Int J Earth Sci (Geol Rundsch) (2007) 96:599–611
DOI 10.1007/s00531-006-0123-5

ORIGINAL PAPER

Isotopic connections between basement rocks exposed in the St. Francois Mountains and the Arbuckle Mountains, southern mid-continent, North America

C. Renee Rohs · W. R. Van Schmus

Received: 10 March 2006 / Accepted: 9 September 2006 / Published online: 25 October 2006

Abstract Two distinct crustal provinces have been identified in the southern mid-continent based on U–Pb crystallization ages. Both contain large volumes of undeformed granite and rhyolite, with minor amounts of metamorphic rock and mafic intrusions. The Eastern Granite-Rhyolite province is characterized by felsic rocks with crystallization ages of 1,470 ± 30 Ma and exposures are restricted to the St. Francois Mountains in southeastern Missouri. Similarly, the Southern Granite-Rhyolite (SGR) province is characterized by felsic units with ages of 1,370 ± 30 Ma with primary exposures in the eastern Arbuckle Mountains of southern Oklahoma. Within the SGR province three magmatic pulses can be identified starting at 1,400, 1,370, and 1,340 Ma. Although the crystallization ages are different, the Sm–Nd isotopic signatures are similar for the units exposed in these areas as well as the buried basement in between. Depleted mantle model ages for rocks within the Arbuckle Mountains range from 1,530 to 1,430 Ma with $\varepsilon_{Nd}(t)$ values of +3.2 to +4.1 while units of the St. Francois Mountains range from 1,550 to 1,430 Ma and +4.5 to +4.7. Comparison of Sm–Nd isotopic data also indicate similarities between the $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ ratios for the rock units in these areas suggesting a common source.

C. Renee Rohs (✉)
Northwest Missouri State University, 800 University Dr., Maryville, MO 64468, USA
e-mail: rrohs@nwmissouri.edu

W. R. Van Schmus
Department of Geology, University of Kansas, Lawrence, KS 66045-7613, USA

Keywords Precambrian · St. Francois Mountains · Arbuckle Mountains · Zircon dating · Sm–Nd

Introduction

Across the southern mid-continent region, two distinct granite-rhyolite provinces have been identified as forming during the early Mesoproterozoic. These provinces are the Eastern Granite-Rhyolite (EGR) province and the Southern Granite-Rhyolite (SGR) province, with crystallization ages of ~1,470 and 1,370 Ma, respectively (Bickford and Lewis 1979; Bickford et al. 1981; Thomas et al. 1984; Bickford and Van Schmus 1985; Van Schmus et al. 1987; Van Schmus et al. 1993a). These provinces along with other major crustal features of the mid-continent region are shown in Fig. 1.

The EGR province represents an extensive belt of relatively undeformed silicic magmatism and is represented by basement rocks exposed in the St. Francois Mountains of southeast Missouri (Lidiak et al. 1993). Basement rocks in the St. Francois Mountains consist of both volcanic and plutonic units and include ignimbritic rhyolite, trachy-andesite, and several types of granite. Minor amounts of metamorphic rock and mafic rock also occur within the St. Francois Mountains (Sylvester 1984; Walker et al. 2002). The EGR province continues into the subsurface (Kisvarsanyi 1981), underlying parts of at least ten states in the eastern mid-continent region (Lidiak et al. 1993). The EGR province represents a major pulse of continental growth during the Mesoproterozoic at ~1,470 Ma (Van Schmus et al. 1987, 1993b; Lidiak et al. 1993).

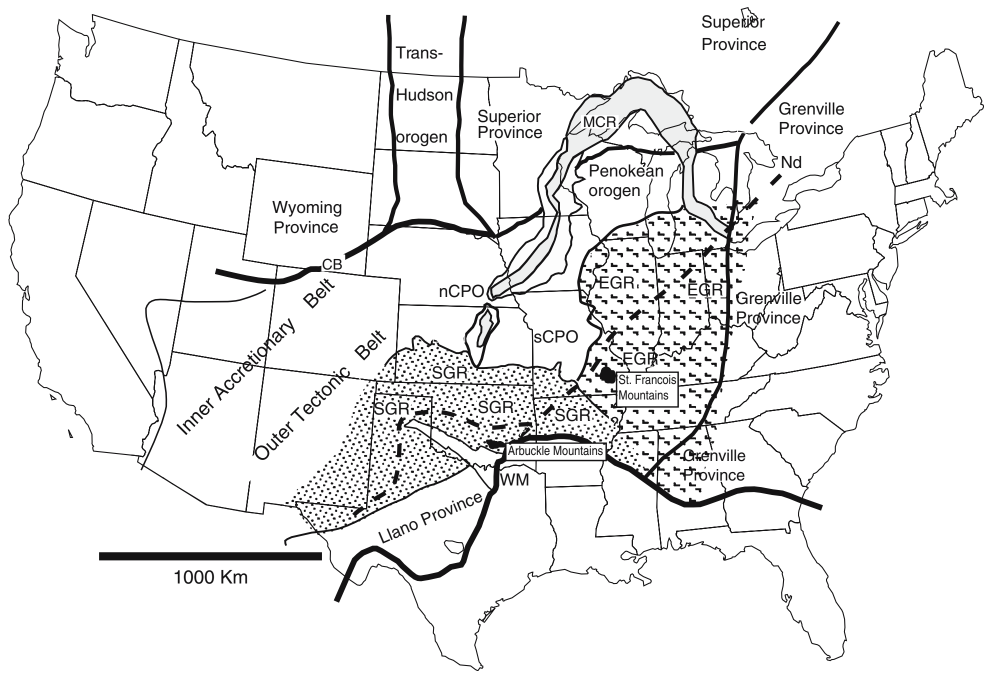

Fig. 1 Mid-continent region of North America showing crustal provinces as defined by crystallization ages. The *dashed* Nd *line* indicates the eastern limit of Paleoproterozoic crustal residence ages. Abbreviations include the following: Southern Granite-Rhyolite (*SGR*) province, Eastern Granite-Rhyolite (*EGR*) province, north Central Plains Orogen (*nCPO*), south Central Plains Orogen (*sCPO*), Mid-continent Rift (*MCR*), Wichita Mountains (*WM*) province, and craton boundary (*CB*) (modified from Van Schmus et al. 1996)

The ~100 millionyear younger SGR province is characterized by basement rocks exposed in the Eastern Arbuckle Mountains of southern Oklahoma. These rocks include granite, granodiorite, and granitic gneiss with crystallization ages of ~1,370 ± 30 Ma (Bickford and Lewis 1979; Thomas et al. 1984; Van Schmus et al. 1993b). Mafic rock units also occur in the Arbuckle Mountains as metamorphosed amphibolite dikes and unaltered diabase dikes (Lidiak and Denison 1999). The SGR province has been mapped in the subsurface in parts of Arkansas, Kansas, Missouri, New Mexico, Oklahoma, and Texas. Extensive studies of the Precambrian basement in the subsurface of the Texas Panhandle region have identified three separate magmatic episodes at ~1,380, ~1,360, and ~1,340 Ma (Barnes et al. 2002).

Crustal studies in the southern mid-continent region have focused on Sm–Nd isotopic analyses for depleted mantle model ages (T_{DM}) and original Nd composition $\varepsilon_{Nd}(t)$ values when crystallization age is known, to gain a better understanding of the tectonic history leading to the formation of the Proterozoic basement. This isotopic tool was employed by Nelson and DePaolo (1985) to determine the rapid production of continental crust between 1,700 and 1,900 Ma. Various studies throughout the mid-continent indicate that T_{DM} ages range from the Mesoproterozoic into the Late Paleoproterozoic, 1,300 to 2,000 Ma (Nelson and DePaolo 1985; Bennet and DePaolo 1987; Van Schmus et al. 1993b, 1996). The limit of Paleoproterozoic crust underlying the EGR and SGR provinces has been mapped using T_{DM} values >1,550 Ma (Van Schmus et al. 1996; Rohs 2001). These studies, along with ongoing work in the western United States, have provided some insight to the growth of the continent during the Proterozoic.

