The Southern Oklahoma transform-parallel intracratonic fault system

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ABSTRACT

The "Southern Oklahoma Aulacogen" is recognized as a linear zone of igneous rocks with ages of ~539 to 530 Ma, extending into the Laurentian continent from the large-scale Ouachita embayment in the Iapetan rifted continental margin, as well as from a large-scale salient in the late Paleozoic Ouachita thrust belt. The well-documented Cambrian igneous rocks are associated with less well defined, contemporaneous basement faults that were overprinted by larger magnitude late Paleozoic basement faults along the Arbuckle and Wichita basement uplifts. Two distinctly different tectonic interpretations have evolved for the basement faults and igneous rocks: (1) that the Southern Oklahoma fault system is a transform-parallel intracratonic fault system associated with transforms of the Iapetan rift system, and (2) that the "Southern Oklahoma Aulacogen" is the failed arm of a three-armed radial-rift triple junction. Most internal geological characteristics within the Southern Oklahoma fault system are not exclusive to either interpretation. The larger regional context of rift and transform components of the Iapetan margin, as well as analogs from modern transform margins, however, strongly supports the interpretation of a transform-parallel intracratonic fault system. The purposes of this article are (1) to review the factors, both regional and internal, that illuminate the distinction between the alternatives; and (2) to consider modern analogs for the Southern Oklahoma crustal structures in the context of transform margins and transform-parallel intracratonic fault systems.

INTRODUCTION

The Southern Oklahoma basement fault system is highly significant to a general understanding of the tectonic evolution of basement fault systems that extend into continental cratons from rifted and subsequently contractional orogenic margins of continental crust. The nearly linear fault system extends >500 km into the North American craton from a cratonward-convex bend (the Ouachita salient) of the late Paleozoic Appalachian-Ouachita orogen and from a corresponding oceanward-concave angular bend (the Ouachita embayment) in the late Neoproterozoic–Cambrian Iapetan rifted margin of Laurentia (Fig. 1). Although early interpretations generally linked the Southern Oklahoma fault system to the Appalachian-Ouachita orogen, specific genetic relationships were not clear (e.g., King, 1959). More unifying interpretations emerged with the advent of the concept of plate tectonics, and two distinctly different scenarios evolved: (1) that the Southern Oklahoma fault system is a transform-parallel intracratonic fault system, which propagated into the craton from the rifted margin near the intersection of a rift segment and a large-scale transform fault that outline the Ouachita embayment (Thomas, 1976, 1977, 1983, 1993); and (2) that the Southern Oklahoma fault system is the failed arm of a plume-generated three-armed radial-rift system, the two successful arms of which outline the Ouachita embayment (previously called reentrant) of the Iapetan margin of Laurentia (Burke and Dewey, 1973; Hoffman et al., 1974). The purpose of this article is to outline the basis for the interpretation of the Southern Oklahoma fault system as a transform-parallel intracratonic fault system.

The Southern Oklahoma fault system does not form part of the Iapetan rifted continental margin of Laurentian crust; instead, it is a fault system that extends into the continental craton from the Ouachita orogenic belt at the continental margin (Fig. 1). In that context, the Southern Oklahoma fault system fits the original definition of an "aulacogen" (Shatski, 1946a, b, as cited in Hoffman et al., 1974)—a system of basement faults that extends into a continent from a marginal orogenic belt. Shatski's definition evidently was purely descriptive, not genetic. Later usage has linked the term aulacogen to the failed arm of a three-armed radial-rift triple junction (e.g., Hoffman et al., 1974), giving it a genetic meaning that was not originally intended. Because the genetic meaning confuses a discussion of alternative mechanisms for intracratonic fault

