The Iapetan rifted margin of southern Laurentia

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ABSTRACT

The Iapetan rifted margin of southern Laurentia includes the northeast-striking Blue Ridge, Ouachita, and Marathon rifts, which are offset by the northwest-striking Alabama-Oklahoma and Texas transform faults, framing the Alabama and Texas promontories and the Ouachita and Marathon embayments of the continental margin. Interpretations of the original trace, structural style, and age of the rifted margin rest on identification of synrift rocks and structures, as well as continental-shelf and offshore sedimentary deposits on the passive margin. Both late Paleozoic Ouachita-Appalachian allochthons and post-orogenic Atlantic-Gulf passive-margin deposits cover the Iapetan rift margin, necessitating the use of data from deep wells and geophysical surveys along with geologic maps of the exposed Ouachita-Appalachian thrust belts to characterize the synrift and post-rift rocks and structures. The continental margin and passive-margin shelf stratigraphy are characterized by the footwall of the Ouachita allochthon; however, some Ouachita thrust faults displaced shelf-margin basement and cover. Appalachian thrust faults imbricate synrift fill of the intracratonic Birmingham graben and the passive-margin shelf. Palinspastic restoration of thrust-belt structures uses balanced cross sections to locate the original trace of the Iapetan margin. Thickness and subsidence history of the passive-margin successions, as well as a general lack of preserved synrift deposits, indicate an upper-plate structure along the Blue Ridge rift on the Alabama promontory and along the Ouachita rift on the Texas promontory. The upper plate on the Texas promontory is conjugate to a lower-plate rift structure on the Argentine Precordillera. Although data are limited, the evolution of the passive margin along the Marathon rift in the Marathon embayment suggests a lower-plate structure.

Geophysical modeling supports a steep continental margin along the Alabama-Oklahoma transform, and a similar structure can be inferred for the Texas transform. The Blue Ridge rift north of the Alabama promontory is dated by synrift volcanic rocks as young as 564 Ma, and passive-margin transgression beginning in earliest Cambrian is documented along the Alabama promontory and farther north. The age of the Ouachita rift is documented by the 530–539 Ma synrift volcanics of the transform-parallel intracratonic Southern Oklahoma fault system, by Early Cambrian synrift sediment along the conjugate rift margin in the Argentine Precordillera, and by late synrift graben-fill of Early to early Late Cambrian age in the rift-parallel intracratonic Mississippi Valley and Birmingham graben systems, as well as by subsidence history of the passive margin on the Texas promontory. The diachrony of rifts reflecting an inboard shift from the Blue Ridge rift to the Ouachita rift along the Alabama-Oklahoma transform and rift of the Argentine Precordillera from the Ouachita embayment.

INTRODUCTION

The late Precambrian–Cambrian Iapetan rifted margin, as well as the subsequent Cambrian-Ordovician passive margin, of southern Laurentia is covered by late Paleozoic Ouachita-Appalachian allochthons (emplaced during the assembly of supercontinent Pangaea) and by Mesozoic-Cenozoic synrift and passive-margin strata of the Gulf Coastal Plain (deposited during opening of the Atlantic Ocean and Gulf of Mexico) (summary in Thomas, 2006). Because of the younger tectonic and sedimentary cover, interpretations of the geometry and tectonic elements of the Iapetan margin are based on data from deep wells and geophysical surveys. Resolution of the Iapetan margin in the subsurface requires palinspastic reconstruction of the early post-rift passive margin to remove the effects of Ouachita-Appalachian orogenesis, including subsidence of synorogenic foreland basins, and of Atlantic-Gulf rift-stage extension and passive-margin subsidence. The objective of this article is to summarize the relevant data for interpretation of the trace, structure, and age of the Iapetan rifted margin of southern Laurentia, using the large-scale elements of the rifted margin as an outline.

The large-scale framework of the Iapetan rifted margin of Laurentia is interpreted in the context of northeast-trending rift segments offset by northwest-trending transform faults (Fig. 1) (e.g., Thomas, 1976, 1977, 1991, 2006). In southern Laurentia, intersections of two large-scale transform faults (Alabama-Oklahoma and Texas transforms) with rift segments (Blue Ridge, Ouachita, Marathon) outline two promontories (Alabama and Texas) and two embayments (Ouachita and Marathon) of the rifted margin (Fig. 1). Inboard from the rifted margin, late synrift intracratonic fault systems include rift-parallel extensional faults (Mississippi Valley and Birmingham graben systems) and transform-parallel faults (Southern Oklahoma fault system). In addition, the rift and transform margins of the Ouachita embayment are conjugate to the Iapetan rift margin of the Argentine Precordillera microcontinent (Fig. 2) (Thomas and Astini, 1996), and the rift history of the Precordillera is complementary to that of southern Laurentia (Thomas and Astini, 1999).

CORNER OF ALABAMA PROMONTORY

In the northeast-striking, northwest-verging Appalachian thrust belt in Alabama and Georgia, the décollement is near the base of the Paleozoic sedimentary succession above Precambrian crystalline basement rocks, and a Cambrian-Ordovician passive-margin (Iapetan post-rift) succession with upward transition from clastic to carbonate rocks is imbricated in the allochthon (Figs. 1, 3, and 4C) (Thomas and Bayona, 2005). Along the trailing (southeastern) edge of the sedimentary thrust belt, the lower-greenschist Talladega slate belt includes similar passive-margin stratigraphy (Tull et al., 1988). In the Appalachian Piedmont, southeast...
of the Talladega slate belt, northwest-directed, accreted metamorphic terranes rest on the same footwall décollement as that beneath the sedimentary thrust belt to the northwest (Fig. 3). Along the southeastern (trailing) edge of the metamorphic terranes, the Pine Mountain internal basement massif includes Grenville-age basement rocks and isoclinally infolded cover of metasedimentary passive-margin facies and laterally discontinuous synrift meta-clastic rocks (Fig. 3) (Steltenpohl, 1988; Steltenpohl et al., 2008). Although interrupted by some rift-related normal faults, the top of Precambrian basement beneath the allochthon dips gradually southeastward at a relatively shallow level from the Appalachian foreland on the northwest to the Pine Mountain internal basement massif, and a basement-rooted thrust fault beneath the massif apparently merges into the Appalachian décollement above the extensive shallow basement (Fig. 3) (McBride et al., 2005).

Mylonite zones (Goat Rock and Bartlett's Ferry fault zones) along the southeast side of the Pine Mountain internal basement massif mark the leading edge of a relatively wide Suwannee-Wiggins suture zone between Laurentian crust on the northwest and African crust and sedimentary cover of the Suwannee terrane on the southeast (Figs. 1 and 3) (summary in Thomas, 2010). To the south beneath the Gulf Coastal Plain, the suture zone is imaged seismically as a wide band of southeast-dipping reflectors that extend down to the Moho (Nelson et al., 1985; McBride et al., 2005), suggesting that the suture zone consists of highly tectonized lithons interlaced with mylonite zones. Crystallization ages of the most southerly exposed metamorphic rocks (Uchee belt, southeast of the exposed mylonite zones) indicate a peri-Gondwana arc terrane, suggesting comparisons with the peri-Gondwanan Carolina terrane to the northeast along Appalachian Piedmont strike and with the Suwannee terrane across strike to the south (Fig. 1) (Steltenpohl et al., 2008). The footwall of the leading edge of the Suwannee-Wiggins suture zone forms the present limit of Laurentian crust at the corner of the Alabama promontory (Figs. 1 and 3).

Palinspastic restoration (minimum restoration, using line-length and area balancing) of thrust sheets in the sedimentary thrust belt places the trailing thrust sheets approximately at the present location of the Pine Mountain internal basement massif, showing that the early Paleozoic passive-margin carbonate-shelf succession (now imbricated in the thrust belt) covered all of the area of shallow crystalline basement rocks (now beneath the thrust belt and Piedmont metamorphic terranes) (Fig. 3) (Thomas and Bayona, 2005). The extent of the palinspastically restored passive-margin succession leaves little or no space on the present shallow basement for the palinspastic location of the passive-margin facies in the Talladega slate belt, indicating that the Laurentian continental shelf originally extended farther southeast than the present location of Pine Mountain (Fig. 3).

