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# Wilson cycles, tectonic inheritance, and rifting of the North American Gulf of Mexico continental margin

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## ABSTRACT

The tectonic evolution of the North American Gulf of Mexico continental margin is characterized by two Wilson cycles, i.e., repeated episodes of opening and closing of ocean basins along the same structural trend. This evolution includes (1) the Precambrian Grenville orogeny; (2) formation of a rift-transform margin during late Precambrian opening of the Iapetus Ocean; (3) the late Paleozoic Ouachita orogeny during assembly of Pangea; and (4) Mesozoic rifting during opening of the Gulf of Mexico. Unlike the Atlantic margins, where Wilson cycles were first recognized, breakup in the Gulf of Mexico did not initially focus within the orogen, but was instead accommodated within a diffuse region adjacent to the orogen. This variation in location of rifting is a consequence of variations in the prerift architecture of the orogens. The Appalachian-Caledonian orogeny involved substantial crustal shortening and formation of a thick crustal root. In contrast, the Ouachita orogeny resulted in minimal crustal shortening and thickening. In addition, rather than a crustal root, the Ouachita orogen was underlain by the lower plate of a relatively pristine Paleozoic subduction system that is characterized by a shallow mantle. A finite element model simulating extension on the margin demonstrates that this preexisting structure exerted fundamental controls on the style of Mesozoic rifting. The shallow mantle created a strong lithosphere beneath the orogen, causing extension to initiate adjacent to, rather than within, the orogen. On the Atlantic margins, the thick crustal root resulted in a weak lithosphere and initiation of extension within the interior of the orogen. Major features of the modern Gulf of Mexico margin, including the Interior Salt Basin, outboard unextended Wiggins arch, and an unusually broad region of extension

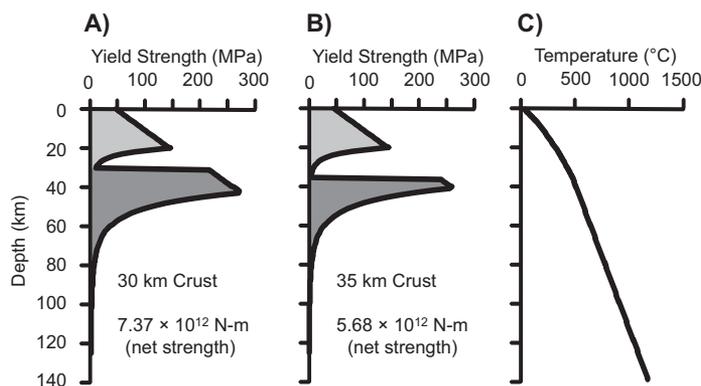
beneath the coastal plain and continental shelf, are direct consequences of the prerift structure of the margin.

## INTRODUCTION

The spatial association between continental breakup and preexisting orogens is often described within the context of a Wilson cycle, wherein orogenic belts formed by continental collision during closure of ancient ocean basins are reactivated during subsequent rifting episodes (Wilson, 1966; Vauchez et al., 1997). A classic example is the U.S. Atlantic margin, where opening of the North Atlantic Ocean began with a continental rifting episode within the late Paleozoic Appalachian-Caledonian orogen (Ziegler, 1989). The association between the positions of continental breakup and older orogenic belts is usually attributed to weakening of the lithosphere due to faulting in the brittle upper crust and the presence of a crustal root. The presence of the crustal root reduces the

strength of the lithosphere by replacing strong ultramafic mantle with relatively weak felsic crust (Fig. 1) (Braun and Beaumont, 1987; Dunbar and Sawyer, 1989; Chery et al., 1990; Krabbendam, 2001).