The purpose of this study is to examine, in detail, isotopic data of Precambrian rocks exposed in both the St. Francois Mountains and the Arbuckle Mountains to establish a relationship along the southern margin of the continent during the Mesoproterozoic that can be extended into the subsurface. Ages and field relationships in the St. Francois Mountains have previously been determined for many of the volcanic and plutonic units (cf. Lidiak et al. 1993). However, additional isotopic information from a few mafic intrusions provides insight to the character of the lower crust or lithospheric mantle. Detailed zircon ages in the Arbuckle Mountains are also critical in this study of the Precambrian basement to identify episodes of magmatic activity related to the SGR province and intrusions found in the St. Francois Mountains.

St. Francois Mountains

Precambrian rocks in the St. Francois Mountains record at least two major episodes of magmatic activity. Most of the basement rocks in the area are attributed to a magmatic episode that occurred at approximately 1,470 30 Ma (Bickford and Mose 1975; Van Schmus et al. 1996). These are shown as both volcanic and plutonic rocks in Fig. 2. Based on field relationships, widespread silicic volcanism occurred followed by caldera collapse and intrusion of ring plutons (Kisvarsanyi 1981). The ring plutons have ages similar to those of the surrounding volcanic units and are interpreted as part of the same magmatic event (Van Schmus et al. 1993b, 1996). A second magmatic event occurred ~100 millionyears later with the intrusion of the Munger and Graniteville granite plutons with ages of ~1,350 to 1,380 Ma (Thomas et al. 1984; Van Schmus et al. 1996). These younger plutons are also shown on Fig. 2. Chemical analyses of the high-silica rhyolite and granite suggest derivation from lower silica magmas that were altered through fractional crystallization (Bickford et al. 1981; Cullers et al. 1981).

Relatively minor mafic intrusions within the St. Francois Mountains have been grouped based on geochemical signatures (Sylvester 1984) into the Silvermines group and Skrainka group. Diabase dikes near Silver Mines have been geochemically linked with mafic volcanic material contained within the volcanic sequence exposed at Johnson's Shut-Ins (Sylvester 1984) and, therefore, estimated to be ~1,470 Ma in age. In contrast, mafic intrusions of the Skrainka group have been dated from 1,316 to 1,300 Ma based on U–Pb isotopic analysis of badelleyite (Rämö et al. 1994).

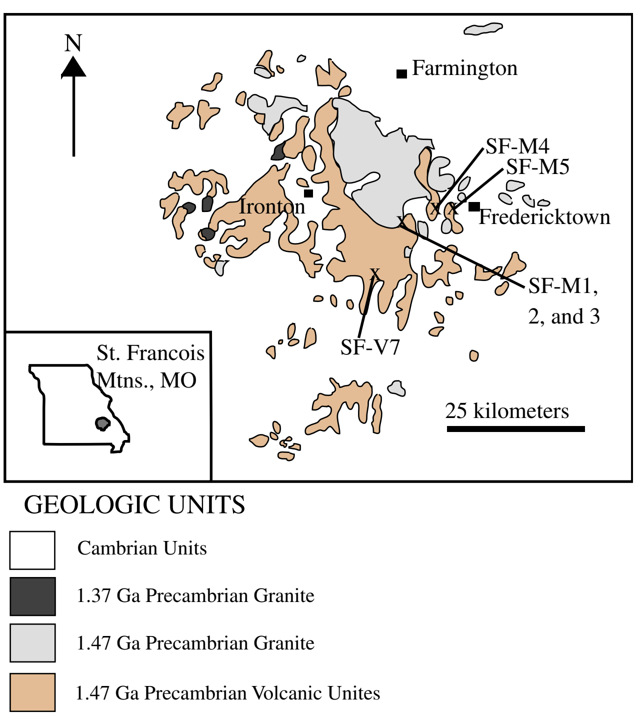

Fig. 2 Geologic map of the St. Francois Mountains with sample locations for this study (modified from Bickford and Mose 1975)

Arbuckle Mountains

Precambrian rocks in the eastern Arbuckle Mountains of Oklahoma are the single most extensive exposure of the SGR province. These granitic rocks are exposed in the core of the Belton-Tishomingo anticline and provide a window into the crust of the Mid-continent region (Denison 1973). Within the Arbuckle Mountains, four major crystalline basement units have been identified and mapped, namely the Blue River Gneiss, Burch Granodiorite, Troy Granite, and Tishomingo Granite (Lidiak and Denison 1999) as indicated in Fig. 3. Field relationships among these units indicate that the Tishomingo Granite is the youngest and crosscuts both the Troy Granite and Blue River Gneiss. The Troy Granite intrudes the Burch Granodiorite, but there is no exposed field relationship between the Burch Granodiorite and the Blue River Gneiss. Zircon U–Pb dating of these units by Bickford and Lewis (1979) gave the following ages: Blue River Gneiss 1,396 ± 40 Ma, Troy Granite 1,399 ± 95 Ma, and Tishomingo Granite 1,374 ± 15 Ma. Thomas and others (1984) later determined the age of the Burch Granodiorite as 1,397 ± 7 Ma. In each case, the crystallization age was determined using relatively large, multi-grain zircon fractions, and relatively large uncertainties limited interpretation of precise age relationships among these units. However, it is evident from the ages of the Burch Granodiorite and Tishomingo Granite, that there were at least two individual magmatic events that produced these units ~25 millionyear apart.

Nelson and DePaolo (1985) reported Sm/Nd depleted mantle model ages (T_{DM}) of 1.98 and 1.81 Ga for the Tishomingo Granite and Blue River Gneiss units, respectively. These ages are anomalously older than others reported for southern Oklahoma (e.g., Van Schmus et al. 1996). Although this raised the possibility of older crust being present here, our new data confirm that the original data of Nelson and DePaolo (1985) were inaccurate for unknown reasons.

Geochemical modeling of data from the Blue River Gneiss indicates two possible tectonic settings for the formation of this unit (Lidiak and Denison 1999). The first interpretation employs partial melting (25%) from the lower crust and depleted mantle wedge at an Andean-type continental margin. A second interpretation requires greater partial melting (30–35%) of basaltic andesite and silicic andesite crustal rocks to produce similar results for the Blue River Gneiss ranging from granodioiritic to granitic compositions. This second interpretation requires ponding of mafic magma in the lower crust in a noncollisional setting (Lidiak and Denison 1999).

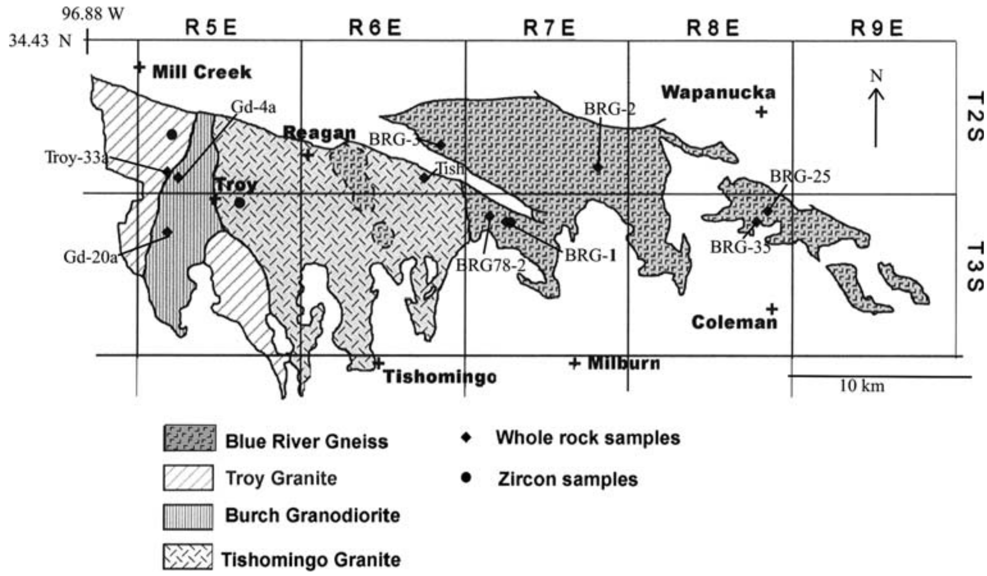

Fig. 3 Geologic map of the eastern Arbuckle Mountains with sample locations for this study (modified Denison 1973)

Most of the basement units within the SGR province have been interpreted as a thin (1–3 km) veneer of high-silica volcanic fields and associated epizonal granite plutons overlying older basement (Van Schmus et al. 1987). However, original emplacement levels of crystalline rocks in the Arbuckle Mountains were at mesozonal depths as indicated by crystalline textures such as large perthitic microcline phenocrysts and a lack of granophyric textures more common in epizonal plutons to the north (Bickford and Lewis 1979). In the Arbuckle Mountains mafic material occurs as relict dikes of amphibolite within the Blue River Gneiss (Lidiak and Denison 1999) and as undeformed diabase dikes across the area. Crystallization ages have not been determined for the minor mafic intrusions in this area.

