeny in the Sierra de Pie de Palo, San Juan, Argentina: Gondwana Research, v. 7, p. 1041–1056, doi:10.1016/S1342-937X(05)71083-2.

Wright, J.E., Hogan, J.P., and Gilbert, M.C., 1996, The Southern Oklahoma aulacogen: Not just another B.L.I.P.: EOS (Transactions, American Geophysical Union), v. 77, no. 46, F845.