The Gulf of Mexico continental margin is similar to the U.S. Atlantic margin in that the axis of Mesozoic continental breakup trended subparallel to the buried middle Paleozoic Ouachita fold-and-thrust belt (Pindell and Dewey, 1982; Salvador, 1991a; Thomas, 1976, 1991). However, extension on the central North American Gulf of Mexico margin is restricted to regions south of the Ouachita fold-and-thrust belt and terminates abruptly on the southern (oceanward) flank of the orogen (Ewing, 1991). The Ouachita fold-and-thrust belt has undergone very little extensional deformation. Thus, the two margins differ in that the Ouachita orogen appears to have acted as a strong region during continental rifting rather than a zone of weakness like the Appalachian orogen. In the Gulf of Mexico, the weakest lithosphere must



**Figure 1.** The role of crust thickness on lithosphere strength. (A) Schematic illustration of the rheology of the lithosphere showing reference model with 30-km-thick crust. Net strength of the lithosphere, obtained by integrating the yield stress over depth, is indicated at the bottom. (B) A weak model with a 35-km-thick crust. (C) Geotherm used for yield strength calculations.

have been outboard of the orogenic belt, within the allochthonous terrane that was accreted to the southern North American continent during the Ouachita orogeny.

We propose that the differences in the style of extension of the two Mesozoic rifts can be attributed to differences in the preceding Paleozoic orogens. The Appalachian orogeny was a “hard” continent-continent collision that produced substantial shortening in both the hinterland and internides, with significant crustal thickening in the central part of the orogenic belt and exhumation of a deep metamorphic core (Fig. 2A) (Thomas, 1976; Pratt et al., 1988; Thomas et al., 1989; Hatcher et al., 1989; Sheridan et al., 1993). The ensuing Mesozoic rifting initiated within the interior of the orogen, where the crust was thickest and the lithosphere weakest. Remnants of the crustal root are still present beneath the southern Appalachian fold-and-thrust belt and in New England (Pratt et al., 1988; Taylor, 1989).

The Ouachita orogen is considered to be a “soft” collision, resulting from arc-continent

collision between Laurentia and Gondwana during assembly of Pangea (Fig. 2B) (Thomas, 1976; Arbenz et al., 1989; Thomas et al., 1989; Viele, 1989; Viele and Thomas, 1989). Deformation in the orogenic belt was buffered by its position within the Ouachita Embayment of the early to middle Paleozoic Laurentian rift margin, with most compressional deformation occurring to the east on the Alabama Promontory and to the west on the Texas recess (Thomas, 1976, 1991; Pindell, 1985; Houseknecht, 1986; Hale-Erich and Coleman, 1993). As a consequence, shortening within the Ouachita orogen in the central North American Gulf of Mexico coast is much less pronounced than in the Appalachian system, with no evidence of a crustal root or exposure of high-grade metamorphic rocks (Arbenz et al., 1989; Viele, 1989; Thomas, 1991). Instead, the Ouachita orogen in the central Gulf of Mexico region is underlain by a relatively pristine Paleozoic subduction system with thin crystalline crust and a relatively shallow mantle (Chang and McMechan,

1989; Keller et al., 1989; Mickus and Keller, 1992; Harry et al., 2003; Harry and Londono, 2004). Following collision, the shallow mantle beneath the Ouachita suture would have thermally reequilibrated during the ~50 m.y. that elapsed between collision and rifting, resulting in strong lithosphere, whereas the accreted arc would have had a relatively thick crust and weak lithosphere that was susceptible to extensional deformation.

A two-dimensional finite element model of continental rifting is used to test the hypothesis that lateral strength variations in the lithosphere inherited from Paleozoic tectonic events exerted a primary control on the distribution and nature of Mesozoic extensional deformation on the Gulf of Mexico continental margin. The model begins with a lithospheric thermal and rheological structure that is based on reconstructions of southern North America after accretion of the allochthonous terrane during middle Paleozoic time. The model allows for thermal reequilibration during a tectonically quiescent period from