Precambrian basement in the subsurface

Several drill holes in northern Arkansas, southern Kansas, southwestern Missouri, and across Oklahoma penetrate into basement of the SGR province. Rhyolite and minor dacite are the primary volcanic rocks found in the subsurface of northeastern Oklahoma and these often have preserved textures suggestive of pyroclastic origin (Denison 1981). Associated granitic plutons in these areas are generally granophyric to micrographic (epizonal), but coarser-grained granite plutons are also present in some locations. Mafic rocks occur as diabase dikes and sills but represent a small percentage, volumetrically, of the basement (Denison 1981). Subsurface samples throughout this area have yielded zircon ages between 1,400 and 1,340 Ma (Thomas et al. 1984; Van Schmus et al. 1996), which is within the range for the SGR province as a whole.

Van Schmus et al. (1993b, 1996) present a Nd model age boundary separating lower crust with late Paleoproterozoic ages of ~1,800 Ma to the north and west from Mesoproterozoic ages of ~1,500 Ma to the south and east. This boundary extends from southern Ontario, to the south and west into central Oklahoma as shown in Fig. 1. Our data from this study not only confirm the general north–south division into older versus younger primary crust, but also constrain its location much better.

Sampling and analytical procedures

Whole-rock samples were used for the Sm–Nd analyses in this study. Samples collected in the St. Francois Mountains included diabase, granite, and trachy-andesite. These samples were prepared and analyzed according to the procedures described in Van Schmus et al. (1996). Methods for dissolution and extraction of the rare earth elements are similar to those used by Patchett and Ruiz (1989). Isotopic ratios of $^{143}Nd/^{144}Nd$ and $^{147}Sm/^{144}Nd$ were determined and are presented in Table 2. Nd data were normalized using $^{146}Nd/^{144}Nd$ = 0.72190 and adjusted for instrumental bias using $^{143}Nd/^{144}Nd$ = 0.512638 for present day CHUR (chondritic uniform reservoir). The decay constant of 6.54×10^{-9} year^{-1} was used for the data reduction. The present-day epsilon value [εNd(0)] for the rock sample represents the present-day $^{143}Nd/^{144}Nd$ ratio and is calculated based the current composition of Nd in the bulk earth. The epsilon value at the time of crystallization [$\varepsilon_{Nd}(t)$] is the $^{143}Nd/^{144}Nd$ ratio at time " t" in the past and was calculated based the composition of Nd in the bulk earth at time " t". Crystallization ages were used to calculate $\varepsilon_{Nd}(t)$ where U–Pb analyses were available; a representative age of 1,370 Ma (SGR) or 1,470 Ma (EGR) was used for other samples. Pseudo isochrons were plotted to visualize the Sm/Nd relationships among suites of samples better. Apparent ages were calculated using ISOPLOT (Ludwig 1998).

Single-grain U–Pb zircon data are summarized from Rohs (2001). Zircon crystals were separated into magnetic fractions, picked for clarity, and air abraded. Individual crystals were then selected and dissolved in HF/HNO_3 and HCl solutions. A $^{205}Pb/^{235}U$ tracer was added to the solution prior to analysis at the University of Kansas Isotope Geochemistry Laboratory using a VG Sector thermal ionization mass spectrometer with ion-counting Daly multiplier for isotopic ratios. The radiometric ages reported here are based upon analysis of at least three single zircon magnetic fractions. For ^{238}U the decay constant of 0.155125×10^{-9} year^{-1} was used and for ^{235}U the value 0.98485×10^{-9} year^{-1} was used as the decay constant (Steiger and Jäger 1977). Nonradiogenic original Pb was corrected for zircon analyses using the two-stage Pb evolution model of Stacey and Kramers (1975). Regression of zircon data was completed using ISOPLOT (Ludwig 1998). If probabilities were better than 20% then Model 1 regressions were accepted; otherwise Model 2 regressions were used. Concordia intercept ages are recalculated to 2-sigma error limits (Van Schmus et al. 1996).

New U–Pb ages for the Arbuckle Mountains

Data from single-grain analyses of zircon are presented in Table 1 and plotted in Fig. 4. These data yield the following ages: Burch Granodiorite 1,390 ± 7 Ma, Blue River Gneiss 1,389 ± 10 Ma, Troy Granite 1,368 ± 3 Ma, and the Tishomingo Granite 1,363 ± 8 Ma (Rohs 2001). These ages are more precise but still within the error range of those previously published (Bickford and Lewis 1979; Thomas et al. 1984). The Burch Granodiorite and Blue River Gneiss are analytically indistinguishable at ~1,390 Ma, while the Troy Granite and Tishomingo Granite comprise a younger pair at ~1,365 Ma. These ages are consistent with relative age relationships seen in the field and support the idea of two separate magmatic events ~25 millionyear apart.

Sm–Nd isotopic links between the St. Francois and Arbuckle Mountains

Sm–Nd isotopic studies of basement samples from the St. Francois Mountains indicate T_{DM} ages similar to or slightly older than the crystallization ages (Van Schmus et al. 1993b, 1996). These represent some of the youngest T_{DM} ages within the EGR province with a general decrease in age to the south and east within the province. This part of the EGR province is interpreted as having lower crustal rocks with a primary age of ~1,500 Ma that may have formed by accretion along an active continental margin (Van Schmus et al. 1996). Previously published Sm–Nd isotopic data from this area are included in Table 2.

Depleted mantle model ages for basement units from the St. Francois Mountains selected in this study range from 1,550 to 1,430 Ma. There does not appear to be a distinct difference in the Sm–Nd isotopic signature between the felsic, intermediate, and mafic units. These values are similar to existing Sm–Nd data for basement units within the area including the Butler Hill Granite (Nelson and DePaolo 1985) as well as granite and gabbro from a drill hole in Ste. Genevieve County (Van Schmus et al. 1996). Because these rock units have crystallization ages that are very close to the T_{DM} ages, the resulting $\varepsilon_{Nd}(t)$ values for units with U–Pb ages of 1,470 ± 30 Ma are strongly positive ranging from +3.7 to +4.8. One granite sample from Ste. Genevieve County with a U–Pb crystallization age of 1,328 ± 4 Ma resulted in a lower $\varepsilon_{Nd}(t)$ value of +2.8 as expected with the 100millionyear younger age of emplacement. When plotting the Sm–Nd isotopic ratios, these samples lie along a linear trend as shown in Fig. 5.

Within the Arbuckle Mountains, Sm–Nd isotopic data show similar characteristics. Depleted mantle model ages of the basement units exposed in this area range from 1,530 to 1,430 Ma (Rohs 2001). Previous studies in the Arbuckle Domain gave distinctly different depleted mantle model ages, as determined by Sm–Nd isotopic analysis, than others within the SGR province. Initial work by Nelson and DePaolo (1985) resulted in crustal residence ages of 1,810 and 1,980 Ma for rocks exposed in the Arbuckle Mountains. None of the data summarized in this study support these older model ages. Given the more precise crystallization ages discussed previously, $\varepsilon_{Nd}(t)$ values were positive ranging from +3.2 to +4.1 and distinct differences were not

Table 1 U–Pb data for zircon fractions from units of the eastern Arbuckle Mountains