The Pine Mountain internal basement massif may be a thrust sheet from near the rifted margin of Laurentian crust (e.g., Thomas, Neathery, and Ferrill, in Hatcher et al., 1989), a Laurentian microcontinent thrust over the rifted margin (Thomas, 1977; Steltenpohl et al., 2004), or a far-traveled allochthonous basement terrane (McBride et al., 2005). If the Pine Mountain basement massif is Laurentian, the palinspastic
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Figure 2. Block diagram, showing interpretation of rifting of the Argentine Precordillera from the Ouachita embayment of southern Laurentia (modified from Thomas and Astini, 1999). Diagram illustrates a low-angle detachment with the Precordillera on the lower plate and the Texas promontory on the upper plate; the Alabama-Oklahoma transform fault forms a steep continental margin orthogonal to the rift.

location must be southeast of the present location and could be either southeast or northwest of the palinspastic location of the Talladega slate belt (Fig. 3). Similarity of the Talladega passive-margin stratigraphy to that in the trailing part of the sedimentary thrust belt (Figs. 3 and 4C) (Tull et al., 1988) suggests that originally these successions may have been in close proximity. The Talladega fault truncates several of the trailing sedimentary thrust sheets along strike, however, indicating that some unquantified space for the excised thrust sheets must separate the palinspastic location of the Talladega slate belt from that of the present immediate footwall (Fig. 3). In contrast, the highly metamorphosed sedimentary cover of the Pine Mountain basement massif differs from the successions in the trailing sedimentary thrust sheets and in the Talladega slate belt (Figs. 3 and 4C). In Pine Mountain, a compositionally mature quartzite stratigraphically overlies schists that may represent less mature late synrift or very early post-rift sediment (Steltenpohl et al., 2004). A marble stratigraphically above the quartzite may represent the Cambrian passive-margin transgression; however, the state of deformation precludes accurate stratigraphic correlation of the marble. Although penetrative deformation precludes an accurate estimate of original thickness, the evident volume of the Pine Mountain cover rocks indicates lesser stratigraphic thickness than in the Talladega slate belt or sedimentary thrust belt. The stratigraphic comparisons and contrasts favor restoring the Talladega slate belt adjacent to the trailing part of the sedimentary thrust belt, thereby placing Pine Mountain basement and cover outboard from the palinspastic Talladega and at or near the original rifted margin of Laurentian crust (Fig. 3). Alternatively, a geometrically acceptable reconstruction places the Pine Mountain massif between the sedimentary thrust belt and Talladega belt. In either alternative, the relatively thin and mature Pine Mountain passive-margin cover indicates a separate basement horst block (Fig. 3).

Palinspastic restoration of the passive-margin facies in the sedimentary thrust belt, Talladega slate belt, and Pine Mountain massif shows that the original trace of the Iapetan rifted margin at the southeast corner of the Alabama promontory must have been at least 80 km southeast of the present truncated margin of Laurentian crust along the Suwannee-Wiggins suture (Figs. 1 and 3). No passive-margin shelf-edge facies or off-shelf facies have been recognized; therefore, the restored extent of the continental shelf is a minimum. The Suwannee-Wiggins suture penetrates through the entire crust, indicating that Laurentian crust was excised and replaced by Gondwanan (African) crust.

The early Paleozoic stratigraphy in the sedimentary thrust belt records passive-margin transgression over the rifted margin of Laurentia. The base of the sedimentary succession is deeply buried in the Appalachian footwall on the Alabama promontory, and the oldest exposed rocks are Lower Cambrian sandstone (Chilhowee Group) (Fig. 4C). Further northeast along the Blue Ridge, the Chilhowee Group rests on synrift rocks and oversteps rift-stage faults onto Precambrian basement (summary in Thomas, 1991); the transition from rift to passive margin is within the lowermost Chilhowee Group (Unicoi Formation) (Simpson and Erickson, 1989) and is of earliest Cambrian age (Laurence and Palmer, 1963; Simpson and Sundberg, 1987). An upward transition from Chilhowee sandstones to the middle Lower Cambrian Shady Dolomite (e.g., Sloss, 1963; Palmer, 1971; Mack, 1980) is consistent with early post-rift thermal subsidence and cratonward transgression over a passive margin. Above the Shady Dolomite, however, the Rome Formation (upper Lower Cambrian) of red and green mudstones, sandstones, and carbonates indicates a cratonic supply of clastic sediment (e.g., Thomas et al., 2004). The overlying Middle to lower Upper Cambrian Conasauga Formation (Fig. 4C) encompasses an upward transition from clastic to carbonate deposition; however, the stratigraphic level of the transition varies laterally from near the base to near the top of the Conasauga, consistent with active extension along basement faults (Thomas et al., 2000a). The Upper Cambrian–Lower Ordovician Knox Group (Fig. 4C) of massive carbonates constitutes the fully developed passive margin, sometimes called the Great American Carbonate Bank.

BIRMINGHAM GRABEN AND ASSOCIATED SYNrift BASEMENT FAULTS

More than 150 km inboard from the Laurentian rifted margin and the Suwannee-Wiggins suture, seismic reflection profiles image the Birmingham basement graben beneath the Appalachian sedimentary thrust belt in Alabama (Figs. 1 and 3) (Thomas and Bayona, 2005; Thomas, 2007). Large-scale thin-skinned frontal ramps of the sedimentary thrust sheets (Big Canoe Valley thrust sheet, and Jones Valley thrust sheet along strike to the southwest) rise northwestward over the down-to-southeast basement faults (Birmingham basement fault), and over thick ductile duplexes (Gadsden mudwad, and others along strike to the southwest) of the shale-dominated Conasauga Formation (Fig. 3) (Thomas, 2001). Palinspastic restoration of the thrust sheets and ductile duplexes places shale-dominated facies (dark-colored...
Figure 3. Structural cross section of Appalachian structures, including Pine Mountain internal basement massif and Suwannee-Wiggins suture, and palinspastic reconstruction of Iapetan margin along the Blue Ridge rift beneath the Appalachian orogen in Alabama (no vertical exaggeration; line of cross section shown in Fig. 1). Cross section compiled from data in Neathery and Thomas (1983); Sears and Cook (1984); Nelson et al. (1985, 1987); Steltenpohl (1988); Tull et al. (1988); Thomas, Neathery, and Ferrill, in Hatch et al. (1989); Thomas (1991, 2001); Thomas et al. (2000a); Thomas and Bayona (2005); and Steltenpohl et al. (2008).
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**EXPLANATION:** dominant lithology

**cratonic shelf facies**
- chert
- limestone, dolostone
- shale, mudstone
- sandstone

**off-shelf facies**
- chert
- limestone
- dark-colored shale
- sandstone

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**Figure 4 (on this and following two pages).** Correlation chart of representative stratigraphic sections along the Iapetan rifted margin of southern Laurentia. A—Sections from the Marathon embayment (including a list of Mississippian-Pennsylvanian formations in the Marathon synorogenic clastic wedge), Texas promontory, and Southern Oklahoma intracratonic fault system; chart compiled from data in Rozendal and Erskine (1971); Nicholas and Rozendal (1975); Nicholas (1983); Denison, in Johnson et al. (1988); Arbenz (1989a); and McBride (1989); and correlations from Hills and Kottlowski (1983); Adler (1986); and Mankin (1986).
Figure 4 (continued). B—Sections from Ouachita embayment, Alabama-Oklahoma transform margin, and Southern Oklahoma and Mississippi Valley intracratonic fault systems; chart compiled from data in Maher and Lantz (1953); Denison, in Johnson et al. (1988); Thomas (1988, 1989a, 1991); and Arbenz (1989a); and correlations from Mankin (1986).
Figure 4 (continued). C—Sections from Alabama-Oklahoma transform margin and Alabama promontory; chart compiled from data and correlations in Butts (1926); Mack (1980); Thomas (1988, 1989a, 1991); Tull et al. (1988); Thomas et al. (2000a); Thomas and Bayona (2005); and Steltenpohl et al. (2008).
The Birmingham basement graben is bounded by northeast-striking faults parallel with the Blue Ridge rift farther southeast, and northwest-southeast extension is coaxial with Iapetan rifting along the Blue Ridge rift. The ages of initial passive-margin cover over the rift-stage faults (Early Cambrian along the Blue Ridge rift, and middle Late Cambrian along the Birmingham graben) show that extension on the Birmingham graben was later than rifting along the Blue Ridge rift.

ALABAMA-OKLAHOMA TRANSFORM FAULT

The trace 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., 1989a; 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 trace of the transform, the Ouachita allochthon is covered by post-orogenic Mesozoic-Cenozoic sediment of the Gulf Coastal Plain (Fig. 1). Interpretation of the structure of the Ouachita thrust belt from outcrop geology, deep wells, and seismic reflection profiles shows that the off-shelf sedimentary rocks were 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).