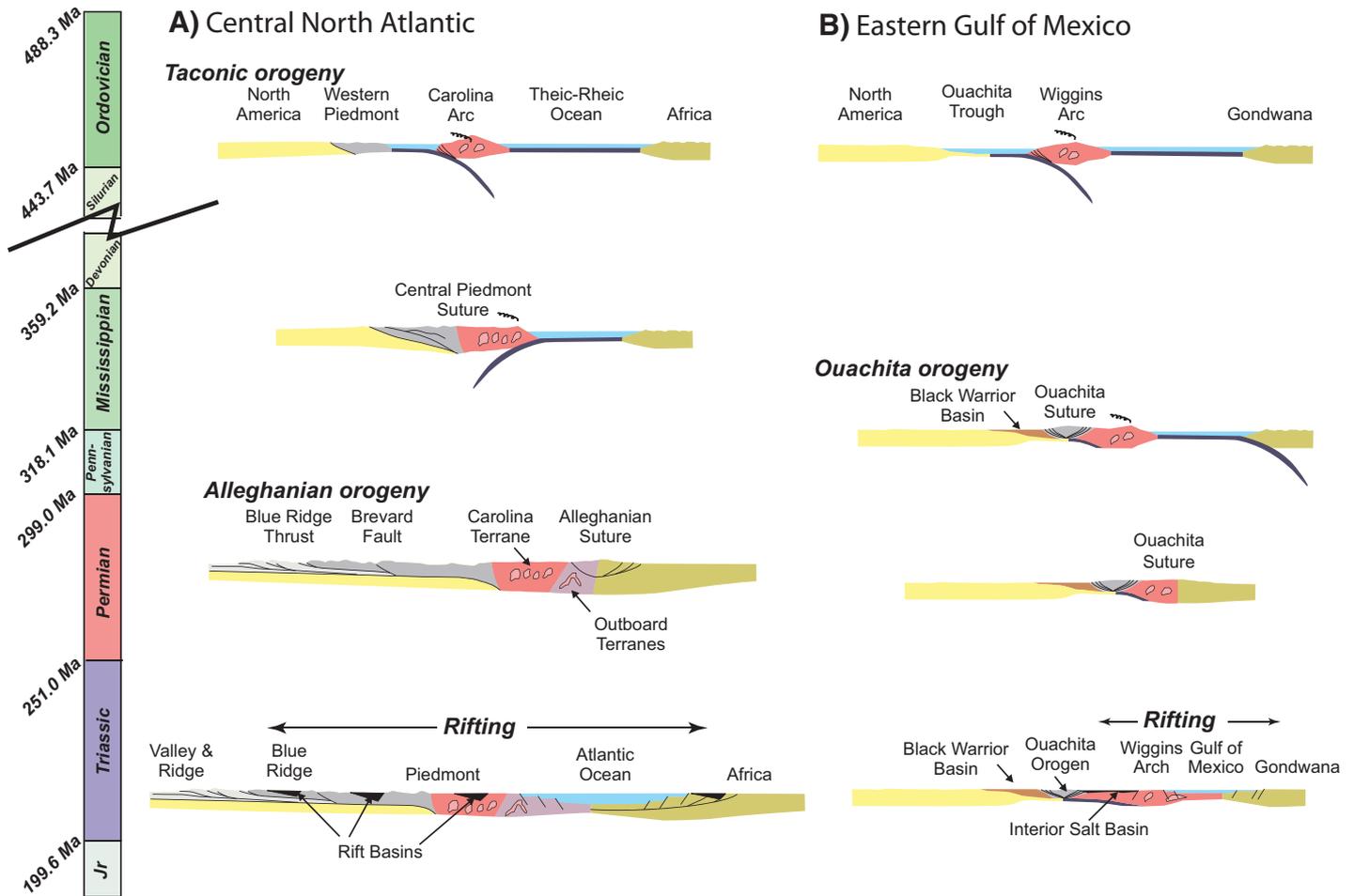


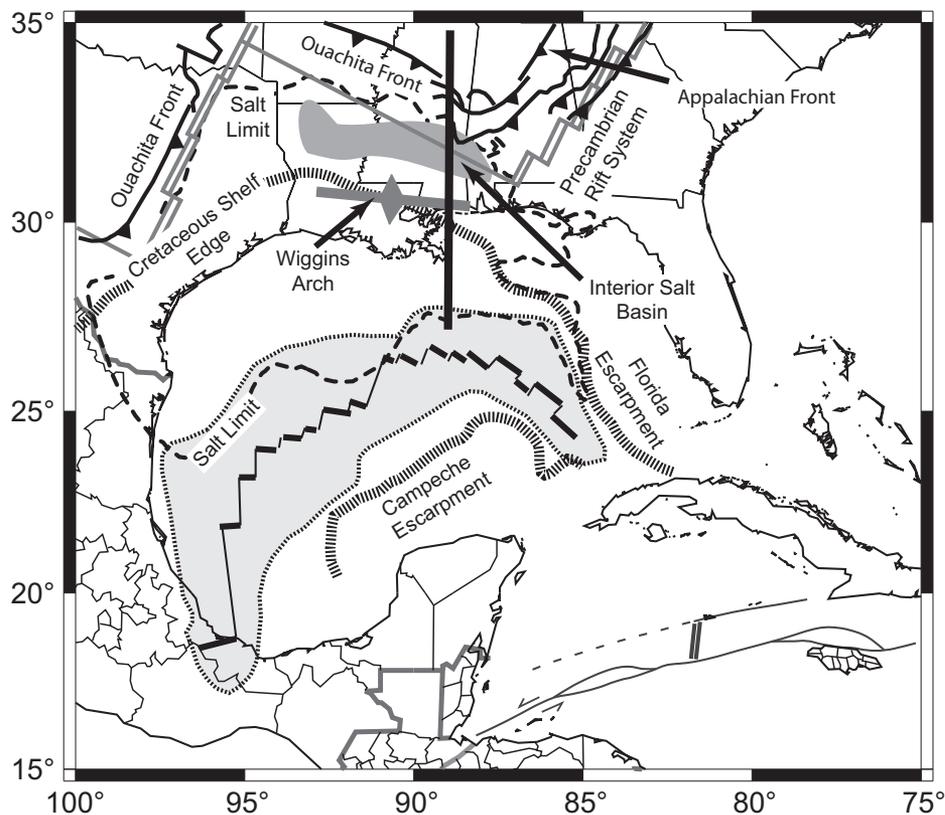
Figure 2. (A) Tectonic evolution of the eastern New Jersey continental margin and Appalachian orogen. (B) Tectonic evolution of the Mississippi Gulf of Mexico margin and Ouachita orogen.

late Paleozoic through Early Triassic time, prior to the onset of extensional deformation that led to opening of the Gulf of Mexico during the Early Jurassic. The model results are consistent with the geologic and geophysical features of the region, including the distribution of major extensional structures, the amount and location of crustal thinning, and the duration of rifting on the central Gulf of Mexico margin.

## REGIONAL GEOLOGY

The coastal plain of the North American Gulf of Mexico continental margin is covered almost entirely with mostly conformable Late Jurassic through Quaternary sedimentary strata. North of the Ouachita orogen, the basement is generally thought to consist of Grenville age (ca. 1.2 Ga) granitic crust that formed the southern edge of the Proterozoic Laurentian craton (Taylor, 1989; Culotta et al., 1992; James and Henry, 1993; Mosher et al., 2008). The southern boundary of the Laurentian craton is a Neoproterozoic through early Paleozoic passive continental margin composed of a series of rift and transform segments that accommodated a generally east-southeast direction of extension (Thomas, 1976, 1989, 1991, 2011; Viele, 1989; Hatcher et al., 1989) (Fig. 3). A change from a passive margin to a convergent tectonic setting occurred during middle Paleozoic time in the central Gulf of Mexico (Thomas, 1976, 1989). This was due to encroachment of an allochthonous terrane upon the southern Laurentian margin that is generally associated with docking of a magmatic arc along a southward-dipping subduction system (Pindell, 1985; Houseknecht, 1986; Viele, 1989; Thomas, 1989; Chowns and Williams, 1983; Dallmeyer, 1989; Loomis and Weaver, 1994; Pindell and Kennan, 2009) (Fig. 2B). Cross sections based on seismic profiles and gravity modeling show that the Precambrian–early Paleozoic passive margin, middle Paleozoic subduction system, and a remnant of the subducted Paleozoic oceanic crust are preserved beneath the Ouachita orogen and northern Gulf of Mexico coastal plain (Fig. 4) (Harry and Londono, 2004).