Sample fraction	Size (mg)	U (ppm)	Pb (ppm)	Radiogenic ratios (isoplot data)						Age (Ma)		Age (Ma)		Age (Ma)	
				$^{206}Pb/^{204}Pb$ (observed)	$^{207}Pb^{a}/^{235}U$	± 2σ (pct)	$^{206}Pb^{a}/^{238}U$	± 2σ (pct)	Correl. Coeff (rho)	$^{206}Pb^{a}/^{238}U$	± 2σ	$^{207}Pb^{a}/^{235}U$	± 2σ	$^{207}Pb^{a}/^{206}Pb^{a}$	± 2σ
Blue River Gneiss															
NM (– 1)	0.006	438	108	1,088	2.740	0.93	0.2254	0.91	0.988	1,310	12	1,339	12	1,387	2.8
M (– 1)a	0.006	258	67	611	2.874	1.36	0.2368	1.35	0.990	1,370	18	1,375	19	1,383	3.7
M (– 1)b	0.006	58	20	112	2.928	3.49	0.2398	3.40	0.978	1,386	47	1,389	48	1,394	14.0
M (0)	0.010	447	104	1,229	2.557	0.71	0.2110	0.70	0.986	1,234	9	1,289	9	1,380	2.3
M (1)	0.006	596	131	607	2.370	0.86	0.1956	0.85	0.982	1,152	10	1,234	11	1,379	3.1
Regression U.I. 1,389 ± 10 Ma (2-sigma); L.I. 82 ± 140 Ma (2-sigma), model-2, MSWD = 2.6, P = 0.0503															
Burch Granodiorite															
NM (– 1)	0.008	461	117	1,211	2.820	0.67	0.2321	0.66	0.976	1,345	9	1,361	9	1,385	2.8
M (– 1)	0.004	547	186	155	2.770	1.43	0.2283	1.32	0.932	1,326	17	1,348	19	1,383	10.0
M (0)	0.011	558	144	3,442	2.858	0.61	0.2351	0.60	0.985	1,361	8	1,371	8	1,387	2.0
Regression U.I. 1,390 ± 7 Ma (2-sigma); L.I. 198 ± 330 Ma (2-sigma), model-1, MSWD = 0.0071, P = 0.93															
Troy Granite															
M (– 1)a	0.011	304	79	1,170	2.729	0.63	0.2269	0.63	0.986	1,318	8	1,336	8	1,365	2.1
M (– 1)b	0.008	293	55	116	1.328	11.90	0.1095	11.80	0.993	670	79	858	102	1,382	27.0
M (0)a	0.008	333	84	1,288	2.647	0.77	0.2197	0.76	0.992	1,280	10	1,314	10	1,369	1.9
M (0)b	0.012	971	302	336	2.774	0.59	0.2303	0.57	0.977	1,336	8	1,349	8	1,369	2.4
M (1)a	0.015	73	19	502	2.740	1.46	0.2270	1.44	0.991	1,319	19	1,339	20	1,373	3.8
M (1)c	0.024	107	27	1,637	2.764	0.50	0.2297	0.49	0.985	1,333	7	1,346	7	1,367	1.7
Regression U.I. 1,368 ± 3 (2-sigma); L.I. – 21 ± 23 Ma (2-sigma), model-2, MSWD = 3.1, P = 0.015															
Tishomingo Granite															
Single-grain analyses															
NM (– 1)	0.004	62	12	148	2.110	6.99	0.1763	6.89	0.991	1,047	72	1,152	81	1,356	18.0
M (– 1)	0.007	55	19	107	2.491	3.68	0.2072	3.55	0.971	1,214	43	1,269	47	1,365	17.0
M (1)a	0.006	33	10	116	2.769	6.38	0.2313	6.28	0.988	1,342	84	1,347	86	1,357	19.0
Multiple-grain analyses															
M(– 1)m	0.024	49	12	593	2.569	0.72	0.2135	0.70	0.976	1,247	9	1,292	9	1,367	3.0
M(0)m	0.016	68	18	597	2.738	0.79	0.2273	0.78	0.985	1,320	10	1,339	11	1,369	2.6
M(1)m	0.013	45	11	473	2.549	1.13	0.2130	1.09	0.968	1,245	14	1,286	15	1,356	5.4
M(2)m	0.029	53	15	531	2.740	0.79	0.2284	0.76	0.967	1,326	10	1,339	11	1,361	3.9
Regression U.I. 1,363 ± 8 Ma (2-sigma); L.I. 23 ± 100 Ma (2-sigma), model-2, MSWD = 5.1, P = 0.000															

[a] corrected for non-radiogenic lead

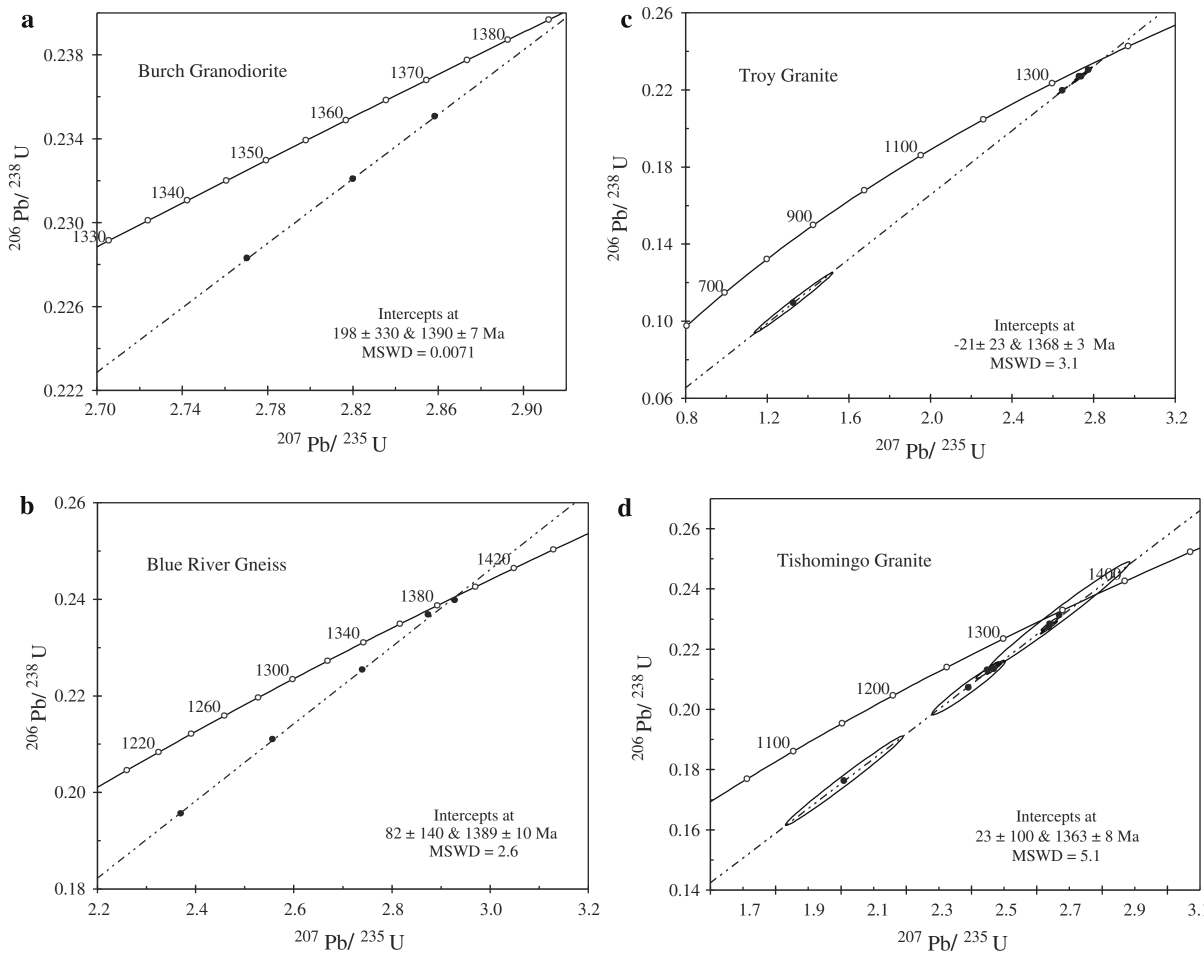

Fig. 4 Concordia diagrams for U–Pb data provided in Table 1. **a** Zircon data from the Burch Granodiorite. **b** Zircon data from the Blue River Gneiss. **c** Zircon data from the Troy Granite. **d** Zircon data from the Tishomingo Granite