Northwestern Part of Alabama-Oklahoma Transform Margin, Arkansas-Oklahoma

In Arkansas, the exposed Ouachita thrust belt verges northward into the northward shallowing Arkoma foreland basin, which contains an upper Paleozoic synorogenic clastic wedge (Fig. 5). Up dip to the north of the Arkoma basin, Precambrian basement rocks exposed in the crest of the intracratonic Ozark dome belong to the Granite-Rhyolite province with ages of 1.38–1.48 Ga (Lidiak, Bickford, and Kisvarsanyi, in Van Schmus et al., 1993). Overlying the basement rocks around the Ozark dome, a classic passive-margin succession (Fig. 4B) includes a basal quartzarenite (Lamotte) of late Middle Cambrian age (Denison, in Johnson et al., 1988) and shallow-marine carbonate rocks (Bonne-terre, Elvins, Arbuckle), the Sauk sequence of Sloss (1963). The Upper Cambrian to Lower
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Ordovician succession is a massive carbonate; various parts contain quartz sand both as scattered grains in carbonate rocks and as sandstone interbeds. The craton-wide post-Sauk unconformity (Sloss, 1963) marks the top of the massive carbonate; however, shallow-marine-shelf deposition persisted into the Mississippian (Viele and Thomas, 1989). Drill data show that the Cambrian-Ordovician and younger passive-margin shelf-carbonate facies extends southward in the subsurface beneath the Arkoma foreland basin and Ouachita thrust belt; however, the southward limit of the passive-margin facies is not closely constrained because of the great depth (>8 km) and lack of deep wells. Southward extent of the carbonate facies beneath the Ouachita thrust belt is inferred from the character of seismic reflectors (Lillie et al., 1983).

The exposed Ouachita thrust belt consists of disharmonically deformed thrust sheets of early and middle Paleozoic deep-water offshore passive-margin facies and late Paleozoic synorogenic turbidites (Figs. 4B and 5) (summary in Arbenz, 2008). The oldest strata in the allochthon comprise the Upper Cambrian Collier Shale (Fig. 4B). The Cambrian–Middle Mississippian offshore passive-margin succession is exposed almost exclusively in the central Benton and Broken Bow uplifts, and the late Paleozoic synorogenic turbidites dominate outcrops of both the frontal and trailing (southern) parts of the thrust belt. 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 Cambrian–Lower Ordovician passive-margin offshore succession is characterized by dark-colored shale, and includes sandstone, calcareous mudstone, chert, and carbonate-clast conglomerates (summary in Arbenz, 1989a; Viele and Thomas, 1989). The 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, Fig. 4B) contains 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). The granite boulders have U-Pb zircon ages of 1284 ± 12, 1350 ± 30, 1407 ± 13, and 1300–1350 Ma (Bowring, 1984). Although Grenville-age (1.0–1.35 Ga) rocks extend along most of the Laurentian rifted margin, data are not adequate to closely constrain the trace of the Grenville front in the subsurface in the region northeast of the Alabama-Oklahoma transform.

The ages of the granite boulders suggest that the transform locally cut across the Grenville front, leaving rocks of the Granite-Rhyolite province along the transform margin (e.g., Bickford and Anderson, in Van Schmus et al., 1993). 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 or oceanic crust. Submarine canyons evidently penetrated the passive-margin shelf edge and cut into crystalline basement rocks at the transform margin of Laurentia.

A seismic velocity model from the wide-angle reflection/refraction PASSCAL survey and a gravity model, extending across the Ouachita thrust-belt structures in Arkansas and southward beneath the Gulf Coastal Plain, show an abrupt southern margin of Laurentian continental crust at the location of the Alabama-Oklahoma transform fault (Keller et al., 1989a; 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 boundary consistent with the geometry of a near-vertical transform fault.

In the Ouachita thrust belt, the off-shelf rocks are thrust over the carbonate-shelf rocks, which remained in the footwall of the Ouachita allochthon (Fig. 5) (Viele, 1979; Arbenz, 1989a, 2008; Viele and Thomas, 1989). The regional detachment is in the lower part of the off-shelf passive-margin succession and ramps upward into the late Paleozoic synorogenic turbidites toward the foreland. Beneath the central uplifts, in which the stratigraphically and structurally lower components of the allochthon are exposed, broad ramp anticlinal surfaces are associated with thrust faults in basement rocks (e.g., Nelson et al., 1982; Lillie et al., 1983; Viele, 1989; Arbenz, 2008). The basement ramp anticlines warped the Ouachita detachment and overlying allochthon (Nelson et al., 1982; Lillie et al., 1983; Viele, 1989; Arbenz, 2008). The shortening of the basement rocks may be as much as 23 km, an order of magnitude less than that of the thin-skinned Ouachita allochthon (Fig. 5) (Arbenz, 2008). The basement-rooted thrust faults and associated ramp anticlines represent the only deformation of the continental crust along the transform margin; otherwise the rift-stage geometry of the transform fault has been preserved.

The off-shelf rocks in the Ouachita allochthon must be palinspastically restored on the outboard side of the carbonate-shelf facies (Fig. 5), and the restored shelf-edge facies boundary is inferred to mark the edge of continental crust along the transform margin. No shelf-edge facies have been identified, and the trace and restored position of the shelf edge are constrained only by the palinspastic reconstruction of the continental-shelf and off-shelf facies.

Southeastern Part of Alabama-Oklahoma Transform Margin, Mississippi-Alabama

Southeastward from Arkansas, the traces of 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 across the subsurface Ouachita thrust belt in Mississippi show abrupt southward thinning of the crust from ~35 km thickness to <10 km thickness within a distance of <50 km (Fig. 6) (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 Ouachita thrust front curves from eastward strike in outcrop in Arkansas to southeastward strike in the subsurface in eastern Mississippi along the southwest side of the Black Warrior foreland basin, where the leading edge of the Ouachita allochthon is as much as 170 km inboard from the transform margin of Laurentian crust (Fig. 1). The Black Warrior basin is a southwest-dipping homoclinal broken by northwest-striking normal faults; the homoclinal dips beneath the northwest-striking Ouachita thrust front (Fig. 6). Drill data indicate that, as in the outcrops in Arkansas, the Ouachita allochthon consists of deep-water facies, and the allochthon was emplaced over the passive-margin carbonate succession, which remained in the footwall (Thomas, 1973, 1985). The Ouachita thrust faults ramp over the normal faults in the Black Warrior basin (Fig. 6).

Deep wells in the Black Warrior basin show that a relatively thick carbonate succession (Fig. 4C) overlies a generally thin and laterally discontinuous basal sandstone, which rests on Precambrian crystalline basement rocks (Thomas, 1988, 1989a). The age of the base of the sedimentary cover is unconstrained biotatigraphically, but farther east in the Appalachian thrust belt in Alabama, the oldest documented Paleozoic strata are Early Cambrian age (Butts, 1926; Copeland and Raymond, 1984). If the basal sandstone in the Black Warrior basin is Early Cambrian, it represents post-rift transgression that is much earlier than that across the Arkansas segment of the transform margin (Fig. 4B); however, the shelf is partitioned by the late synrift intracratonic Mississippi Valley graben between
the Arkansas outcrops and the Black Warrior basin (Fig. 1). The southwestward extent of the shelf carbonate succession toward the transform margin beneath the Ouachita allochthon in Mississippi is unconstrained by available data. Distinctive seismic reflectors allow tracing of the carbonate beneath the frontal Ouachita thrust sheets; however, where the Ouachita allochthon thickens southwestward to >7 km, seismic resolution of the sub-detachment rocks is lost.

Some indication of the extent of the carbonate facies may be gained from the Appalachian thrust sheets, which can be traced (using seismic reflection data and deep wells) from the outcrops in Alabama westward in the subsurface (Thomas, 1973; Thomas et al., 1989; Surles, 2007). In eastern Mississippi beneath the Gulf Coastal Plain, the westward striking Appalachian thrust front truncates southeast-striking Ouachita thrust faults (Fig. 1), indicating that northeast-directed Ouachita thrusting along the southwest side of the southwest-deepening Black Warrior basin preceded northwest-directed Appalachian thrusting (Thomas, 1989a; Whiting and Thomas, 1994; Thomas and Whiting, 1995). Although Ouachita thrust faults emplaced off-shelf sedimentary facies over the shelf edge, leaving the passive-margin shelf facies in the footwall (“Ouachita-style structure”), Appalachian thrust sheets are detached in mud-dominated strata near the base of the passive-margin carbonate succession; and the Cambrian-Ordovician massive carbonate unit is translated within Appalachian thrust sheets (“Appalachian-style structure”). These characteristics distinguish the Appalachian and Ouachita thrust sheets in the subsurface, and the Appalachian thrust sheets are internally much more coherent than the Ouachita thrust sheets. The massive carbonate unit serves as a regional stiff layer, controlling the geometry of Appalachian thrust sheets and thrust ramps; and palin- spastic restoration of Appalachian thrust sheets can rely on line-length balancing. Restoration of the Appalachian thrust sheets shows that the passive-margin carbonate facies extended to near the projected trace of the Alabama-Oklahoma transform fault on the corner of the Alabama promontory (Thomas, 1991).

MISSISSIPPI VALLEY GRABEN

The Mississippi Valley graben (also called Reelfoot rift in some publications) is an intracratonic basement fault system now beneath the Mississippi Embayment of the Gulf Coastal Plain (Figs. 1 and 7). The graben is parallel with the Blue Ridge rift, which is ~500 km to the southeast. The early Paleozoic stratigraphy on the opposite shoulders of the Mississippi Valley...
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The Cambrian stratigraphy in the graben contrasts markedly with that outside the graben (Fig. 4B). Although the basal sandstone (late Middle Cambrian) west of the graben evidently is younger than that to the east, where the basal sandstone may be of Early Cambrian age, the post-Sauk unconformity caps the Lower Ordovician carbonates regionally.