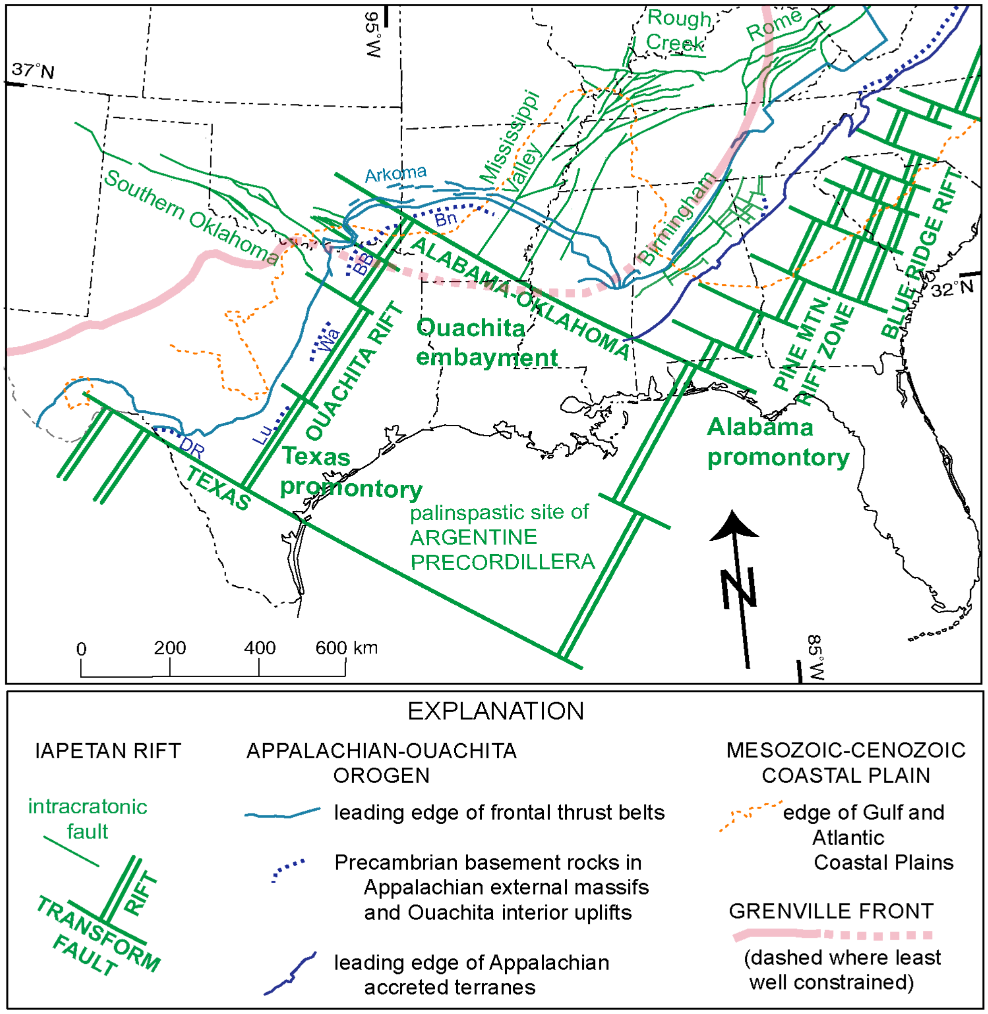

Figure 1. Map of reconstructed Iapetan rifted margin of Laurentia, showing location of the transform-parallel intracratonic Southern Oklahoma fault system with respect to transform faults of the rifted margin (adapted from Thomas, 1977, 1991, 2011). The Grenville Front separates the Grenville province on the southeast from the Granite-Rhyolite province on the northwest. Labels identify synrift intracratonic fault systems and grabens (Birmingham, Mississippi Valley, Rome, Rough Creek, and Southern Oklahoma), and the late Paleozoic Arkoma foreland basin. Abbreviations for names of Ouachita interior uplifts: Bn—Benton, BB—Broken Bow, Wa—Waco, Lu—Luling, DR—Devils River.

systems, to avoid misunderstanding, I will not use the term aulacogen here, although as originally defined it is perfectly appropriate.

SOUTHERN OKLAHOMA FAULT SYSTEM

The geology and geophysics of the Southern Oklahoma fault system are chronicled in an extensive literature, and only a brief summary will be presented here. The Southern Oklahoma fault system includes two distinct episodes of tectonic activity: (1) emplacement of a bimodal suite of igneous rocks in the Early Cambrian during Iapetan rifting; and (2) large-scale vertical separation along basement faults, generating high-relief uplifts and deep basins in the late Paleozoic (Denison, 1989).

The Early Cambrian bimodal suite of plutonic and volcanic rocks includes layered gabbro, basalt, granite, and rhyolite, the compositions of which indicate mantle sources of magma (Hogan and Gilbert, 1998; Hanson et al., 2013). The total volume of igneous rocks is estimated to be more than 250,000 km^3 (Hanson et al., 2013). Identity of specific synrift basement faults is obscured by the large volume of igneous rocks, as well as by overprinting by late Paleozoic large-magnitude basement faults (Denison, *in* Johnson et al., 1988). Evidence of Cambrian synrift faults is found in displacements of the Cambrian volcanic rocks with respect to Precambrian basement, ponding of flows against basement faults, faults within the volcanic rocks, and angular discordances within the layered igneous rocks, suggesting rift-bounding faults with >1 km of vertical separation and cumulative extension across the system of 17 to 21 km (Ham et al., 1964; McConnell and Gilbert, 1986). Crystallization ages of 539±5 to 530±1 Ma from U/Pb analyses of zircons (Wright et al., 1996; Hogan and Gilbert, 1998; Hanson et al., 2009, 2013; Thomas et al., 2012) define a short time span of magmatism (possibly as short as 534 to 531 Ma, or as long as 544 to 529 Ma, considering the uncertainties of the ages). The igneous rocks are approximately coeval with the initial deposition in sediment-filled intracratonic grabens (Birmingham, Mississippi Valley, Rough Creek, and Rome; Fig. 1) of southern Laurentia (Thomas, 1991) and with the age of synrift sediment along the conjugate margin in the Argentine Precordillera (Astini and Vaccari, 1996; Thomas and Astini, 1999; Thomas et al., 2004). The alignment of basement faults appears nearly continuous along strike from the continental margin >500 km into the craton (Fig. 1), encompassing an anastomosing array of en echelon faults on a regional scale; however, most mappable faults are late Paleozoic, possibly reactivated from Cambrian faults. Linear, northwest-trending, high-amplitude, short-wavelength gravity and magnetic anomalies outline a steeply bounded zone of dense mafic rocks ~65 km wide in the shallow continental crust (Keller and Stephenson, 2007).

The large volume of igneous rocks dominates the fill of the Southern Oklahoma fault system, and known sedimentary rift-fill rocks are rare. Drill and outcrop data document an arkosic sandstone unit (<50 m thick) within the volcanic succession and tuffaceous sedimentary interbeds with peperites at the bases of rhyolite flows (Hanson et al., 2013). The Meers Quartzite is a minor sedimentary component within the igneous rocks (Ham et al., 1964). A thick sedimentary succession (the Tillman Metasedimentary Group) extends southward in the subsurface from the Southern Oklahoma fault system in the Wichita Mountains, where wells penetrated variably metamorphosed graywacke, shale, and rare chert (Ham et al., 1964). COCORP seismic reflection profiles show a layered succession ~12 km thick (Quanah sequence of Pratt et al., 1992). Although the metasedimentary rocks were inferred to extend widely beneath the Cambrian rhyolites along the Southern Oklahoma fault system (Ham et al., 1964), the seismic reflection profiles show that the layered reflectors end abruptly northward beneath the Wichita Mountains and are not recorded farther north, suggesting a fault or intrusive boundary (Brewer et al., 1981; Pratt et al., 1992). The age of the Tillman Metasedimentary Group is not well constrained; however, regional relationships to dated rocks suggest a depositional age of ~1.2 to 1.0 Ga (Muehlberger et al., 1967; Denison et al., 1984; Coffman et al., 1986), significantly older than the rift-related Cambrian igneous rocks along the Southern Oklahoma fault system.