Table 2 Sm-Nd isotopic data from the midcontinent region

Sample name	Rock type	Latitude	Longitude	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(0)$	Age[a] (Ma)	$\varepsilon_{Nd}(t)$	$T_{(DM)}$	Ref
Samples from the St. Francois Mountains										
SFM1	Diabase	37.55	90.44	0.14805	0.512373	– 5.2	*1,470*	4.01	1.54	0
SFM2	Diabase	37.56	90.44	0.11846	0.512110	– 10.3	*1,470*	4.47	1.48	0
SFM4	Diabase	37.56	90.35	0.13972	0.512292	– 6.7	*1,470*	4.01	1.53	0
SFM5	Diabase	37.56	90.37	0.16612	0.512591	– 0.9	*1,470*	4.86	1.43	0
Silver mines	Granite	37.54	90.45	0.12339	0.512135	– 9.8	1,484	4.02	1.52	0, 4
SFV7	Trachyte	37.46	90.80	0.12017	0.512087	– 10.8	*1,470*	3.69	1.55	0
MOFR-9	Granite	38.30	90.82	0.13520	0.512256	– 7.5	1,493	4.1	1.52	2, 2
MOSCh-5	Rhyolite	38.61	90.73	0.11480	0.512058	– 11.3	1,472	4.1	1.52	2, 2
MOSG-1A	Gabbro	37.74	90.24	0.1292	0.512212	– 8.3	*1,500*	4.4	1.50	2
MOSG-1B	Granite	37.74	90.24	0.1109	0.512047	– 11.5	*1,500*	4.7	1.47	2
MOSG-3	Granite	38.03	90.45	0.1086	0.512014	– 12.2	1,328	2.8	1.49	2, 2
MOSG-HPGn	Gneiss	37.78	90.23	0.1205	0.512104	– 10.4	1,478	4.3	1.53	2, 2
Arbuckle Mountains and subsurface of surrounding counties										
BRG-1	Gneiss	34.32	96.60	0.1343	0.512185	– 8.8	1,389	2.2	1.64	1, 1
BRG-2	Gneiss-granodiorite	34.35	96.55	0.1377	0.512299	– 6.6	1,389	3.9	1.48	1, 1
BRG-3	Gneiss-granofels	34.28	96.63	0.0768	0.511749	– 17.3	1,389	4.0	1.43	1, 1
BRG-11	Granofels	34.32	96.60	0.0853	0.511834	– 15.7	1,389	4.1	1.43	1, 1
BRG-25	Gneiss-granodiorite	34.31	96.45	0.1118	0.512044	– 11.6	1,389	3.5	1.49	1, 1
BRG-35	Amphibolite	34.32	96.44	0.1248	0.512144	– 9.6	1,389	3.2	1.53	1, 1

Table 2 Continued

Sample name	Rock type	Latitude	Longitude	$^{147}Sm/^{144}Nd$	$^{143}Nd/^{144}Nd$	$\varepsilon_{Nd}(0)$	Age[a] (Ma)	$\varepsilon_{Nd}(t)$	$T_{(}DM)$	Ref
BRG-78-2	Amphibolite	34.33	96.63	0.0975	0.511936	– 13.7	1,389	3.9	1.45	1, 1
Gd-4a (Burch)	Granodiorite	34.35	96.80	0.1279	0.512211	– 8.3	1,390	3.8	1.47	1, 1
Gd-20a (Burch)	Granodiorite	34.31	96.81	0.1165	0.512115	– 10.2	1,390	3.9	1.45	1, 1
Troy-33a	Granite	34.35	96.81	0.1073	0.512013	– 12.2	1,368	3.5	1.47	1, 1
Tishomingo	Granite	34.34	96.65	0.1168	0.512089	– 10.7	1,363	3.3	1.49	1, 1
OKAT-1	Rhyolite	34.23	96.30	0.1031	0.511981	– 12.8	*1,370*	3.6	1.46	1
OKBR-2-29	Granite	34.11	96.11	0.0905	0.511853	– 15.3	*1,370*	3.3	1.47	1
OKJF-10	Granite	34.01	97.84	0.1162	0.512111	– 10.3	*1,370*	3.9	1.45	1
Subsurface samples from the SGR province in Arkansas, southern Kansas, and Oklahoma										
ARFU-001	Granite	36.30	91.69	0.1028	0.511954	– 13.4	1,347	2.9	1.50	2, 2
ARSP-001	Diorite	36.48	91.40	0.1279	0.511201	– 8.5	1,376	3.4	1.49	2, 2
OKHK-1	Rhyolite	35.12	94.93	0.0998	0.511910	– 14.2	*1,370*	2.8	1.51	2
OKMS-5	Microgranite	35.53	95.28	0.1142	0.512030	– 11.9	*1,370*	2.6	1.54	1
OKSQ-2	Rhyolite	35.41	94.58	0.1153	0.512046	– 11.6	*1,370*	2.8	1.54	2
Subsurface samples from the SGR province in Arkansas, southern Kansas, and Oklahoma cont.										
KSHG-2	Rhyolite	38.24	99.72	0.1187	0.511874	– 14.9	*1,370*	– 1.2	1.86	1
KSHS-8	Granite	37.48	101.0	0.0989	0.511794	– 16.5	1,354	0.9	1.64	1, 3
KSPR-8	Granite	37.52	98.99	0.1050	0.511822	– 15.9	*1,370*	0.2	1.70	1
KSPR-10	Granite	37.74	98.65	0.1112	0.511941	– 13.6	*1,370*	1.5	1.63	1
KSSU-9	Granite	37.39	97.66	0.1206	0.512052	– 11.4	*1,370*	1.9	1.61	1
OKAF-1	Granite	36.83	98.22	0.0659	0.511560	– 21.3	1,380	2.1	1.55	2, 2
OKCG-1	Andesite.tuff	36.87	95.20	0.1206	0.512033	– 11.8	*1,370*	1.6	1.65	2
OKCK-1	Granite	36.01	96.06	0.1198	0.512068	– 11.1	*1,370*	2.4	1.58	2
OKKY-1	Granite	36.91	97.08	0.1104	0.511934	– 13.7	*1,370*	1.4	1.63	2
OKMY-SG4c	Granite	36.40	95.07	0.1159	0.512029	– 11.9	1,370	2.3	1.58	2, 7
OKNW-2	Granite	36.62	95.46	0.1250	0.512079	– 10.9	*1,370*	1.7	1.65	2
OKOS-16	Rhyolite	36.40	96.60	0.1135	0.511947	– 13.5	*1,370*	1.1	1.66	1
OKOS-27	Rhyolite	36.61	96.47	0.1141	0.512020	– 12.1	*1,370*	2.5	1.56	2
OKOS-35	Rhyolite	36.18	96.08	0.1304	0.512150	– 9.5	1,371	2.1	1.63	2, 4
OKPW-1	Rhyolite	36.28	96.47	0.1098	0.511921	– 14.0	*1,370*	1.3	1.63	2
OKPW-7	Rhyolite	36.44	96.98	0.1200	0.512008	– 12.3	*1,370*	1.2	1.69	2
OKSM-2	Granite	35.26	96.65	0.1097	0.511931	– 13.8	*1,370*	1.5	1.62	1
OKTU-1	Rhyolite	36.15	96.07	0.1301	0.512141	– 9.7	*1,370*	2.0	1.63	1
OKWS-9	Granite	36.97	96.99	0.1177	0.511984	– 12.8	*1,370*	1.1	1.67	1
Subsurface samples from the EGR province and the sCPO										
IAJK-001	Granite	42.15	90.28	0.1028	0.511712	– 18.1	1,485	0.2	1.83	2, 6
ILHY-001	Granite	41.35	90.43	0.1235	0.512012	– 12.2	1,466	1.6	1.74	2, 6
INPO-001	Granite	41.62	87.12	0.1232	0.511983	– 12.8	1,446	1.1	1.78	2, 6
KSDG-003	Granite	39.02	95.48	0.0917	0.511669	– 19.4	1,339	– 1.8	1.78	2, 5
KSMI-004	Granite	38.48	94.90	0.1115	0.511815	– 15.2	1,361	– 1.6	1.9	2, 5
MOAU-02a	Aplite	39.25	91.74	0.0948	0.51174	– 17.5	*1,500*	1.7	1.67	2
MOAU-02b	Gabbro	39.25	91.74	0.1379	0.51216	– 9.3	*1,500*	1.8	1.77	2
MOFR-006	Granite	38.43	90.92	0.1215	0.51207	– 11.0	1,458	3.1	1.60	2, 2
MOOR-003	Gabbro	36.86	91.65	0.1518	0.51239	– 4.8	*1,500*	3.7	1.59	2
MOSCh-01b	Gabbro	38.88	90.89	0.1222	0.51203	– 12.0	*1,500*	2.1	1.69	2
MOSCh-01a	Gabbro	38.88	90.89	0.1128	0.51194	– 13.6	*1,500*	2.2	1.66	2
MOSCh-04	Rhyolite	38.65	90.77	0.1641	0.51252	– 2.3	*1,470*	3.8	1.60	2