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The Cambrian stratigraphy in the graben contrasts markedly with that outside the graben (Fig. 4B). Although the basal sandstone (late Middle Cambrian) west of the graben evidently is younger than that to the east, where the basal sandstone may be of Early Cambrian age, the post-Sauk unconformity caps the Lower Ordovician carbonates regionally.
salient of the thrust belt; that bend of the thrust belt has been the basis for interpretation of the shape of the Ouachita embayment of the Iapetan rifted margin, which is outlined by the intersection of the northwest-striking Alabama-Oklahoma transform fault and the northeast-striking Ouachita rift (Fig. 1) (Thomas, 1976, 1977, 2006). The lower Paleozoic passive-margin succession of sandstone and limestone extends southeastward in the footwall beneath the Ouachita allochthon of off-shelf facies. The northeast-trending Broken Bow uplift in the apex of the Ouachita salient (Fig. 1) is similar to the Benton uplift in that the older off-shelf facies are exposed above a ramp anticline of basement rocks on a basement-rooted thrust fault (Arbenz, 2008). Two deep wells on the Broken Bow uplift penetrated meta-carbonate rocks (interpreted to be Ordovician shelf facies) beneath thrust sheets of Ouachita off-shelf facies, showing that the shelf carbonate extends at least as far southeast as the palinspastic location of the basement rocks in the Broken Bow uplift (Nicholas and Waddell, 1989; Arbenz, 2008). A linear positive gravity anomaly extends along the Broken Bow uplift (Kruger and Keller, 1986).

In the foreland of the Ouachita embayment, the transgressive passive-margin succession reverts directly on basement, and no synrift sedimentary rocks are known. A large gravity minimum just north of the apex of the curved trace of the Ouachita thrust-belt salient, and northwest of the gravity high along the Broken Bow uplift, indicates a subsurface mass of low-density rocks (Kruger and Keller, 1986). The gravity minimum may be the expression of a locally thick synrift sedimentary accumulation (Keller et al., 1989b), which is now deep in the subsurface and along the northwesterly projected trace of the Alabama-Oklahoma transform fault. Similarly thick synrift sediment accumulations are associated with other transform faults along the Laurentian margin (Thomas, 2006).

**OUACHITA RIFT ZONE**

Southward from the abrupt bend in the Ouachita thrust belt in southeastern Oklahoma, the thrust belt trends south-southwestward and passes southward beneath the cover of the Gulf Coastal Plain (Fig. 1). The relatively straight trace of the thrust front in the subsurface has been used to infer the shape of the pre-orogenic rifted margin. Abundant drill data document a frontal thrust belt of off-shelf sedimentary facies like those in the Ouachita outcrops in Arkansas and Oklahoma, and a trailing metasedimentary belt (low-grade metamorphic rocks of the "Ouachita interior zone") (Thomas et al., 1989).

Prominent positive gravity and magnetic anomalies extend along the Ouachita interior zone, around an abrupt curve from south-southwest strike east of the Llano uplift to northwest strike south of the Llano uplift (Fig. 1) (Keller et al., 1989b). Although several possible sources may be proposed for the potential field anomalies, modeling requires a major transition in crustal structure, indicating the location of the continental margin. Specific palinspastic reconstruction of the crustal structure of the Ouachita rift is somewhat uncertain because of the overprint of Mesozoic rifting and opening of the Gulf of Mexico along the same alignment (Mickus et al., 2009).

A lower Paleozoic passive-margin succession of basal sandstone and overlying carbonate (Fig. 4A) dips eastward in the Fort Worth basin and from the Llano uplift beneath the Ouachita thrust front (summary in Thomas and Astini, 1999). As in the Ouachita thrust belt in Arkansas and Oklahoma, off-shelf rocks have been thrust over the shelf edge onto the shelf carbonate facies (Fig. 8).

In east Texas, east of the Fort Worth foreland basin, the Waco uplift (Fig. 1) is a subsurface basement structure, in which basement and cover rocks are significantly uplifted relative to the elevation of comparable rocks beneath the leading part of the Ouachita thrust belt (Fig. 8) (Rozendal and Erskine, 1971; Nicholas and Waddell, 1989). A deep well on the Waco uplift penetrated thrust sheets of "Ouachita facies" off-shelf strata, below which marble and quartzite overlies basement facies (Figs. 4A and 8). The well data indicate that the shallow-marine shelf-carbonate facies extends to the palinspastic location of the Waco uplift and that the palinspastic location of the Ouachita thrust sheets of deep-water facies must lie farther east than the shelf edge at the rifted margin of Laurentian crust (Fig. 8).

Farther south, southeast of the Llano uplift, COCORP seismic reflection profiling images the Luling uplift (Fig. 1) beneath the Ouachita thrust belt (Culotta et al., 1992). The uplift is interpreted to be similar in geometry and composition to the Waco uplift. Along with the Broken Bow uplift, the Waco and Luling uplifts suggest an alignment of basement thrust ramp anticlines along most of the Ouachita rift margin of Laurentia. These basement structures may be similar to the northern Blue Ridge basement ramp anticline in Virginia (e.g., Harris, 1979; Pratt et al., 1988; Costain et al., 1989; Thomas and Becker, 2007); however, in contrast, the basement uplifts along the Ouachita rift margin are covered by thrust sheets of off-shelf facies.

The passive-margin succession exposed around the Llano uplift and drilled in the Fort Worth basin has a basal sandstone of latest Middle Cambrian age, and an overlying carbonate generally less than 1000 m thick (Fig. 4A) (summary in Thomas and Astini, 1999). The basal beds overlap a paleotopographic surface with more than 200 m of relief on the Precambrian basement (Barnes et al., 1972). The age of the base of the passive-margin succession shows that post-rift thermal subsidence began later along the Ouachita rift than along the Blue Ridge rift, where the basal transgressive succession is of Early Cambrian age (Fig. 4). The age of passive-margin transgression onto the Laurentian margin along the Ouachita rift indicates a time of rifting consistent with the age of igneous rocks along the Southern Oklahoma fault system and with the stratigraphically constrained age of the end of extensional fault movement along the Mississippi Valley and Birmingham grabens.

**SOUTHERN OKLAHOMA FAULT SYSTEM**

The Southern Oklahoma fault system extends >500 km northwesterly into the Laurentian craton from the Ouachita thrust front ~100 km south of the abrupt bend in strike of the Ouachita salient (Fig. 1) (Ham et al., 1964; Johnson et al., 1988; Keller and Stephenson, 2007). The fault system is most evident in outcrop because of large-magnitude basement faults of late Paleozoic age. A bimodal suite of igneous rocks with crystallization ages of 530–539 Ma (Hogan and Gilbert, 1998; Thomas et al., 2000b) records a Cambrian-age synrift component of the fault system. Linear, northwest-trending, high-amplitude short-wavelength gravity and magnetic anomalies outline a steeply bounded zone of dense igneous rocks ~65 km wide (Gilbert, 1983; Coffman et al., 1986; Denison, 1989; Keller and Stephenson, 2007). The anomalies end abruptly southeastward, indicating the intersection of the zone of mafic rocks with the rifted continental margin (Keller et al., 1989b). Evidence of Cambrian synrift faults is found in displacements of the Cambrian volcanic rocks with respect to Precambrian basement, faults within the volcanic rocks, and angular discordances within the layered igneous rocks (Ham et al., 1964; McConnell and Gilbert, 1986).

The igneous rocks include gabbro, basalt, granite, and rhyolite (Hogan and Gilbert, 1998); the composition reflects deep sources in the upper mantle. The steep gradients on both sides of the potential field anomalies document steep boundaries of the mafic rocks in the shallow crust. The geometry and composition indicate crust-penetrating near-vertical fractures as magma conduits, consistent with a leaky transform fault. The evident large volume and short time span of magma production, however,
The Iapetan rifted margin of southern Laurentia

suggest a possible convergence of multiple causes of melting.

A transgressive passive-margin succession of basal sandstone and overlying shallow-marine carbonates overlaps the Cambrian igneous rocks (Fig. 4B), and the age of the base of the transgressive succession is middle Late Cambrian (Denison, in Johnson et al., 1988). Within the limits of resolution, the onlap here is coeval with the overstep of the graben boundary faults of the Mississippi Valley and Birmingham grabens by the carbonate rocks of the basal Knox Group (Fig. 4) (Thomas, 1991). Above the basal sandstone along the Southern Oklahoma fault system, the overlying carbonate succession is exceptionally thick (Fig. 4A), consistent with synrift thermal uplift followed by post-rift cooling of the shallow igneous rocks (Thomas and Astini, 1999).