REGIONAL CONTEXT OF THE SOUTHERN OKLAHOMA FAULT SYSTEM

Because it extends into the craton from the rifted margin, the Southern Oklahoma fault system must be considered in the context of the rifted margin to which it is temporally and genetically linked in both alternative interpretations. The Southern Oklahoma fault system extends into the Laurentian continent from near, but not at, the corner of the Ouachita embayment in the rifted margin (Fig. 1).

In the context of a transform-parallel intracratonic fault system, the Southern Oklahoma fault system strikes N 65° W (295°) into the continent from the rifted margin (Fig. 1). Along the Iapetan continental margin of Laurentia, the Alabama-Oklahoma transform fault strikes N 65° W (295°), defining the northeastern margin of the Ouachita embayment (Fig. 1) (Thomas, 1977, 2011). Although rift segments of the margin are not necessarily perfectly orthogonal to transform faults, a simplifying generalization of orthogonal rifting uses a rift striking S 25° W (205°) as the northwestern margin of the Ouachita embayment (Fig. 1). That rift location and orientation coincide with the interpreted location of the rifted margin from mapping of gravity and magnetic anomalies (Keller et al., 1989a; Viele and Thomas, 1989).

In the context of a three-armed radial-rift triple junction, the Southern Oklahoma fault system is the failed arm, striking N 65° W (295°) into the Laurentian craton from the corner of the Ouachita embayment (Fig. 2). In ideal triple-junction geometry, the two successful arms strike N 55° E (055°) and S 05° E (175°), defining the northern and western rift margins, respectively, of the Ouachita embayment.

In contrasting the alternative interpretations, the northern margin of the Ouachita embayment is either a northeast-striking rift or a northwest-striking transform fault; therefore, the resolution of that margin is especially critical for distinction between the two alternatives. The western margin of the embayment is a rift in both interpretations; however, the projected orientations diverge by ~30°, providing a distinction between the alternative interpretations.

ALABAMA-OKLAHOMA TRANSFORM FAULT

The location and geometry of the Alabama-Oklahoma transform fault were interpreted initially from palinspastic reconstructions of early Paleozoic passive-margin shelf deposits and coeval off-shelf, continental slope and rise deposits (Cebull et al., 1976; Thomas, 1976, 1977; Viele and Thomas, 1989), and have been documented more recently by seismic velocity and gravity models (Keller et al., 1989b; Mickus and Keller, 1992; Harry et al., 2003; Harry and Londono, 2004). The Alabama-Oklahoma transform fault is in the footwall of the late Paleozoic Ouachita allochthon; along most of the transform, the Ouachita allochthon is covered by post-orogenic Mesozoic-Cenozoic deposits of the Gulf Coastal Plain (Fig. 1) (Thomas, 2011).

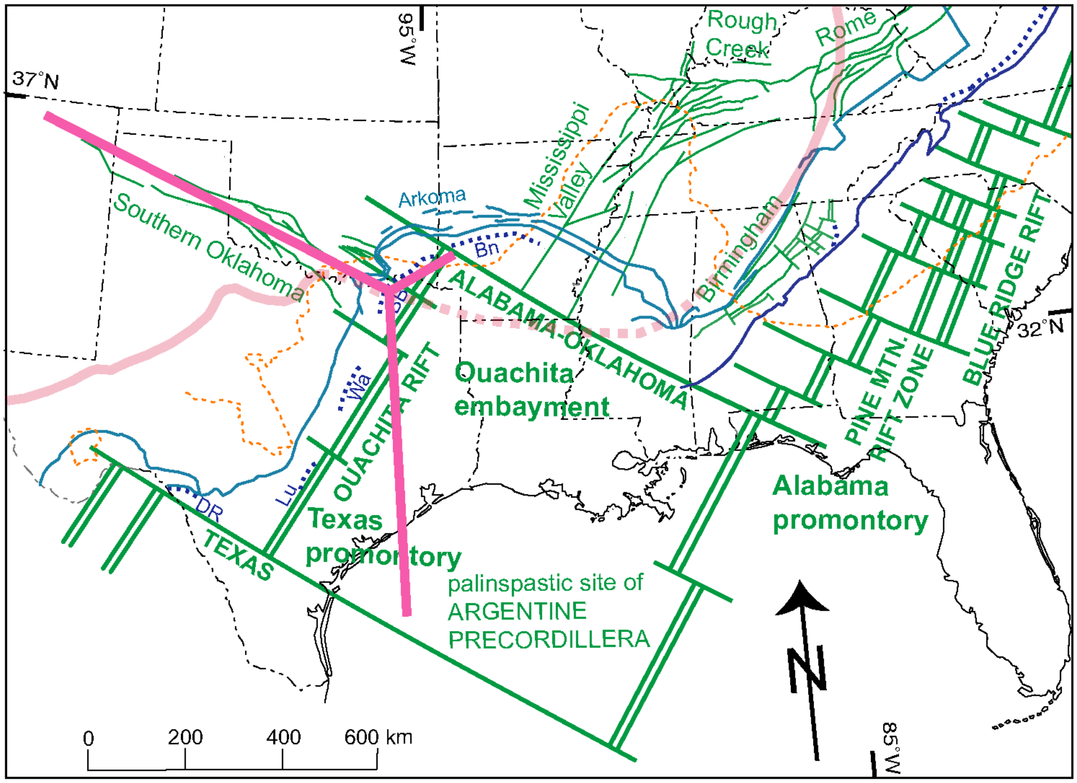

Figure 2. Map of reconstructed Iapetan rifted margin of Laurentia with overlay (bold pink lines) showing the Southern Oklahoma fault system interpreted as the "failed arm" of a three-armed radial-rift triple junction (overlay adapted from Burke and Dewey, 1973; Hoffman et al., 1974; Keller and Stephenson, 2007).