Ref. 0 = this project, 1 = Rohs (2001, unpublished data), 2 = Van Schmus et al. (1996), 3 = Thomas et al. (1984), 4 = Bickford and Mose (1975) recalculated, 5 = Steeples and Bickford (1981), 6 = Hoppe et al. (1983), 7 = Bickford and Lewis (1979)

Calculations based on $^{146}Nd/^{144}Nd = 0.72190$, present $^{143}Nd/^{144}Nd = 0.512638$ for CHUR, and depleted mantle curve of Nelson and DePaolo (1981). All Nd data adjusted to $^{143}Nd/^{144}Nd = 0.511860$ for La Jolla Nd. Uncertainties in T_{DM} due to analytical errors for samples with normal crustal $^{147}Sm/^{144}Nd$ ratios (e.g., 0.11 ± 0.02) are typically ± 0.05Ga at 2σ uncertainty levels

[a] Zircon U/Pb ages ± 2σ; ages in italics estimated from regional geology or chosen for convenient reference to other data

observed in association with rock type. Sm–Nd isotopic ratios from units exposed in the Arbuckle Mountains are also plotted in Fig. 5.

Sm–Nd isotopic data from subsurface samples between these two major exposures fall into two groups. The first group, the northern subprovince

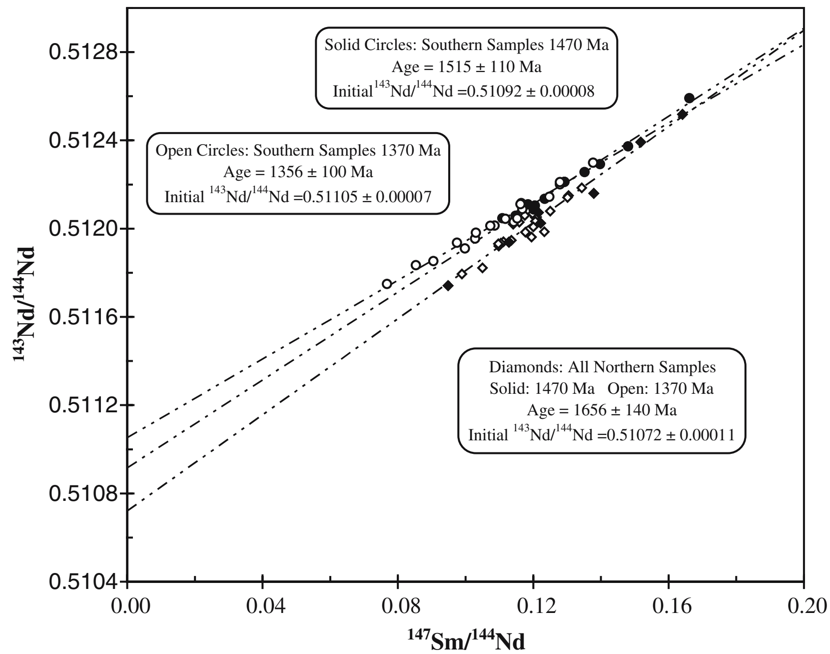

Fig. 5 Pseudoisochron diagram for Sm–Nd data provided in Table 2. Southern samples indicate locations south of the 1.55Ga Nd *line* as shown in Fig. 1. Northern samples are those to the north and west of the Nd line

of the SGR province, is concentrated in northern Oklahoma and southern Kansas. These basement units have T_{DM} ages of 1,860 to 1,550 Ma with an average of 1,640 Ma (Van Schmus et al. 1996; Rohs 2001). These older model ages are interpreted as an area of the continent that is underlain by Paleoproterozoic crust. Values of $\varepsilon_{Nd}(t)$ were calculated assuming a crystallization age of 1,370 Ma where the crystallization age was unknown since the samples were within the defined limits of the SGR province and are shown in Fig. 6.

The second group, the southern subprovince, exhibits T_{DM} ages and epsilon values that are essentially the same as those found in the Arbuckle Mountains. These samples were obtained from drill hole penetrations into Precambrian basement in Arkansas and the southern part of Oklahoma as indicated in Fig. 6. This southern subprovince resulted in T_{DM} ages of 1,450 to 1,540 Ma and values of $\varepsilon_{Nd}(t)$ from +2.6 to +3.9.

In the pseudo-isochron plot of Sm–Nd isotopic ratios, samples from the St. Francois Mountains and from the Arbuckle Mountains overlap and the trend lines relating samples from these areas converge at intermediate compositions. Mafic samples from these areas have the highest $^{147}Sm/^{144}Nd$ and $^{143}Nd/^{144}Nd$ while more felsic samples plot with lower ratios for

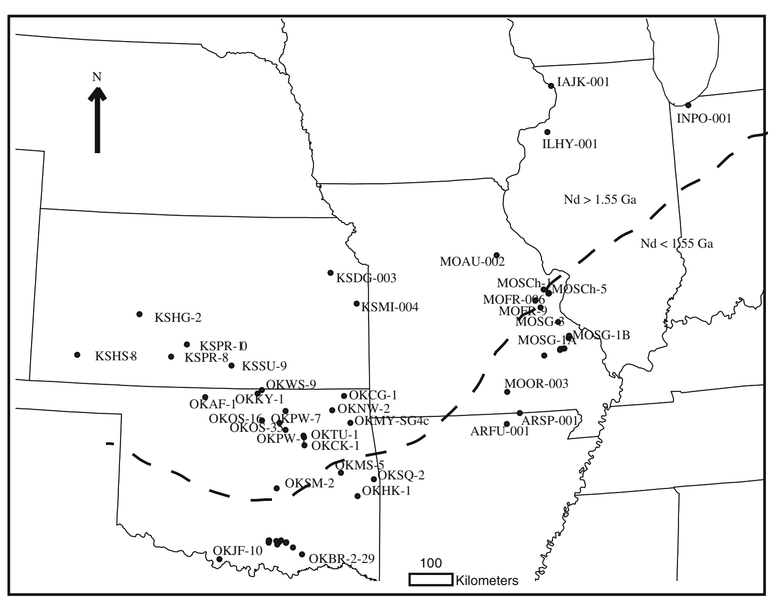

Fig. 6 Regional map within the mid-continent of North America with locations for subsurface samples. Sample names, location, and isotopic data are given in Table 2

both of these sets of isotopic ratios. Although the concentrations of both Sm and Nd generally increase with increasing SiO_2, Nd becomes slightly more fractionated so that Sm/Nd ratios decrease for more felsic plutonic igneous rocks (Faure and Mensing 2005). This explains the higher $^{147}Sm/^{144}Nd$ ratios in mafic samples from the St. Francois Mountains because of greater Sm/Nd elemental ratios. The higher $^{143}Nd/^{144}Nd$ ratios are also higher due to the production of ^{143}Nd through the decay of ^{147}Sm. This is generally true for the units exposed in the Arbuckle Mountains as well with the exception of one amphibolite dike in the Blue River Gneiss.

Sm–Nd data from St. Francois Mountains, Arbuckle Mountains, and the southern subprovince in the subsurface are distinctly different from basement units in the subsurface to the north and west. Sm–Nd ratios from other areas within the EGR and SGR provinces, interpreted as underlain by Paleoproterozoic crust (Van Schmus et al. 1993b, 1996; Rohs 2001) and have been plotted for comparison; they have lower $^{143}Nd/^{144}Nd$ reflecting derivation of the respective magmas from older continental crust.