Opening of the Gulf of Mexico began during the Late Triassic (ca. 215 Ma) with the development of fault-bounded rift basins and horst systems. These extensional structures formed throughout the central Gulf of Mexico margin immediately south of the Ouachita orogen and extend beneath the modern shelf (Buffler and Sawyer, 1985; Salvador, 1987, 1991a, 1991b). Rifting culminated in seafloor spreading during the early Late Jurassic, 158–160 Ma (Ibrahim et al., 1981; Pindell, 1985; Ebeniro et al., 1988; Salvador, 1987; Pindell and Kennan,



**Figure 3. Tectonic map of the central U.S. Gulf of Mexico coastal plain and continental shelf. Solid line shows the location of the cross section shown in Figure 4. Light gray area indicates outline of oceanic crust proposed by Pindell and Kennan (2009). Structure of the Precambrian rift–transform margin from Thomas (1991).**

2009). Opening of the Gulf of Mexico resulted in formation of early synrift basins such as the Interior Salt Basin on the modern gulf coastal plain south of the Ouachita orogen (Figs. 3 and 4) (Salvador, 1987). These early synrift basins became tectonically quiescent by Oxfordian time as the locus of extension concentrated in a broad region farther south beneath the modern continental shelf and slope. In the central Gulf of Mexico province, the northward extent of extensional deformation terminates abruptly on the southern flank of the Ouachita orogen at the peripheral fault trend, which coincides roughly with the northern limit of synrift evaporite deposition (Buffler and Sawyer, 1985; Thomas, 1988; Dobson and Buffler, 1991; Ewing, 1991). Extension estimates, measured as the ratio of postrift to prerift widths of an extended region (McKenzie, 1978), range from  $\beta = 1.2$  in the Interior Salt Basin immediately south of the Ouachita orogen to  $\beta \approx 3.5$ –4.0 beneath the shelf and slope (Nunn et al., 1984; Dunbar and Sawyer, 1987; Driskill et al., 1988). This variation in extension is displayed in basement (crystalline) crust with variable