Interpretation of the structure of the Ouachita thrust belt from outcrop geology, deep wells, and seismic reflection profiles shows that the Ouachita allochthon, consisting of off-shelf sedimentary rocks, was thrust over the shelf edge onto passive-margin-shelf facies, leaving the passive-margin shelf and the transform margin of Laurentian crust in the Ouachita footwall (e.g., Viele and Thomas, 1989; Arbenz, 2008; Thomas, 2011). Within the Ouachita thrust belt, the Benton central uplift includes the lower Paleozoic cover strata and overlying Ouachita allochthon over a basement-cored ramp anticline, which is associated with basement-rooted thrust faults (Lillie et al., 1983; Arbenz, 2008). The basement rocks are tectonically shortened by as much as 23 km, an order of magnitude less than in the thin-skinned allochthon; otherwise the rift-stage structure of the transform margin has been preserved intact.

A seismic velocity model from the wide-angle reflection/refraction PASSCAL survey and a gravity model extend across the Ouachita thrust-belt structures in Arkansas and southward beneath the Gulf Coastal Plain and show an abrupt southern margin of Laurentian continental crust at the location of the Alabama-Oklahoma transform fault (Keller et al., 1989b; Mickus and Keller, 1992). The crust thins southward, within a distance of ~25 km, from thick (~39 km) continental crust to thin transitional or oceanic crust, indicating a steep crustal boundary consistent with the geometry of a near-vertical transform fault. The abrupt transition from thick continental crust to oceanic crust has a modern analog in the transform margin along the south side of the Grand Banks of Newfoundland on the Atlantic margin of North America (Keen, 1982; Keen and Haworth, 1985).

Southeastward from Arkansas, the Alabama-Oklahoma transform fault and the Ouachita thrust belt pass eastward beneath a southward thickening cover of the Gulf Coastal Plain (Fig. 1) and are relatively deep in the subsurface across Mississippi. Gravity models along two profiles in Mississippi show abrupt southward thinning of the crust from ~35 km thick to <10 km thick within a distance of <50 km (Harry et al., 2003; Harry and Londono, 2004). The abrupt thinning of the crust and the transition from thick continental crust to thin transitional or oceanic crust define the location and geometry of the Alabama-Oklahoma transform fault. The gradient of crustal thinning and the abrupt transition from thick to thin crust are similar in geometry to six examples (Exmouth Plateau, Flemish Cap, southwest Grand Banks, Ghana, Hornsrund, and Oman) of modern transform margins (Harry et al., 2003).

Beneath the Ouachita allochthon and in the foreland, a Cambrian–Ordovician classic passive-margin carbonate-shelf succession overlies Precambrian crystalline basement of the Laurentian craton. Within the Ouachita allochthon, the Cambrian–Ordovician passive-margin off-shelf succession is characterized by black shale and includes sandstone, calcareous mudstone, chert, and carbonate-clast conglomerates (summary in Arbenz, 1989; Viele and Thomas, 1989). Carbonate detritus (both clasts and mud) and quartzose sand link the off-shelf facies to a supply of sediment from the nearby shelf. 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, 1350±30, and 1284±12 Ma; and detrital zircons from arkosic sandstone in the Blakely Sandstone have ages of 1350 to 1300 Ma (Bowring, 1984). Although rocks of the Grenville orogen (1325 to 1000 Ma) extend along most of the Laurentian rifted margin both northeast and southwest of the Ouachita embayment, the ages of the granite 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. 1) (e.g., Bickford and Anderson, *in* Van Schmus et al., 1993; Thomas et al., 2012). Within the disharmonically folded thrust sheets of the off-shelf passive-margin strata, rare tectonically bounded pods of ultramafic rocks (serpentinite) probably are fragments of the oceanic crust on which the deep-water sediments were deposited (Morris and Stone, 1986; Nielsen et al., 1989). The sedimentary facies, shelf-derived detritus, and associated ultramafic rocks are consistent with a steep continental margin along a transform fault and with deposition of mud-dominated sediment on the continental slope and rise over thin transitional and/or oceanic crust. Submarine canyons evidently penetrated the passive-margin shelf edge and cut into crystalline basement rocks at the steep transform margin of Laurentia.

The off-shelf rocks in the Ouachita allochthon must be palinspastically restored on the outboard side of the carbonate-shelf facies (Fig. 1), and the restored shelf-edge facies boundary is inferred to mark the edge of continental crust along the transform. Although no shelf-edge facies have been identified, the trace and restored position of the shelf edge are constrained by the palinspastic reconstruction of the continental-shelf and off-shelf facies (Thomas, 2011).

The Alabama-Oklahoma transform fault, as defined primarily by the gravity models and palinspastic reconstructions, trends ~N 65° W (295°) from the corner of the Alabama promontory to the corner of the Ouachita embayment (Fig. 1) (Thomas, 1977, 1991). Available data are consistent with a single continuous transform fault; however, the detail of resolution allows a set of closely spaced en echelon transform faults linked by short rift segments along the margin of the Ouachita embayment. The intersection of the Alabama-Oklahoma transform fault and the southern segment of the Blue Ridge rift (Pine Mountain rift zone) outlines the corner of the Alabama promontory of Laurentian crust (Fig. 1) (Thomas, 1991, 2011). Inboard, northeast of the transform fault, two northeast-trending rift-parallel basement graben systems (Mississippi Valley and Birmingham) indicate extension in the same sense as that of the Blue Ridge rift (Fig. 1). Northeastward along strike, the Mississippi Valley graben merges into the east-trending Rough Creek graben, along which transtensional faults bound exceptionally deep (as much as 8 km) pull-apart basins (Hickman, 2011). Farther east, the Rome trough is a regionally northeast-striking, rift-parallel intracratonic graben; however, the southwestern part curves westward and merges with the eastern end of the Rough Creek graben (Fig. 1) (Thomas, 1993; Hickman, 2011). Together the Rough Creek graben and southwestern Rome trough comprise a transform-sense oblique offset (a transform-parallel transfer system) from the rift-parallel Mississippi Valley graben to the rift-parallel Rome trough (Fig. 1) (Thomas, 1993; Hickman, 2011). The well-defined Mississippi Valley graben beneath the Mississippi Embayment of the Gulf Coastal Plain projects southwestward toward an orthogonal intersection with the Alabama-Oklahoma transform fault (Fig. 1); however, the basement faults are not well resolved beneath the Ouachita thrust belt. The Alabama-Oklahoma transform fault intersects the Ouachita rift in the corner of the Ouachita embayment; the rift extends, with some small transform offsets, southwestward to an intersection with the Texas transform at the corner of the Texas promontory (Fig. 1).