Discussion

Within the Arbuckle Mountains, the Precambrian basement units fall into at least two separate periods of igneous activity. The first pulse occurred ~1,390 Ma with the formation of the Burch Granodiorite and Blue River Gneiss. Other units within the southern mid-continent that formed around this time included the Munger Granite Porphyry (Thomas et al. 1984) in the St. Francois Mountains and the first pulse of granitic magmatism within the Texas Panhandle region of the SGR province as quartz monzonite (Barnes et al. 2002). The second period of magmatism exhibited in the Arbuckle Mountains is the emplacement of granite plutons including the Troy and Tishomingo Granites between 1,370 and 1,360 Ma. Other igneous plutons occurring at approximately this same time include the main stage granite in the Texas Panhandle region (Barnes et al. 2002) and possibly the Graniteville Granite in the St. Francois Mountains (Van Schmus et al. 1996) although the error for the latter is fairly large at ± 25 Ma.

A third stage of magmatism is recorded in the subsurface of the southern mid-continent at ~1,340 to 1,330 Ma. Drill hole penetrations into the Precambrian basement have indicated granite plutons of this age range in northeast Kansas (Bickford et al. 1981), southeast Missouri and northern Arkansas (Van Schmus et al. 1996), and as late-stage quartz-syenite in the Texas Panhandle region (Barnes et al. 2002). Most of the crystallization ages have small error bars of ± 6 to 12 Ma.

Based on the crystallization ages of silicic magmatism across the southern mid-continent, it is evident that magmatism extended from about 1,400 to 1,340 Ma and may fall into three distinct events to form the Precambrian basement of the SGR province. These events are also represented in areas outside of the SGR province, specifically within the St. Francois Mountains area, NE Kansas–NW Missouri (Van Schmus et al. 1987) and the southern Wet Mountains of Colorado (Thomas et al. 1984).

However, the magmatic activity that took place ~100 Ma prior to the formation of the SGR province also provides clues to the temporal structure of the continental crust. Within the St. Francois Mountains, the crystallization ages, at ~1,480 Ma, and depleted mantle model ages, at ~1,500 Ma, are very close in comparison to other rocks within the granite and rhyolite provinces. Formation of this temporal relationship could be accomplished by rapid accretion of juvenile volcanic arcs along the continental margin (1,500 to 1,480 Ma) followed immediately (~1,470 Ma) by an active continental arc magmatism to form highly silicic igneous rocks (e.g., Van Schmus et al. 1996). This new crust then formed the substrate upon which a younger arc developed ~1,390–1,370 Ma, and plutons of this age were preserved as volcanic and plutonic outliers of the EGR province in the St. Francois Mountains and in NE Kansas–NW Missouri.

Depleted mantle model ages of plutonic units within the Arbuckle Mountains and the buried basement of the southern subprovince of the SGR province are similar to those within the St. Francois Mountains, and Sm–Nd data also indicate that the younger rocks could have been readily formed by significant partial melting of the 1,480 Ma juvenile crust (Fig. 5). Therefore, interpretation of the temporal relationship is similar to that suggested for volcanic and older plutonic rocks in the St. Francois Mountains. Accretion of juvenile volcanic arcs occurred ~1,480 Ma not only in the St. Francois Mountains area, but also to the south and west. Renewed igneous activity from 1,400 to 1,330 Ma, probably related to north-directed subduction, occurred to form the SGR province, plus isolated plutons intruding older terranes to the north, northeast, and west.

In contrast, it is evident that older, late Paleoproterozoic crust lies at depth within the western and northern SGR province. Depleted mantle model ages within the Texas Panhandle region (Barnes et al.

1999), northern Oklahoma (Van Schmus et al. 1996; Rohs 2001), and southern Kansas (Rohs 2001) all indicate older crust at depth. A much larger range of depleted mantle model ages from 1,940 to 1,560 Ma suggest multiple mixing scenarios and a more complex temporal framework for the older continental crust.

Conclusions

Precambrian basement rocks within the St. Francois Mountains fall into two distinct magmatic events ~100 million years apart, at ~1,470 and 1,370 Ma. Units that formed as part of the EGR province around 1,480 Ma have T_{DM} ages that are similar to or slightly older than the crystallization ages. Crystallization ages of 1,390 to 1,370 Ma within the Arbuckle Mountains are distinctly younger than the depleted mantle model ages by 100 to 150millionyear. A clear relationship between Precambrian units in the St. Francois Mountains and Arbuckle Mountains is evident from the pseudo-isochrons and depleted-mantle model ages as determined from Sm–Nd isotopic analyses. These relationships can be used to support the following hypothesis: Precambrian units in the Arbuckle Mountains and the surrounding subsurface are younger than most of the units in the St. Francois Mountains, but they were derived from lower crustal rocks with very similar Sm–Nd isotopic properties. Since the crystallization ages and depleted mantle model ages are very similar in the St. Francois Mountains, this area of the EGR province is interpreted as continental growth by accretion of juvenile arc terranes along the southern margin of Laurentia followed shortly by an active continental margin from 1,480 ± 20 Ma as preserved in the St. Francois Mountains. Crust that was added along the continental margin from 1,500 to 1,480 Ma extended from the St. Francois Mountains region to the south and west to the Arbuckle Mountains, from where it probably continued into West Texas.

Acknowledgments Support for this research came from several different sources. Financial support was provided through the endowment summer research support at the University of Kansas as well as Northwest Missouri State University as Faculty and Applied Research Grants. Extended thanks, from the senior author, go to fellow geology students Allen Fetter, Marianne Kozuch, and Leah Macneill for their assistance in the KU-Isotope Geology Lab. The authors would like to thank Tim Denison, Edward Lidiak, Lynn Watney, and the Kansas Geological Survey, as well as personnel at the Oklahoma Geologic Survey for providing samples across the area. Rohs gives special thanks to Tim Denison for assistance in the field of the eastern Arbuckle Mountains. Van Schmus acknowledges support from the Department of Geology, University of Kansas, various NSF grants, and collegial help from J. D. Walker to maintain operation of the Isotope Geochemistry Laboratory.

Appendix: Sample locations

See Table 3.

Table 3

Sample name	State	County	Sec., T, R	Latitude	Longitude
ARFU-001	Arkansas	Fulton	13-19N-07W	36.30	91.69
ARSP-001	Arkansas	Sharp	09-21N-04W	36.48	91.40
IAJK-001	Iowa	Jackson	29-85N-06E	42.15	90.28
ILHY-001	Illinois	Henry	30-16N-01E	41.35	90.43
INPO-001	Indiana	Porter	28-37N-06W	41.62	87.12
KSHG-2	Kansas	Hodgeman	10-21S-22W	38.24	99.72
KSHS-8	Kansas	Haskell	33-29S-34W	37.48	101.05
KSPR-8	Kansas	Pratt	17-29S-15W	37.52	98.99
KSPR-10	Kansas	Pratt	32-26S-12W	37.74	98.65
KSSU-9	Kansas	Sumner	25-30S-01E	37.33	97.78
KSDG-003	Kansas	Douglas	13-12S-17E	39.02	95.48
MOFR-9	Missouri	Franklin	17-41N-02E	38.30	90.82
MOSCh-5	Missouri	Dent	06-34N-04W	37.69	91.40
MOSG-1A	Missouri	St. Genevieve	15-35N-07E	37.74	90.24
MOSG-1B	Missouri	St. Genevieve	15-35N-07E	37.74	90.24
MOSG-3	Missouri	St. Genevieve	05-38N-06E	38.03	90.45
MOSG-HPGn	Missouri	St. Genevieve	14-36N-07E	37.78	90.23
MOAU-02a	Missouri	Audrain	06-50N-07W	39.25	91.74
MOAU-02b	Missouri	Audrain	06-50N-07W	39.25	91.74
MOFR-006	Missouri	Franklin	33-43N-01E	38.43	90.92
MOOR-003	Missouri	Oregon	07-25N-06W	36.86	91.65
MOSCh-01b	Missouri	St. Charles	34-48N-01E	38.88	90.89
MOSCh-01a	Missouri	St. Charles	34-48N-01E	38.88	90.89