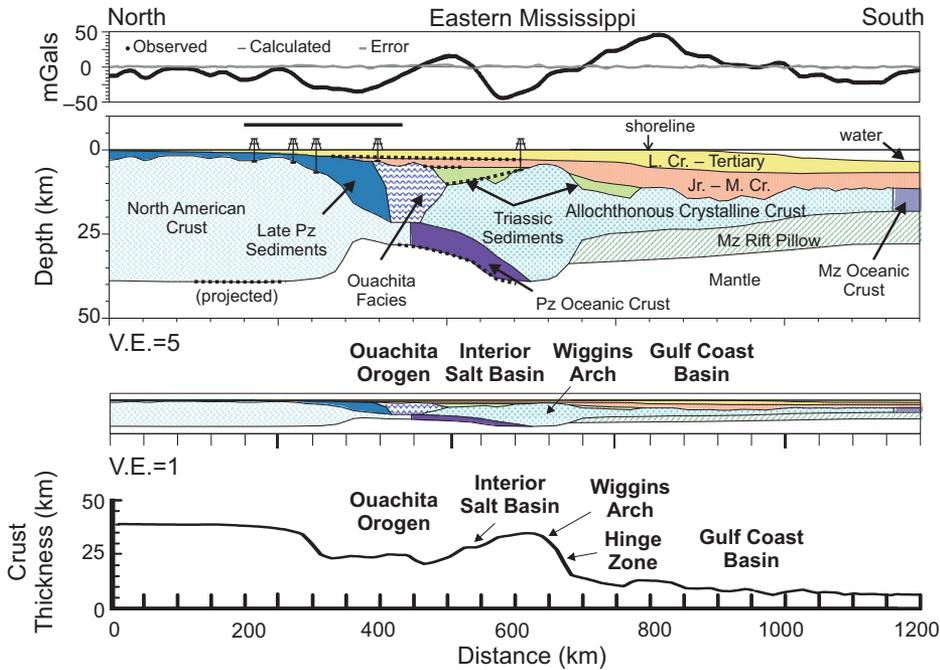
thickness (Fig. 4). The maximum crustal thickness of 35–40 km is located on the Laurentian craton north of the Precambrian passive margin (Warren et al., 1966; Sawyer et al., 1991). Southward, the crystalline crust thins to ~12 km on the Precambrian margin beneath the Ouachita orogen, thickens again to ~35 km beneath the Wiggins arch (an unextended fragment of the accreted allochthonous terrane south of the Ouachita orogen), and progressively thins southward to ~10 km adjacent to the oldest Mesozoic oceanic crust (Ibrahim et al., 1981; Ibrahim and Uchupi, 1982; Kruger and Keller, 1986; Ebeniro et al., 1988; Nakamura et al., 1988; Sawyer et al., 1991).

An unusual aspect of the central and eastern North American Gulf of Mexico rifted margin is the extremely wide (~425–500 km) region of highly extended crust that is present from the hinge zone beneath the continental shelf to the ocean-continent transition beneath the continental rise in the central gulf (Sawyer et al., 1991; Buffler and Thomas, 1994) (between ~650 and 1150 km in Fig. 4). This is in contrast to most rifted margins, which are typically

**DYNAMIC MODEL OF GULF OF MEXICO RIFTING**

A two-dimensional finite element model of continental rifting is developed to examine the influence that Paleozoic orogenic architecture had on Mesozoic opening of the Gulf of Mexico. The finite element model solves for two-dimensional deformation of the lithosphere governed by Stoke's flow with a pressure, strain rate, and temperature-dependent rheology that simulates brittle deformation at shallow depths and ductile deformation at greater depths (Dunbar and Sawyer, 1989). Constant velocity boundary conditions are applied at the sides of the model, and an isostatic boundary condition is applied at the base. Temperature is governed by the two-dimensional heat equation, including heat production in the crust. Constant heat flux boundary conditions are used at the sides of the model, and constant temperature boundary conditions are used at the top and bottom. The finite element mesh used to represent the 120 km × 850 km initial model domain consists of 15 rows ranging from 2 to 15 km thick and 35 columns ranging from 20 to 25 km wide. Larger elements are used at the edges and bottom of the model, where velocity gradients are relatively small. Models run with twice as many rows and columns yielded similar results, so the mesh size was deemed sufficient.

The starting geometry of the model is based on palinspastic reconstruction of the margin in late Pennsylvanian time, just after the end of the Ouachita orogeny (Fig. 5). The reconstruction is based on area balancing of the cross section shown in Figure 4, requiring an assumption