DISCUSSION OF INTERPRETATIONS OF THE SOUTHERN OKLAHOMA FAULT SYSTEM

"Plume-Generated Three-Armed Radial-Rift Triple Junction"

The conceptual tectonic model for the role of "plume-generated three-armed radial-rift triple junctions" in continental rifting and breakup was based originally on observations of numerous examples of three-armed systems in which two "successful" arms became continental rifted margins and the third "failed" arm extended as a basement fracture system into the continent (Burke and Dewey, 1973). One of the original examples was the Southern Oklahoma fault system, which was identified as the "failed arm" of the "Dallas junction" (Fig. 2). Soon afterwards, the concept was elaborated in a multi-step genetic model for evolution of the "Southern Oklahoma Aulacogen" along with a more detailed application to the "Athapuscow aulacogen" and associated Coronation geosyncline in the region of Great Slave Lake in northwest Canada (Hoffman et al., 1974). The interpretation also used analogy with the Benue trough of West Africa as an example of a failed arm of a triple junction, and the Benue trough has commonly been cited as an analog for the "Southern Oklahoma Aulacogen." In a later paper, the Athapuscow aulacogen was reinterpreted and described as a continental transform, while the concept of the Athapuscow aulacogen as a "failed arm" was questioned as a "failed model" (Hoffman, 1987).

The concept of the "Southern Oklahoma Aulacogen" as the failed arm of a three-armed radial-rift triple junction was supported in part by interpretation of a thick succession of clastic sedimentary rocks (the Tillman Metasedimentary Group) associated with the Cambrian-age igneous rocks (Hoffman et al., 1974). If, however, the Tillman depositional age is ~1.2 to 1.0 Ga (Muehlberger et al., 1967; Denison et al., 1984; Coffman et al., 1986), the thick sedimentary succession is significantly older than the Cambrian rift-stage faults and igneous rocks, and is not related to the Cambrian-age fault system.

The interpretation of a triple junction is supported by a distinctive three-armed pattern of linear gravity highs at the junction of the Southern Oklahoma fault system and the Ouachita orogen (Keller and Stephenson, 2007), including the distinct, northwest-trending, high-amplitude, linear anomaly associated with the synrift igneous rocks along the Southern Oklahoma fault system (Fig. 2). The south-trending linear gravity high corresponds to the subsurface trace of the Ouachita orogenic belt, particularly the interior zone of metasedimentary rocks and basement uplifts; the gravity anomaly commonly is called the "interior zone gravity maximum" (Rozendal and Erskine, 1971; Nicholas and Rozendal, 1975; Keller et al., 1989a; Culotta et al., 1992). The interior zone maximum extends southward along the east side of the Texas promontory and curves ~90° westward around the corner of the promontory along the trend of the Texas transform (Fig. 1). Along the entire trace of the interior zone maximum, the magnitude of the anomaly requires a significant transition in crustal structure/composition, indicating that it also marks the margin of continental crust (Keller et al., 1989a), both along the Ouachita rift margin and along the Texas transform margin. The northeast-trending (third arm) linear gravity high extends only about 140 km from the triple junction and ends abruptly along trend (Fig. 2) (Keller and Stephenson, 2007), clearly showing an abrupt end of the source of the anomaly. The northeast end of the northeast arm anomaly corresponds to the location of the Alabama-Oklahoma transform, suggesting an association with the margin of continental crust. The trend of the northeast arm may represent an abrupt bend in the interior zone of the Ouachita orogen, generally paralleling the curved trace of the frontal thrust faults in the Ouachita salient (Fig. 2). The northeast-trending linear gravity high also parallels the Broken Bow basement-cored uplift (Arbenz, 2008) within the Ouachita thrust belt, and it bounds the southeast side of a very large magnitude gravity low along the Arkoma foreland basin (Kruger and Keller, 1986). The abrupt termination of the linear gravity high indicates that, if it does reflect a segment of the rifted continental margin, the trace of the continental margin must bend abruptly at the intersection with the Southern Oklahoma intracratonic fault system and must end at the Alabama-Oklahoma transform fault.

The Transform-Parallel Intracratonic Southern Oklahoma Fault System

In the context of Iapetan rifting, the Southern Oklahoma fault system is parallel to the Alabama-Oklahoma transform fault and extends northwesterly into Laurentian continental crust from the Ouachita embayment in the rifted margin (Fig. 1). The Southern Oklahoma fault system is not directly aligned with the Alabama-Oklahoma transform fault in the corner of the Ouachita embayment; instead, it intersects the Ouachita rift margin about 150 km south of the corner of the embayment (summaries in Thomas, 2010, 2011). The fault geometry and composition of the igneous rocks along the Southern Oklahoma fault system suggest transtensional, crust-penetrating, near-vertical fractures as magma conduits, consistent with a leaky transform fault.