Table 3 Continued

Sample name	State	County	Sec., T, R	Latitude	Longitude
MOSCh-04	Missouri	St. Charles	26-45N-02E	38.65	90.77
SFM1	Missouri	Madison	12-33N-5E	37.55	90.44
SFM2	Missouri	Madison	12-33N-5E	37.56	90.44
SFM4	Missouri	Madison	10-33N-6E	37.56	90.35
SFM5	Missouri	Madison	10-33N-6E	37.56	90.37
SFM7	Missouri	Iron	05-32N-3E	37.46	90.80
Silver Mines	Missouri	Madison	10-33N-5E	37.54	90.45
BRG-1	Oklahoma	Johnson	05-3S-7E	34.32	96.60
BRG-2	Oklahoma	Johnson	26-2S-7E	34.35	96.55
BRG-3	Oklahoma	Johnson	24-2S-6E	34.28	96.63
BRG-11	Oklahoma	Johnson	06-3S-7E	34.32	96.60
BRG-25	Oklahoma	Johnson	02-3S-8E	34.31	96.45
BRG-35	Oklahoma	Johnson	02-3S-8E	34.32	96.44
BRG-78-2	Oklahoma	Johnson	05-3S-7E	34.33	96.63
Gd-4a (Burch)	Oklahoma	Johnson	32-2S-5E	34.35	96.80
Gd-20a (Burch)	Oklahoma	Johnson	08-3S-5E	34.31	96.81
Troy-33a	Oklahoma	Johnson	32-2S-5E	34.35	96.81
Tishomingo	Oklahoma	Johnson	35-2S-6E	34.34	96.65
OKBR-2-29	Oklahoma	Bryan	24-5S-11E	34.11	96.11
OKJF-10	Oklahoma	Jefferson	32-6S-6W	34.01	97.84
OKHK-1	Oklahoma	Haskell	36-8N-22E	35.12	94.93
OKMS-5	Oklahoma	Muskogee	34-12N-19E	35.53	95.28
OKSQ-2	Oklahoma	Sequoyah	20-11N-26E	34.83	96.85
OKAF-1	Oklahoma	Alfalfa	1-27N-10W	36.83	98.22
OKCG-1	Oklahoma	Craig	31-28N-20E	36.87	95.20
OKCK-1	Oklahoma	Creek	29-18N-12E	36.01	96.06
OKKY-1	Oklahoma	Kay	17-28N-01E	36.91	97.08
OKNW-2	Oklahoma	Nowata	26-25N-17E	36.62	95.46
OKOS-16	Oklahoma	Osage	33-22N-7E	36.33	96.57
OKOS-27	Oklahoma	Osage	29-25N-08E	36.61	96.47
OKOS-35	Oklahoma	Osage	24-20N-11E	36.18	96.08
OKPW-1	Oklahoma	Pawnee	20-21N-08E	36.28	96.47
OKPW-7	Oklahoma	Pawnee	33-23N-03E	36.44	96.98
OKSM-2	Oklahoma	Seminole	23-9N-6E	35.26	96.65
OKTU-1	Oklahoma	Tulsa	6-19N-12E	36.15	96.07
OKWS-9	Oklahoma	Washington	22-29N-13E	36.97	96.99

References

Barnes MA, Rohs CR, Anthony EY, Van Schmus WR, Denison RE (1999) Isotopic and elemental chemistry of subsurface Precambrian igneous rocks, west Texas and eastern New Mexico. Rocky Mt Geol 34:245–262

Barnes MA, Anthony EY, Williams I, Asquith GB (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 Res 119:9–43

Bennet VC, DePaolo DJ (1987) Proterozoic crustal history of the western United States as determined by neodymium isotopic mapping. Geol Soc Am Bull 99:674–685

Bickford ME, Lewis RD (1979) U-Pb geochronology of exposed basement rocks in Oklahoma. Geol Soc Am Bull 90:540–544

Bickford ME, Mose DG (1975) Geochronology of Precambrian rocks in the St. Francois Mountains, southeastern Missouri. Geol Soc Am Spec Pap 165:48

Bickford ME, Van Schmus WR (1985) Discovery of two Proterozoic granite-rhyolite terranes in the buried midcontinent basement: the case fore shallow drill holes. In: Barry Raleigh I (eds) Observation of the continental crust through drilling. Springer-Verlag, New York, pp. 355–364

Bickford ME, Harrower KL, Hoppe WJ, Nelson BK, Nusbaum RL, Thomas JJ (1981) Rb-Sr and U-Pb geochronology and distribution of rock types in the Precambrian basement of Missouri and Kansas. Geol Soc Am Bull 92:323–341

Cullers RL, Koch RJ, Bickford ME (1981) Chemical evolution of magmas in the Proterozoic terrane of the St. Francois Mountains, southeastern Missouri—2. Trace element data. J Geophy Res 68:10388–10401

Denison RE (1973) Basement rocks in the Arbuckle Mountains: regional geology of the Arbuckle Mountains Oklahoma. Okla Geol Surg Spec Pub 73(3):43–49

Denison RE (1981) Basement rocks in northeastern Oklahoma. Okla Geol Surg Cir 84:84

Faure G, Mensing TM (2005) Isotopes principles and applications. The Sm-Nd method. Wiley Inc., NJ, p 195

Hoppe WJ, Montgomery CW, Van Schmus WR (1983) Age and significance of Precambrian basement samples from northern Illinois and adjacent state. J Geophy Res 88: 7276–7286

Kisvarsanyi EB (1981) Geology of the Precambrian St. Francois terrane, Southeastern Missouri. Contr Prec Geol 64(8):58

Lidiak EG, Denison RE (1999) Geology of the Blue River Gneiss, Eastern Arbuckle Mountains, Oklahoma. Basement Tectonics 13:139–153

Lidiak EG, Bickford ME, Kisvarsanyi EB (1993) Proterozoic geology of the eastern midcontinent region. In: Reed J. C. Jr and six others (eds) Precambrian: conterminous US: Boulder, CO. Geol Soc Am Geol North Am C-2:270–281

Ludwig KR (1998) ISOPLOT/Ex—a geochronological tool kit for Microsoft Excel: version 1:00 b. Berkeley Geochronology Center, Special Publication no. 1, p 43

Nelson BK, DePaolo DJ (1985) Rapid production of continental crust 1.7–1.9 b.y. ago: Nd isotoic evidence from the basement of the North American midcontinent. Geol Soc Am Bull 96:746–754

Patchett PJ, Ruiz J (1989) Nd isotopes and origin of Grenville-age rocks in Texas. J Geol 97:685–695

Rämö OT, Boyd WW, Vaaskoki M, Cameron RL, Ryckman DA (1994) 1.3 Ga mafic magmatism of the St. Francois Mountains of SE Missouri, implications for mantle composition beneath mid-continental USA. Miner Mag 58A:754–755

Rohs CR (2001) Identifying Paleoproterozoic and Mesoproterozoic crustal domains within the Southern Granite and Rhyolite province, mid-continent North America. Ph.D. thesis, University of Kansas, pp 1–151

Stacey JS, Kramers JD (1975) Approximation of terrestrial lead isotope evolution by a two-stage model. Earth Planet Sci Lett 26:207–221

Steiger RH, Jager E (1977) Subcomission on geochronology: convention on the use of decay constants in geo- and cosmochromonolgy. Earth Planet Sci Lett 36:359–362

Sylvester PJ (1984) Geology, petrology, and tectonic setting of the mafic rocks of the 1480 Ma old granite-rhyolite terrane of Missouri, USA. Ph.D. thesis, Washington University, Department of Earth and Planetary Sciences, p 455

Thomas JJ, Shuster RD, Bickford ME (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. Geol Soc Am Bull 95:1150–1157

Van Schmus WR, Bickford ME, Zetiz I (1987) Early and middle Proterozoic provinces in the Central United States. Proterozoic Lithospheric Evol AGU Geodynamics Ser 17:43–68

Van Schmus WR, Bickford ME (1993a) Transcontinental Proterozoic provinces. In: Reed J. C. Jr and six others (eds) Precambrian: conterminous US: Boulder, CO. Geol Soc Am Geology North Am C-2:235–239

Van Schmus WR, Bickford ME, Sims PK, Anderson RR, Shearer CK, Treves SB (1993b) Proterozoic geology of western midcontinent basement. In: Reed J. C. Jr and six others (eds) Precambrian: conterminous US: Boulder, CO. Geol Soc Am Geol North Am C-2:239–259

Van Schmus WR, Bickford ME, Turek A (1996) Proterozoic geology of the east-central Midcontinent basement. GSA Spec Pap 308:7–32

Walker JA, Pippin CG, Cameron BI, Patino L (2002) Tectonic insights provided by Mesoproterozoic mafic rocks of the St. Francois Mountains, southeastern MO. Precam Res 117:251–268