The Southern Oklahoma fault system (commonly also called the Southern Oklahoma aulacogen) was interpreted previously to be a failed rift, specifically the failed arm of a three-armed radial-rift triple junction (e.g., Burke and Dewey, 1973; Hoffman et al., 1974), an interpretation that is supported by a three-armed pattern of linear gravity highs at the junction of the Southern Oklahoma fault system and the Ouachita orogen (Keller and Stephenson, 2007). Prominent linear gravity highs define three intersecting arms, each reflecting a different source: a relatively short, northeast-trending arm along the Broken Bow basement uplift; a northwest-trending arm, extending into the continent along the mafic igneous rocks of the Southern Oklahoma fault system; and a south-southwest trending arm, extending along the subsurface interior zone of the Ouachita orogen in east Texas and curving abruptly to the northwest around the corner of the Texas promontory. The concept of a failed rift was supported in part by interpretation of a subsurface, thick clastic metasedimentary succession as rift-fill sediment; however, more detailed work has shown that the metasedimentary succession is >1.0 Ga (age of metamorphism) and is unrelated to Cambrian rifting (Muehlberger et al., 1967; Denison et al., 1984; Coffman et al., 1986). Previous analogy with the Benue trough of West Africa as the failed arm of a rift triple junction also has been superseded by the interpretation of the Benue trough as a strike-slip fracture system, projecting into the African continent from transform faults that offset the rifted margin of West Africa (e.g., Francheteau and Le Pichon, 1972; Mascle et al., 1988, 1992; Benkhelil et al., 1998). The latter observations provide an appropriate analog for the Southern Oklahoma fault system as a transform-parallel intracratonic fault projecting into the continent from the Iapetan margin (Thomas, 1991);
however, synrift magmatism dominated the Southern Oklahoma fault system. The Southern Oklahoma fault system is parallel but not aligned with the Alabama-Oklahoma transform fault; instead the Southern Oklahoma transform-parallel fault system intersects the Ouachita rift ~120 km south of the corner of the Ouachita embayment (Fig. 1). The near coincidence in age of the Southern Oklahoma igneous rocks with that of the sedimentary fill of the Birmingham and Mississippi Valley intracratonic extensional grabens suggests a regional system of northwest-southeast extension partitioned by northwest-striking transform faults. In this context, the Southern Oklahoma fault system is a transform-parallel, intracratonic, leaky transform fault.

ARGENTINE PRECORDILLERA

The Argentine Precordillera is an exotic terrane now in the eastern foothills of the Andes in southwestern Argentina (Ramos et al., 1986; Astini et al., 1995, 1996). A wide variety of evidence indicates that the Precordillera was rifted from the Ouachita embayment of Laurentia in Cambrian time and accreted to western Gondwana in Ordovician time (Thomas and Astini, 1996, 2003; Astini and Thomas, 1999; Ramos, 2005). Indications of age and mechanism of rifting show that the rifted margin of the Precordillera is conjugate to the Ouachita rift margin of the Texas promontory of southern Laurentia (Figs. 1 and 2) (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 (Fig. 9) (Astini and Vaccari, 1996). The Cerro Totora Formation has an olenellid fauna identical to that in the Lower Cambrian Rome Formation in the southern Appalachians (Butts, 1926; Palmer, 1971; Astini and Vaccari, 1996; Astini et al., 1996). Lithologic similarities include red mud-cracked sandstones, Salterella-bearing limestones, and evaporites. Strontium isotopes from Cerro Totora and Rome evaporites indicate similar ages and similar depositional settings (Thomas et al., 2001). Detrital-zircon populations from sandstones in the Cerro Totora and in the Rome are similar and suggest a similar source, which is consistent with cratonic Laurentia (Thomas et al., 2004). The carbonate succession above the Cerro Totora clastic-evaporite facies corresponds in age to southern Appalachian carbonates from middle Lower Cambrian through Lower Ordovician (Fig. 9). The Precordillera carbonate succession, however, is much thicker than the carbonate-shelf succession on the Texas promontory of Laurentia, and the base of the carbonate succession in the Precordillera is older than that on the Texas promontory (Fig. 9) (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 consistent with the observations of complementary asymmetry of subsidence on the conjugate rift margins of a simple-shear low-angle-detachment rift system (Fig. 10) (summary in Thomas and Astini, 1999). The lack of synrift sedimentary deposits, as well as the paleotopographic relief beneath the basal transgressive sandstone on the Texas promontory, is characteristic of upper-platte margins, in contrast to lower-platte margins, which are characterized by graben-fills of synrift sediment followed by earlier subsidence and transgression as in the Precordillera (Fig. 10). Specifically, these contrasts show that the Texas promontory was an upper-platte margin and the Precordillera was a lower-platte margin (Thomas and Astini, 1999).

The age of synrift rocks in the Precordillera constrains the time of rifting from Laurentia to Early Cambrian, the age of the Cerro Totora red beds and evaporites (Astini et al., 1995; Thomas and Astini, 1996, 1999). This age of rifting is consistent with the age of synrift igneous rocks along the Southern Oklahoma transform-parallel fault system and with the ages of the graben filling synrift sediment in the Mississippi Valley and Birmingham grabens. Initial rifting in 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. The end of basement fault extension marks the time of separation of the Precordillera microplate from Laurentia.

TEXAS TRANSFORM FAULT

South of the Llano uplift beneath the cover of the Gulf Coastal Plain, the trace of the Ouachita thrust belt bends from south-southwest to west-northwest and extends in that direction in the subsurface across south Texas to the exposed thrust belt in the Marathon region of west Texas (Fig. 1). The trace of the thrust belt has been interpreted to parallel the pre-orogenic rifted margin of continental crust (e.g., Thomas, 1977); however, documentation for the actual location of the margin is limited. The gravity and magnetic anomalies associated with the Ouachita interior zone curve ~90° around the Texas promontory and extend northwestward along the northwest-trending Ouachita thrust belt in south Texas. These anomalies include a crustal boundary (Keller et al., 1989b), interpreted to be the Ouachita rift and Texas transform, which outline the Texas promontory (Fig. 1).

The Devils River uplift (Fig. 1), a basement uplift along part of the northwest-trending Ouachita thrust belt, appears to be generally similar, with some exceptions, to other basement uplifts along the Ouachita system. Deep wells on the uplift have drilled through a meta-carbonate succession into a metasedimentary-metavolcanic succession and underlying basement rocks (Figs. 4A and 11) (Nicholas and Rozendal, 1975; Denison et al., 1977; Nicholas and Waddell, 1989). The details of structure are somewhat uncertain, and available data may be interpreted as a northeast-directed basement-cored ramp anticline (shown in Fig. 11), or alternatively as a fault-bounded basement horst (Nicholas, 1983). In either interpretation, the palinspastic location of the Devils River uplift is not far south of the present location, unless the basement uplift has been displaced along the orogen by strike-slip motion. Unlike the other basement uplifts along the Ouachita orogen, the Devils River uplift is at the leading edge of the thrust belt and is not covered by thrust sheets of deep-water facies; however, off-shelf rocks are recognized in the frontal thrust sheets to both northwest and southeast along Ouachita strike. The Devils River basement rocks and cover are juxtaposed with synorogenic foreland-basin deposits (Nicholas and Waddell, 1989).

The carbonate cover on the Devils River basement marks the minimum extent of the passive-margin shelf toward the transform margin, thereby constraining the location of the shelf edge. The age of the lower part of the carbonate cover is in dispute: either Middle Cambrian (Palmer et al., 1984), or Late Cambrian (Nicholas and Waddell, 1989). The age is critical for constraining the time of initial post-rift passive-margin transgression along this part of the Laurentian rifted margin, but no definitive biostratigraphic data are available. Below the carbonate cover, a metasedimentary-metavolcanic (metarhyolite, metadacite) unit (~850 m thick) overlies Precambrian (1121–1246 Ma, Rb/Sr whole rock isochron dates) basement (Nicholas and Waddell, 1989). Geochronological analyses of the volcanic rocks include Rb/Sr whole rock rock
Figure 9. Correlation chart comparing a stratigraphic section from the Argentine Precordillera terrane with a section on the conjugate rift margin on the Texas promontory and a section on the Alabama promontory. Chart compiled from data and correlations in Astini et al. (1995) and Thomas and Astini (1999). Color code for chronostratigraphic subdivisions same as in Figure 4.
isochron dates of 524 ± 31, 529 ± 31, and 699 ± 26 Ma (Nicholas and Rozendal, 1975; Denison et al., 1977; Nicholas and Waddell, 1989). These dates suggest synrift volcanism contemporaneous either with rifting along the Ouachita rift or with early rifting along the Blue Ridge rift; however, U-Pb zircon data are needed to constrain the correlation.