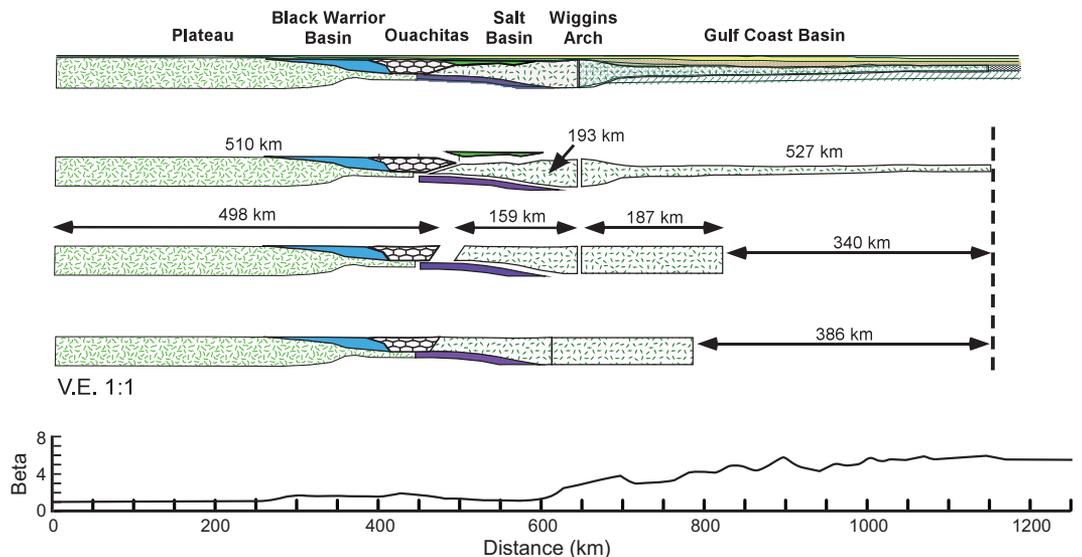


**Figure 4. Cross section across the central Gulf of Mexico North American margin (from Harry and Londono, 2004). Distance is measured relative to positions in the finite element model (shown in Figs. 7–9). Symbols indicate location of petroleum wells and seismic reflection (horizontal solid line) and refraction (dotted lines) profiles that complement the gravity data used to constrain the model.**

<~300 km wide (Harry et al., 2003), including the western portion of the U.S. Gulf of Mexico margin, which may be <250 km wide (Mickus et al., 2009). The total Mesozoic extension on the central and eastern North American Gulf of Mexico continental margin, including the Inte-

rior Salt Basin, coastal plain, shelf, slope, and rise, is estimated to be ~400–480 km (Pindell, 1985; Dunbar and Sawyer, 1987; Driskill et al., 1988), occurring during a period of prolonged (~55 m.y.) extension over a broad area prior to the onset of seafloor spreading.

**Figure 5. Area-balanced palinspastic restoration of the cross section shown in Figure 4. Extended crust is restored to a presumed original thickness of 40 km south of the Ouachita orogen except beneath the Interior Salt Basin, where crust is restored to the present crystalline crust thickness plus the thickness of synrift and postrift sediments in the basin (see text for discussion). From top to bottom, the figure shows the present crustal structure, individual tectonostratigraphic blocks removed and restored during the area-balancing process, area-balanced block configuration, and cross section restored to its prerift configuration.**