Within a regional pattern of diachronous continental rifting and passive-margin subsidence around the margin of southern Laurentia, the Early Cambrian age (~539 to 530 Ma) of the Southern Oklahoma synrift igneous rocks is consistent with the timing of other rift-related structures (Fig. 1). The synrift igneous rocks are overlapped by a passive-margin succession of basal sandstone and overlying carbonates; the base of the passive-margin cover is of middle Late Cambrian age (Denison, *in* Johnson et al., 1988). Along the Blue Ridge rift, northeastward from the corner of the Alabama promontory, the youngest synrift igneous rocks are Late Neoproterozoic (572 to 564 Ma, Aleinikoff et al., 1995), and the transition from synrift to early post-rift passive margin is stratigraphically documented at the beginning of the Cambrian (~541 Ma) (summary in

Thomas, 1991). Rifting of the Argentine Precordillera terrane from the Ouachita embayment (Fig. 1) occurred in the Early Cambrian, as documented by Early Cambrian synrift redbeds and evaporites (Cerro Totora Formation) and an upward transition to post-rift passive-margin carbonates (Los Hornos Formation) at the end of the Early Cambrian (Astini and Vaccari, 1996; Thomas and Astini, 1996, 1999). The conjugate margins of the Precordillera and the Texas promontory of Laurentia have a predictable complementary asymmetry of post-rift subsidence along a low-angle detachment, consistent with rifting in the Early Cambrian (Thomas and Astini, 1999). Although no synrift rocks have been documented along the Alabama-Oklahoma transform, Early Cambrian transform separation of the Precordillera from Laurentia is consistent with evolution of the passive-margin carbonate succession from Oklahoma to Alabama (Thomas, 1991; Thomas and Astini, 1996, 1999). Inboard from the Alabama-Oklahoma transform and Blue Ridge rift margins of the Alabama promontory, two rift-parallel intracratonic basement fault systems and grabens (Mississippi Valley and Birmingham, Fig. 1) have thick, mud-dominated, graben-filling successions, which are correlative with thinner carbonate-dominated successions outside the grabens (summary in Thomas, 1991). The youngest parts of the graben fills are early Late Cambrian in both grabens. The earliest graben-fill deposits are not biostratigraphically documented; however, lithostratigraphic correlations indicate probable Early Cambrian facies (Rome Formation) in the grabens (Thomas, 1991, 2010). Both graben-filling, mud-dominated successions are overlapped by passive-margin shelf-carbonate facies (Knox Group), indicating an end to synsedimentary extensional faulting by middle Late Cambrian. The coincidence in age of igneous rocks along the Southern Oklahoma transform-parallel intracratonic fault system with ages of the sedimentary fills of the Birmingham and Mississippi Valley rift-parallel intracratonic grabens, as well as the age of synrift sedimentary rocks in the Argentine Precordillera and post-rift subsidence of the Texas promontory, suggests an integrated regional system of northwest-southeast extension partitioned by northwest-striking transform faults. In that large context, the Southern Oklahoma fault system is a transform-parallel intracratonic fault system.

TECTONIC INHERITANCE

The location and orientation of the Southern Oklahoma fault system may be at least partly inherited from older structural fabrics (Denison, 1982; Thomas, 2006). Diabase and microgranite porphyry dikes strike N 60° W and cut the basement rocks of the Granite-Rhyolite province in the Arbuckle Mountains; the age of the dikes is ~1350 Ma, near the age of the host rocks (Denison, 1982). Cambrian-age diabase and rhyolite dikes have the identical strike, suggesting tectonic inheritance of the older fabric (Denison, 1982). The strike of the probable northern fault boundary of the Tillman Metasedimentary Group is not closely constrained but may have approximately the same orientation as the dike sets. The location of the Southern Oklahoma fault system, approximately 150 km south of the intersection of the Alabama-Oklahoma transform fault with the rift margin at the corner of the Ouachita embayment, may be a result of tectonic inheritance from the Precambrian structural fabrics (Fig. 1).

A MODERN ANALOG FOR THE SOUTHERN OKLAHOMA FAULT SYSTEM

The Benue trough of West Africa, extending into the African continent from the large continental embayment in which the Niger Delta is centered, was cited by Burke and Dewey (1973) as a characteristic failed arm of a plume-generated three-armed radial-rift triple junction. In that context, the successful rift arms were considered to be the west coast (Cameroon–Gabon) of Africa and the south-facing Ivory Coast–Ghana margin. A variety of data, however, has shown the Ivory Coast–Ghana margin to be defined by transform faults and the Benue trough to be a transtensional strike-slip fault system, projecting into the African continent from the rifted margin of West Africa (Fig. 3) (e.g., Francheteau and Le Pichon, 1972; Mascle et al., 1988, 1992; Benkhelil et al., 1998). Consequently, the Benue trough is an appropriate analog for the Southern Oklahoma fault system as a transform-parallel intracratonic fault system projecting into the continent from the Iapetan margin of Laurentia (Figs. 4 and 5) (Thomas, 1991).

The Ivory Coast–Ghana margin (Equatorial fracture zone belt of Heezen et al., 1964; Sykes, 1978; Mascle et al., 1992) includes multiple en echelon transform faults that together offset the Atlantic margin from the large-scale continental promontory of West Africa to the large-scale continental embayment at the Niger Delta (Fig. 3) (Francheteau and Le Pichon, 1972). Relatively closely spaced transform faults (St. Paul, Romanche, Chain, and Charcot fracture zones, Fig. 3) offset short rift segments to define the transform margin and continental embayment (Mascle et al., 1992; Benkhelil et al., 1998). Exceptionally steep slopes mark the abrupt transition from continental to oce-