**CORNER OF MARATHON EMBAYMENT**

In the Marathon topographic basin in west Texas, the Ouachita thrust belt is exposed in a relatively small area surrounded by extensive Mesozoic strata of the Gulf Coastal Plain (Fig. 1). Strike of the thrust belt curves locally from northwesternly to southwesterly, outlining the Marathon structural salient. The abrupt curve of the thrust front has been the basis for interpretation of the location of the Marathon embayment, outlined by intersection of the Texas transform with the Marathon rift, in the Lapatetan rifted margin of Laurentia (Thomas, 1977). Only limited data from deep wells are available (e.g., Ross, 1986; Muehlberger and Tauvers, 1989a, 1989b), and no seismic reflection surveys are available to support reconstruction of the rifting margin. A prominent, relatively narrow gravity high extends along the subsurface Ouachita interior zone northwestward to the outcrops of the Marathon salient (Handschi et al., 1987; Keller et al., 1989b), marking the trace of the Texas transform (Fig. 1). The gravity high bends abruptly southward within the arc of the Marathon salient, extending along the Ouachita interior zone and marking a crustal boundary (Handschi et al., 1987), which is interpreted to be the Marathon rifted margin of Laurentian crust (Figs. 1 and 12). The abrupt curve of the gravity high outlines the Marathon embayment at the intersection of the Texas transform and Marathon rift (Fig. 1). A gravity low, inside the arc of the Ouachita-interior-zone high, marks the location of the accreted Coahuila terrane, the emplacement of which has obscured the deep crustal structure in much of the Marathon embayment (Dickinson and Lawton, 2001).

The Marathon allochthon, containing a stratigraphic succession of Cambrian-Mississippian off-shelf passive-margin facies (Fig. 4A) and Mississippian-Permian synorogenic turbidites, is thrust over Cambrian-Mississippian carbonate-dominated passive-margin shelf facies and Mississippian-Permian synorogenic shallow-marine deposits (Ross, 1986; Muehlberger and Tauvers, 1989a; McBride, 1989). The extent of the passive-margin shelf southeastward beneath the allochthon is not documented by deep drilling (Fig. 12), and available data are not adequate to support a quantitative palinspastic reconstruction of the locations of the shelf margin and of the rifted margin of continental crust. Because the allochthon contains exclusively off-shelf passive-margin facies and is thrust over the passive-margin shelf facies, the regional detachment must cut through the shelf edge somewhere beneath the allochthon.

Internally the Marathon thrust belt includes a disharmonic array of thrust faults and tight folds of various wavelengths; internal shortening within the allochthon is estimated to be ~3:1 (King, 1937; Muehlberger and Tauvers, 1989a). In addition to the internal shortening, the leading edge of the allochthon has been translated an unknown distance over the passive-margin shelf. Complete palinspastic reconstruction of the allochthon requires restoring the cratonward translation over the footwall, as well as the internal shortening within the allochthon. The palinspastic site of deposition of the strata now in the Marathon allochthon is interpreted to be in an off-shelf setting on transitional or oceanic crust relative to a passive-margin shelf on Laurentian continental crust (e.g., McBride, 1989), and the shelf edge at the rifted margin of continental crust marks the boundary between the contrasting facies.

The oldest strata in the allochthon, Upper Cambrian Dagger Flat Sandstone (Figs. 4A and 12), include coarse arkosic sandstone, shale, quartzose sandstone, calcarenite, and conglomerate, which contains clasts of limestone, shale, chert, sandstone, granite, and mafic igneous rocks (McBride, 1989). The overlying Lower Ordovician Marathon Formation (Fig. 4A) includes limestone, shale, sandstone, limestone-clast conglomerate, and boulder beds (McBride, 1989). One distinctive olistostrome, dominated by dolostone olistoliths, was originally mapped as the Monument Spring Dolomite Member of the Marathon Limestone (King, 1937). Otherwise, the boulders include a variety of limestones, dolostones, and other sedimentary rock types. Significantly, the boulders contain fossils of shallow-water forms in contrast to the deeper water graptolite faunas of the interbedded shales; however, the biostratigraphic ages are indistinguishable. The Dagger Flat and Marathon strata are time-equivalent to a basal sandstone and massive carbonate (Ellenburger Group) of the passive-margin shelf facies (Fig. 4A). Sedimentary structures indicate deposition by turbidity flows from sources along the shelf edge to the northwest of the depositional site (McBride,
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The large size and abundance of the dolostone olistoliths suggests that the depositional site was near the shelf edge; however, the palinspastically restored distance from the leading edge of the allochthon through the extent of the dolostone olistostrome is ~70 km (Fig. 12). The Middle Ordovician Fort Peña Formation and Woods Hollow Shale are dominated by shale but include interbeds of sandstone, limestone, chert, and conglomerate. Both units contain boulder beds, which are most numerous near the top of the Woods Hollow. The boulders include shallow-water carbonate, sandstone, felsite porphyry, and schist (McBride, 1989); and fossils in the carbonate clasts document a range of Late Cambrian and Early Ordovician ages (King, 1937; Wilson, 1954; summary in McBride, 1989). Considering the palinspastically restored length of off-shelf facies within the internally deformed allochthon, the depositional site of the boulders of shallow-water carbonate reached at least 70 km from the shelf edge, which must have been the source of submarine slumps and debris flows that transported the boulders into deeper water (Fig. 12). The clasts of granite and metamorphic rocks suggest that submarine canyons in the shelf edge eroded down into basement rocks.

Boulders in the Marathon synorogenic clastic wedge, specifically in the Pennsylvanian Haymond Formation in the middle part of the allochthon, provide further insight into the nature of the passive margin. The Haymond boulders are of three distinct types: intrabasinal fragments of older strata of the Marathon allochthon, exotic igneous (369–457 Ma Rb/Sr isochron, Denison et al., 1969) and metamorphic rocks of unknown source, and limestone boulders with Middle Cambrian (Marjuman) trilobites distinctive of the seaward margin of a carbonate shelf (King, 1937; Palmer et al., 1984; Ross, 1986; McBride, 1989). The boulders are within a turbidite succession, all of which is generally interpreted as derived from the orogenic belt southeast of a foreland basin (e.g., Denison et al., 1969; Ross, 1986). All of the boulders are inferred to have come from distinct thrust sheets within the orogen, and both the intrabasinal clasts and exotic rocks fit readily into that interpretation. The boulders of Middle Cambrian limestone, which are not in the same Marathon thrust sheet as the intrabasinal or exotic boulders (Fig. 12) (Palmer et al., 1984), however, suggest important constraints on both the age of rifting and the location of the rifted margin/shelf edge.

The Middle Cambrian limestones (Haymond boulders) are older than the base of the transgressive basal sandstones farther inboard around the Ouachita embayment and Texas promontory (on the Ozark dome and Llano uplift) (Fig. 1).
Figure 12. Structural cross section of Marathon thrust-belt structures and alternative interpretations of palinspastic reconstruction of Iapetan margin along the Marathon rift beneath the Marathon thrust belt and post-orogenic cover of Gulf Coastal Plain in west Texas (no vertical exaggeration; line of cross section shown in Fig. 1). All palinspastic cross sections are aligned at the northwest end with end point G at the northwest end of the structural cross section G–G'. Cross section compiled from data in King (1937), Flawn et al. (1961), Ross (1986), Palmer et al. (1984), McBride (1989), Muehlberger and Tauvers (1989a, 1989b), and Thomas et al. (1989).
Alternative 1: If the Middle Cambrian limestone boulders were derived directly from a thrust sheet within the growing Marathon orogen, the shortening within and translation of the allochthon together provide a measure of the original extent of the shelf and location of the margin (e.g., Palmer et al., 1984; Ross, 1986; Muehlberger and Tauvers, 1989a). The Middle Cambrian shelf edge must have been at the palinspastic site of the trailing thrust sheets, the location of which can be inferred only from the dispersal of the boulders.

Within the limitations of available data, several alternatives for palinspastically fitting a Middle Cambrian shelf edge along the Marathon rifted margin can be considered:

Alternative 2: Marathon thrusting, tectonic loading, and foreland subsidence evidently began in Mississippian time with deposition of the thick siliciclastic Tesnus Formation (Ross, 1986; McBride, 1989); therefore, translation onto the shelf and internal shortening of the Marathon allochthon may have progressed significantly before Haymond deposition. A thrust fault propagating through the sub-allochthon shelf edge could have provided a source for the Haymond boulders, which were deposited on the trailing part of the allochthon (Fig. 12-C). Considering the depositional site of the shelf-derived boulders in off-shelf sediment near the shelf edge in deep water suggests a minimum of ~85 km (present width from Marathon thrust front to Haymond boulders with 2:1 shortening) of translation onto the passive-margin shelf before deposition of the Haymond. This reconstruction places the shelf edge at a minimum of ~90 km southeast of the present thrust front and ~50 km southeast of the present location of the Haymond boulders (Fig. 12-C). The primary problem with this reconstruction is the lack of Middle Cambrian boulders in any of the Upper Cambrian–Ordovician formations in the off-shelf facies, although shelf-facies boulders of Late Cambrian–Early Ordovician ages and basement boulders are common. In contrast, the Haymond carbonate boulders are only from the Middle Cambrian. This reconstruction is similar in the magnitude of translation to the ~100 km translation in the Ouachita thrust belt in Arkansas and Oklahoma (Fig. 5).