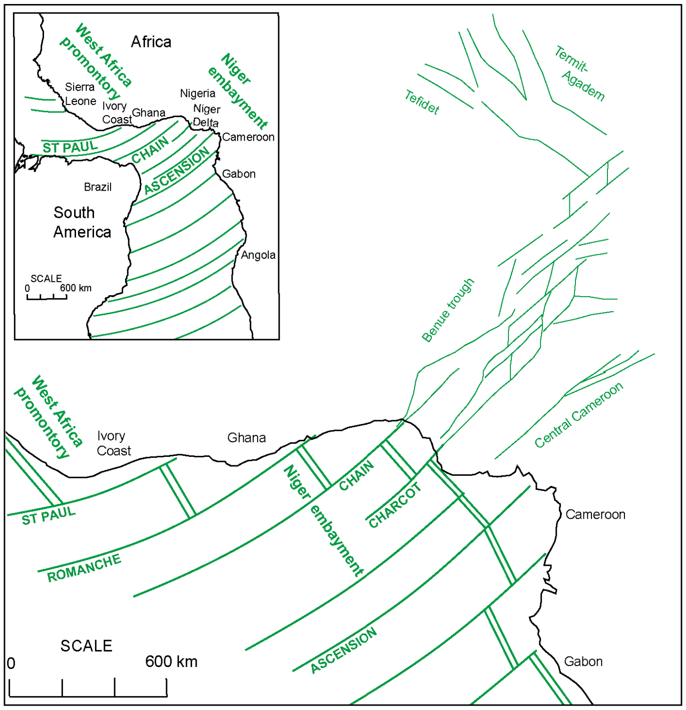

Figure 3. Maps of transform faults and rifts of the Atlantic margin of West Africa, showing location of the transform-parallel intracratonic Benue trough and other intracratonic faults. Inset map shows transform faults of the Mid-Atlantic Ridge in relation to the conjugate continental margins of Africa and South America at an early stage of opening of the South Atlantic Ocean (adapted from Francheteau and Le Pichon, 1972). Larger map shows the transform faults that define the transform margin of West Africa and offset the Atlantic margin of Africa from the West Africa promontory to the Niger embayment, as well as the transform-parallel intracratonic Benue trough and Central Cameroon shear zone and the rift-parallel Tefidet and Termit-Agadem graben systems (map compiled and adapted from Benkhelil et al., 1998; Genik, 1993; Njonfang et al., 2008). Styles of lines and labels are the same as in Figure 1.

anic crust across the transforms (Mascle et al., 1988, 1992); the structural relief reflects both rifting and subsequent thermal adjustments between continental crust and young oceanic crust along the transform margin. The transforms exhibit prolonged tectonic activity (Mascle et al., 1992). The Chain and Charcot fracture zones project into the continental margin within the Niger embayment and within the very thick sediment accumulation in the Niger Delta (Fig. 3) (Benkhelil et al., 1998).

Projection of the Chain and Charcot fracture zones inboard from the African continental margin defines the boundaries of the Benue trough, a transtensional system of pull-apart basins that extends >800 km from the rifted margin into continental crust (Fig. 3) (Benkhelil et al., 1998). The sediment fill of the trough records diachronous movement on various faults, and coeval igneous rocks intrude the sedimentary fill. The Benue trough, extending into continental crust, is parallel to the transform faults of the continental margin (Fig. 3). Another intracratonic fracture system, the Central Cameroon shear zone (Njonfang et al., 2008), parallels the Benue trough and is aligned with another transform fault of the continental margin (Fig. 3). Fault orientations suggest tectonic inheritance from older PanAfrican shear zones and mylonites (Ngako et al., 2006; Déruelle et al., 2007). The transform-parallel Benue trough, within African continental crust, intersects rift-parallel intracratonic graben systems (Termit-Agadem and Tefidet, Fig. 3) (Genik, 1993; Benkhelil et al., 1998). The transform-parallel Benue trough and Central Cameroon shear zone are not aligned with the transform faults that define the Ivory Coast–Ghana margin at the corner of the Niger embayment but, instead, are aligned with other transform faults farther south in the embayment (Fig. 3). Similarly, the transform-parallel Southern Oklahoma fault system is not aligned with the Alabama-Oklahoma transform fault at the corner of the Ouachita embayment, suggesting, by analogy, alignment with other transform faults farther south in the embayment (Figs. 1 and 5).

The relationship of structural geometry of the Benue trough and Central Cameroon shear zone to transform faults of the Atlantic Ocean and African continental margin is similar to the relationship of the Southern Oklahoma fault system to transform faults of the Iapetus Ocean and Laurentian continental margin (Figs. 4 and 5); however, differences in the history of magmatism suggest some differences in magma generation. In contrast to the very short time span (~539 to 530 Ma) of magmatism along the Southern Oklahoma fault system, much longer times of magmatism characterize the Benue trough (~147 to 49 Ma) and Central Cameroon shear zone (~70 to 0 Ma) (Ngako et al., 2006; Déruelle et al., 2007). Volumetrically, synrift magmatism strongly dominated over sedimentation along the Southern Oklahoma fault system, whereas the igneous rocks of the Benue trough are interspersed with the sedimentary fill. Compositional differences suggest contrasts in the nature of the mantle sources of magmas. For a source of synrift magma along the Central Cameroon shear zone, observations of a lack of a regular time-space migration of magmatism have led to interpre-