Alternative 3: Passive-margin shelf and off-shelf deposition may have begun entirely around the Marathon embayment as early as Middle Cambrian, and boulders from the shelf edge could have been incorporated in an older (pre-Dagger Flat) part of the off-shelf succession far out from the shelf edge. The Middle Cambrian boulders could have been recycled from off-shelf passive-margin boulder beds within the orogen into the Haymond in the foreland basin; however, this succession of events requires a remarkable sorting of boulder types. This reconstruction is unconstrained in terms of the palinspastic location of the shelf edge. Further, it requires all off-shelf deposits older than Dagger Flat to have remained in the Marathon footwall, except for those included in the thrust sheet that supplied detritus to the Haymond.

Alternative 4: With only minimal translation of the Marathon allochthon onto the shelf, the depositional site of the Haymond was located generally southwest of the present location of the Devils River uplift, and erosion from the continental margin along the Texas transform at or near the Devils River uplift (Fig. 1) could have supplied the Middle Cambrian limestone boulders to the Haymond depositional site by southwest-directed debris flows and turbidity currents. Paleocurrent data and thickness distribution within the upper Paleozoic Marathon synorogenic clastic wedge (McBride, 1989; Muehlberger and Tauvers, 1989a) are consistent with southwesterly sediment dispersal from the Texas transform margin of the Marathon embayment, as well as from the Marathon orogenic belt on the southeast. This alternative places only general constraints on the location of the Marathon rift margin, and it relies on evolution of a passive-margin carbonate shelf as early as Middle Cambrian along the Texas transform. Considering the palinspastic length of the Marathon allochthon and minimal translation over the shelf, the rifted margin could be between ~160 and ~90 km southeast of the present thrust front of the Marathon salient (Fig. 12).

Alternative 5: The unique age of the Middle Cambrian limestone boulders, as well as the contrast in age with the Upper Cambrian–Lower Ordovician boulders in the passive-margin off-shelf boulder beds, suggests tectonic partitioning and diachronous subsidence of the continental shelf edge. These conditions can be...
met in progressive subsidence of a lower-plate margin, which is partitioned by multiple listric extensional faults (e.g., Lister et al., 1986). Post-rift thermal subsidence of listric fault blocks accounts for passive-margin transgression during Middle Cambrian and deposition of shelf-edge carbonates along the upthrown (seaward-facing) block (Fig. 12-D-1). Continued subsidence may have resulted in drowning of the shelf in latest Middle Cambrian and establishment of a new passive-margin shelf on a structurally higher and more inboard listric fault block (Fig. 12-D-2). With continued thermal subsidence (or sea-level rise), a carbonate buildup at the shelf edge maintained a steep seaward-facing slope, where submarine canyons cut through the Late Cambrian–Ordovician shelf carbonates and underlying basement to supply clasts to the Upper Cambrian and Ordovician deep-water deposits. Deposition of off-shelf (deep-water) passive-margin facies likely extended seaward, possibly forming a mud-dominated cover over the older Middle Cambrian shelf carbonates. The locations of the two essential rift-stage faults are not rigorously constrained, nor is the distance between them. For emplacement of the Marathon allochthon over the shelf, the most inboard possible location of the Late Cambrian shelf edge is \(-42 \text{ km} \) from the present thrust front; to yield the present spacing of thrust sheets, the distance between the Middle Cambrian and Late Cambrian shelf edges can be no more than \(\sim 125 \text{ km} \). Propagation of the Marathon décollement in the off-shelf Upper Cambrian facies led to emplacement of the Marathon allochthon. A break-forward thrust, cutting into the footwall, placed the Middle Cambrian shelf-edge strata in the orogenic provenance of the Haymond Formation (Fig. 12-D-2).

The first four listed alternatives all require fortuitous combinations of processes to generate observed distributions of boulders in the Marathon stratigraphy. The last (fifth) listed alternative is designed specifically to explain patterns of clast dispersal. Although it is speculative at this stage, this alternative offers the best comprehensive interpretation of all currently available data (alternative 5, Figure 12-D).

**DISCUSSION AND CONCLUSIONS**

**Trace of the Rifted Margin**

Both the Ouachita rift margin and the Alabama-Oklahoma transform margin of the Ouachita emplacement are preserved in the footwall of the Ouachita allochthon, which consists of off-shelf facies. Palinspastic reconstruction of basement ramp anticlines provides a reconstruction of the trace of the rift margin and shelf edge, which is consistent with palinspastic restoration of the distribution of passive-margin shelf carbonates and coeval off-shelf facies (Figs. 5 and 8). Geophysical modeling confirms the location of the Alabama-Oklahoma transform fault (Keller et al., 1989a; Mickus and Keller, 1992; Harry et al., 2003; Harry and Londono, 2004). Seismic reflection profiles image basement ramp anticlines, supporting palinspastic reconstruction along the Ouachita rift margin (Rozenlad and Erskine, 1971; Culotta et al., 1992). The traces and intersection of the rift and transform outline the Ouachita embayment (Fig. 1).

The southwestern part of the Blue Ridge rift defines the corner of the Alabama promontory at the intersection with the Alabama-Oklahoma transform (Fig. 1). Palinspastic reconstruction of the passive-margin shelf in the Appalachian orogen shows that the original continental shelf extended as much as 80 km southeast of the present limit of Laurentian crust at the Suwannee-Wiggins suture (Fig. 3). The crust-penetrating Suwannee-Wiggins suture marks continent-continent collision between Laurentian crust and Gondwanan (African) crust of the Suwannee terrane, and truncates Laurentian crust. The suture forms the present margin of Laurentian crust, but it is not at the original rifted margin as previously mapped (e.g., Thomas, 1991).

Intersections of the Ouachita rift with the Texas transform forms the southern corner of the Texas promontory, and intersection of the Texas transform with the Marathon rift forms the Marathon embayment (Fig. 1). The locations and traces of the Ouachita rift, Texas transform, and Marathon rift have been interpreted primarily on the basis of the sinuously curved trace of the Ouachita-Marathon frontal thrust belt around the Texas recess and Marathon salient (e.g., Thomas, 1977), as well as the gravity high along the Ouachita interior zone (Handschy et al., 1987; Keller et al., 1989b). Available data are not adequate to support quantiative palinspastic reconstruction of the extent of the passive-margin shelf or the rift-transform edge of continental crust. As a result both the trace and location of the continental margin are subject to interpretation, largely from reconstructions of the shelf-edge stratigraphy derived from composition of boulder beds in the off-shelf passive-margin strata and synorogenic turbidites (Fig. 12). Using these constraints, the trace of the Texas transform is parallel with the northwest-trending segment of the orogenic belt, and an intersection of the transform with the Marathon rift beneath the bend in the orogen at the Marathon salient defines the Marathon embayment of the continental margin.

**Structure of the Rifted Margin**

The rifted margin of the Alabama promontory is interpreted to be an upper-plate margin in a low-angle-detachment simple-shear rift system (Thomas, 1993). This interpretation is based on the relatively thin passive-margin shelf cover and a general lack of synrift sedimentation between basement and the passive-margin facies. Palinspastic reconstruction shows extensive normal faults (Fig. 3) antithetic to the detachment that dips under the upper plate. An abrupt along-strike change to thick synrift stratigraphy northeastward across the Georgia transform (Fig. 1) indicates a change in polarity of the low-angle detachment, and an along-strike change to lower-plate structure north of the Alabama promontory (Thomas, 1993; Tull and Holm, 2005). Although the original rift margin of the Alabama promontory has been truncated by the Suwannee-Wiggins suture, the upper-plate structure is indicated by the thrust-translated passive-margin strata (Fig. 3).

The Alabama-Oklahoma transform fault forms a steep boundary of Laurentian continental crust, as modeled from geophysical data (Keller et al., 1989a; Mickus and Keller, 1992; Harry et al., 2003; Harry and Londono, 2004). An abrupt shelf edge shed detritus into the off-shelf facies, and boulders of basement rocks indicate that submarine canyons penetrated through the passive-margin cover at the shelf edge. The age of the boulders (Bowring, 1984) shows that the transform fault cut across the Grenville front into rocks of the Granite-Rhyolite province. Pods of ultramafic rocks in the Ouachita allochthon of off-shelf passive-margin strata represent oceanic crust on which the deep-water sediment was deposited (Morris and Stone, 1986; Nielsen et al., 1989), indicating that by Ordovician time the transform margin of Laurentian crust faced an opening ocean and spreading oceanic crust in the Ouachita embayment.

The Ouachita rift margin between the Alabama-Oklahoma and Texas transforms is an upper-plate margin, as indicated by the composition and relatively small thickness of the passive-margin-shelf deposits of Late Cambrian–Early Ordovician age (Thomas and Astini, 1999). Other characteristics of an upper plate include paleotopographic relief on basement rocks beneath the passive-margin cover and lack of preservation of synrift deposits. The Argentine Precordillera microcontinent is the conjugate rift margin of the Ouachita rift and exhibits the characteristics typical of a lower plate (Thomas and Astini, 1999). For example, the Precordillera includes an Early Cambrian synrift succession that grades upward into passive-margin carbonates, and the passive-

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margin carbonate succession is thicker than that on the Texas promontory. Furthermore, the base of the passive-margin carbonate succession on the Precordillera is older than that on the Texas promontory. The stratigraphy confirms that passive-margin subsidence on the rifted margin of the Precordillera began earlier and continued to greater magnitude than that on the Texas promontory, consistent with complementary asymmetry of subsidence history on the opposite margins along an asymmetric low-angle-detachment rift (Fig. 10) (Thomas and Astini, 1999).

Lack of data precludes specific interpretations of crustal structure of the Texas transform and the Marathon rift, which intersect to form the corner of the Marathon embayment beneath the present Marathon salient of the late Paleozoic thrust belt (Fig. 1). Boulders in the offshelf facies are consistent with derivation from a steep continental slope as along a steep transform fault; however, some or all of the boulders may have sources along the Marathon rift margin. Distinct passive-margin offshelf facies in the Marathon allochthon and passive-margin shelf facies in the Marathon footwall, clearly document a shelf margin. Distribution and composition of boulders in both passive-margin and synorogenic deep-water deposits are best explained by a diachronous succession of extensional faults, the distribution of which indicates a relatively wide zone of transitional crust. These characteristics suggest that the Marathon rift is on the lower plate of a low-angle detachment (Fig. 12-D-2).

Age of Rifting

The age of rifting along the Blue Ridge rift on the corner of the Alabama promontory can best be approached using data from the Blue Ridge rift farther north in Tennessee and Virginia, where synrift rocks are exposed. Multiple episodes of synrift magmatism include components as old as ~750 Ma, and the youngest synrift igneous rocks along the Blue Ridge in Virginia have U-Pb zircon ages of 572 ± 5 to 564 ± 9 Ma (Aleinikoff et al., 1995; Walsh and Aleinikoff, 1999). The synrift rocks are overlain by a passive-margin succession of basal sandstone and overlying carbonate of Early Cambrian age. In Tennessee and farther south to the Georgia transform, the Early Cambrian passive-margin succession rests on thick synrift sedimentary deposits (summary in Thomas, 1991). On the Alabama promontory, the base of the passive-margin succession is not exposed, but the oldest strata in Appalachian thrust sheets are Early Cambrian (Fig. 4C) and are stratigraphically similar to the passive-margin succession along the Blue Ridge. The age of transition from rift to passive margin is consistently at the beginning of Cambrian time along the Blue Ridge rift.

The age of the Alabama-Oklahoma transform is based on the age of rifting along the Ouachita rift, the age of both rift-parallel and transform-parallel intracratonic fault systems, and the age of rifting of the Argentine Precordillera. Synrift red beds and evaporites (Cerro Totora Formation) in the Precordillera are Early Cambrian age (Astini et al., 1995; Astini and Vaccari, 1996), and the upward transition to passive-margin carbonates is late Early Cambrian (Fig. 9). In contrast, on the Texas promontory, the base of the passive-margin cover is latest Middle Cambrian, and the basal sandstone rests directly on basement (summary in Thomas and Astini, 1999). In the context of complementary asymmetry of subsidence along a low-angle-detachment rift, the time of initial rifting of the Precordillera from the Texas promontory is Early Cambrian (Fig. 10).

The rift-parallel intracratonic Mississippi Valley graben and Birmingham graben are northeast of and perpendicular to the Alabama-Oklahoma transform fault (Fig. 1). The age of the upper part of the fill of both grabens is biostratigraphically documented as Middle to early Late Cambrian (summary in Thomas, 1991). The fill of another graben southeast of and parallel with the Birmingham graben includes red beds and evaporites that are Early Cambrian, biostratigraphically and geochemically equivalent to the synrift Cerro Totora Formation in the Precordillera (Thomas et al., 2004), and the lower part of the fill of the Mississippi Valley and Birmingham grabens may be of the same age. The graben-fill successions and graben-boundary faults are overlapped by passive-margin carbonates of middle Late Cambrian age, indicating the end of rift extension. Continuing extension on these fault systems is compatible with rifting in Early Cambrian time and movement of the Precordillera microcontinent along the Alabama-Oklahoma transform as the ocean opened along the Ouachita rift; extensional faulting stopped by middle Late Cambrian when the Ouachita mid-ocean ridge migrated past the corner of Laurentian continental crust on the Alabama promontory (Thomas, 1991).

Synrift igneous rocks along the transform-parallel Southern Oklahoma fault system have crystallization ages of 530–539 Ma (Hogan and Gilbert, 1998; Thomas et al., 2000b). A Late Cambrian passive-margin succession overlapped the synrift igneous rocks as a result of post-rift thermal subsidence (Fig. 4A) (Thomas and Astini, 1999). The age of the synrift igneous rocks corresponds to the time of initial rifting along the Ouachita rift, as indicated by the age of synrift deposits in the Precordillera. Spreading of the Ouachita ocean resulted in post-rift thermal subsidence at different times on the opposite conjugate margins, as well as late-synrift extension on rift-parallel intracratonic faults.

Early Cambrian rifting around the Ouachita embayment and Argentine Precordillera contrasts with Early Cambrian evolution of a passive margin along the Blue Ridge rift. The diachronocity is interpreted to be a result of a spreading-ridge shift from the segment of the Blue Ridge rift south of the Alabama-Oklahoma transform to the Ouachita rift at the beginning of Cambrian time (Thomas, 1991; Thomas and Astini, 1996).

The initial transgressive passive-margin carbonate-shelf deposits, overlying Precambrian basement, around the Texas promontory are of late Middle Cambrian age (summary in Palmer et al., 1984); and the oldest offshelf facies in the Marathon allochthon are of Late Cambrian age. Middle Cambrian limestone boulders in the Marathon synorogenic deposits, however, indicate evolution of a passive-margin shelf earlier than deposition of any known strata in the region. Metavolcanic rocks in the Devils River uplift along the Texas transform have yielded Rb/Sr isochron dates of 524–529 Ma (Nicholas and Rozendal, 1975), comparable to the U-Pb zircon ages of synrift igneous rocks along the Southern Oklahoma fault system, and also of 699 Ma (Denison et al., 1977), comparable to ages of early components of the Blue Ridge rift. Evolution of a passive margin in Middle Cambrian is compatible with either date for the volcanic rocks; however, if the younger date of 524–529 Ma signifies the time of rifting, the initiation of subsidence as early as Middle Cambrian is consistent only with the typical subsidence history of a lower-plate structure. The difference in possible ages allows that Marathon rifting either was part of the older Blue Ridge phase, which may have been linked to the Marathon rift by a longer Texas transform south of the pre-rift site of the Precordillera, or was part of the younger Ouachita phase, during which the Precordillera was rifted from Laurentia. Considering the latter, the reconstructed size of the Precordillera microcontinent matches the size of the Ouachita embayment, suggesting that if the Marathon rift were contemporaneous with rifting away of the Precordillera, the Texas transform must have separated the Precordillera from another Laurentian microcontinent, possibly Chilenia (Ramos et al., 1986; Ramos, 2005). Like consideration of trace and structure of the margin, the age of rifting around the Marathon embayment requires more data for documentation.

In summary, Iapetan rifting of the margin of southern Laurentia includes two primary
phases. The older, the Blue Ridge rift, the southern part of which forms the eastern margin of the Alabama promontory, is dated by synrift volcanic rocks as young as 564 Ma and passive-margin transgression beginning in earliest Cambrian. The younger, the Ouachita rift reflects an inboard shift from the Blue Ridge rift and rifiting of the Argentine Precordillera from the Ouachita embayment, beginning at 530–539 Ma. The Ouachita rift is temporally and mechanically associated with the rift-parallel intracratonic Mississippi Valley and Birmingham graben systems, as well as with the transform-parallel intracratonic Southern Oklahoma fault system. The age of the Ouachita rift is documented by the 530–539 Ma synrift volcanics of the Southern Oklahoma fault system, by Early Cambrian synrift sediment along the conjugate rift margin in the Argentine Precordillera, and by late synrift graben-fill of Early to early Late Cambrian age in the Mississippi Valley and Birmingham graben systems.

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