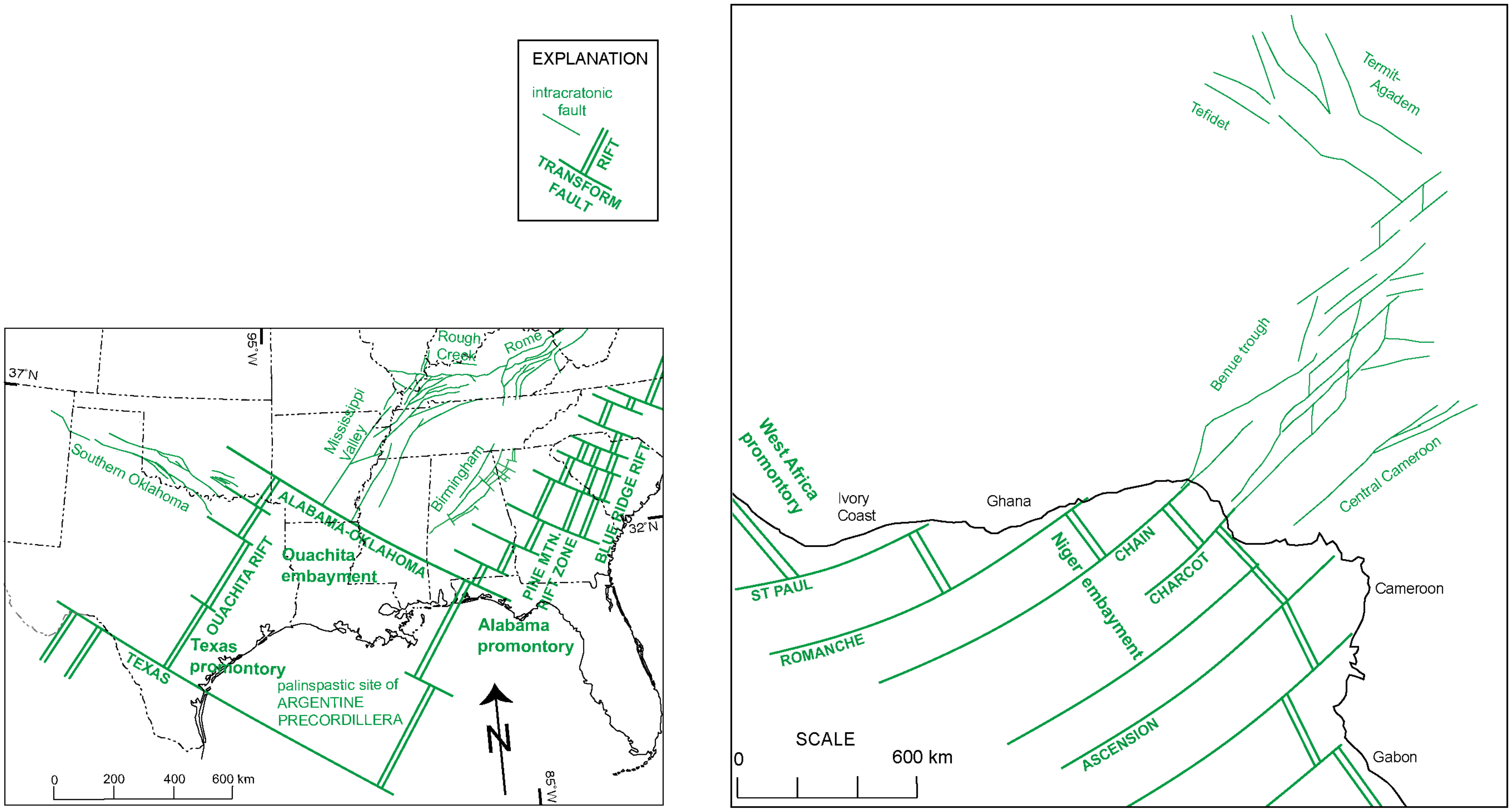

Figure 4. Matched maps, at the same scale, to compare transform faults and rift segments of the Iapetan margin of Laurentia and the transform-parallel intracratonic Southern Oklahoma fault system with transform faults and rift segments of the Atlantic margin of Africa and the transform-parallel intracratonic Benue trough (from sources for Figures 1 and 3).

tations that reject a single mantle plume in favor of either multiple plumes, a mantle hot line, or migration of magma through brittle lithospheric fractures from uniformly distributed (non-hotspot) melt at the base of the lithosphere (Ngako et al., 2006; Déruelle et al., 2007). The "Cameroon Hot Line" is defined by an alignment of volcanoes that obliquely crosses the Central Cameroon shear zone, the orientation of which may be inherited from PanAfrican shear zones (Déruelle et al., 2007). These alternatives for the Central Cameroon shear zone may have application to the Benue trough and to the Southern Oklahoma fault system, which requires a large supply of magma in a relatively short time, possibly as a result of coincidence of location of the transtensional fault system in the brittle lithosphere over a mantle thermal anomaly.

The tectonic and magmatic history of the Southern Oklahoma synrift, transform-parallel, intracratonic fault system and of the analogous structures of Benue trough and Central Cameroon shear zone leave some important questions. For example, do heat flow and magma injection drive rifting or do rift-related fractures tap passive magma sources beneath the brittle lithosphere? Magma sources from non-hotspot reservoirs below the lithosphere or along a mantle hot line have been suggested for volcanic centers and plutonic ring-complexes along the Central Cameroon shear zone (Déruelle et al., 2007). In contrast, lavas along the Southern Oklahoma fault system are from fissure eruptions (Hogan and Gilbert, 1998); however, a very large volume of magma was emplaced in a short time span. Implications for a transtensional system of lithosphere-penetrating, open fractures suggest the potential for rapid depletion of the magma source below the lithosphere, filling the open fractures and limiting accumulation of synrift sediment. If the locations of the fracture systems are dictated significantly by tectonic inheritance, independent of mantle conditions, then the fault systems may cross over deeper magma sources (plumes, hot lines, or non-hotspot reservoirs). Integration of observations from the Southern Oklahoma, Benue, and Central Cameroon systems offers an opportunity to address questions of tectonics of rifting, propagation of transform faults, tectonic inheritance of location and orientation of intracratonic fault systems, and generation and emplacement of synrift magma.

CONCLUSIONS

A fully integrated system of rifts and transforms along the Iapetan rifted margin of Laurentia, as well as rift-parallel and transform-parallel intracratonic fault systems, indicates that each of the parts must be considered in the context of the whole. Rather than a separate independent mechanism (a plume) for each rift intersection, a comprehensive interpretation should consider the kinematic and temporal framework of the entire system of continental-margin rifts and transforms along with transform-parallel and rift-parallel intracratonic basement faults. The large volume of igneous rocks along the Southern Oklahoma transform-parallel intracratonic fault system suggests a mantle thermal anomaly beneath a crust-penetrating transtensional fault system in the brittle lithosphere, consistent with a leaky transform fault. In the broad regional context, faults and synrift igneous rocks define the Southern Oklahoma transform-parallel intracratonic fault system, a temporally and kinematically integral component of the diachronous Iapetan rifted margin of southern Laurentia.

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Figure 5. Modified Figure 4 to enhance visual comparison by using a reoriented and rotated map from Figure 3, thereby showing the Benue trough and the Southern Oklahoma fault system in the same orientations and positions relative to transform faults of the continental margin.

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