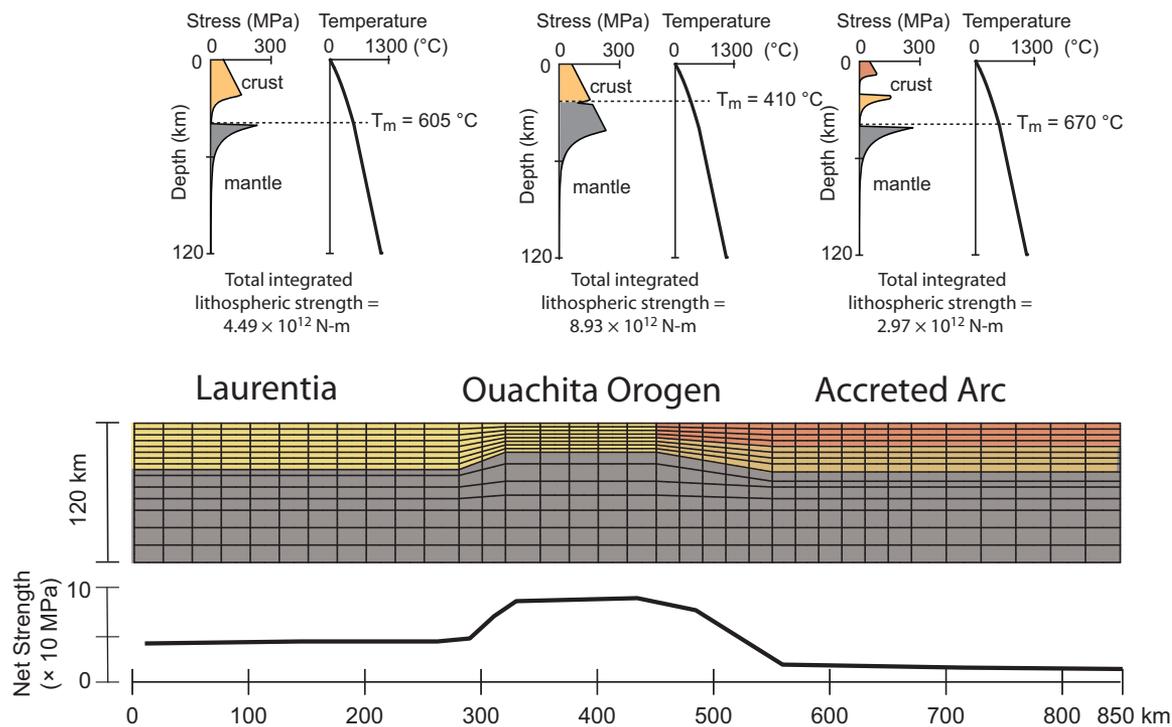


regarding the prerift thickness of the crust in each block used in the restoration. In this case, restoration must account for extension in the Gulf of Mexico Basin (south of the Wiggins arch) and in the Interior Salt Basin (between the Wiggins arch and the southern edge of the Ouachita orogen). The minimal postrift (post-Jurassic) subsidence on the northern flank of the Wiggins arch, as indicated by the shallow basement, suggests that the crust has undergone relatively little extension in this region. The crust here is 40 km thick, assumed to be the thickness of the Wiggins terrane prior to Mesozoic rifting. Consequently, the area-balanced reconstruction assumes a prerift thickness of 40 km for the Wiggins arch and all regions southward. The prerift thickness in the Interior Salt Basin is less certain, but as a minimum it is assumed to equal the present crystalline crust thickness plus the thickness of synrift and postrift sediments filling the basin. The reconstruction results in a predicted net extension of 386 km, somewhat lower than previous estimates of 400–480 km (Pindell, 1985; Dunbar and Sawyer, 1987; Driskill et al.,

1988). This reconstruction results in a preliminary starting model with crustal geometry consisting of 40-km-thick crust in regions north of the orogen (consistent with current thicknesses of the relatively undeformed North American crust); 25-km-thick crust within the Ouachita orogen (based on the current thickness of relatively undeformed Ouachita facies and underlying remnant of the subducted Paleozoic margin); and 40-km-thick crust in the accreted arc terrane located south of the orogen (based on the current thickness of the relatively unextended Wiggins arch). The initial thickness of the arc crust was varied in different model realizations to obtain the best fit between the modeled crust thickness on the coastal plain and shelf at the end of rifting and the modern thickness of the crystalline crust in those regions. This leads to an estimated initial thickness of 42 km for the arc crust prior to extension. The initial rheologic and thermal structure of the model captures key features of the prerift margin, including Grenville continental lithosphere north of the Ouachita fold-and-thrust belt, a south-verging subduction system

beneath the thin-skinned Ouachita orogen, and a relatively young (Paleozoic) accreted arc terrane south of the Ouachita orogen (Fig. 6).

Ductile deformation in the model is governed by power-law creep relations reported by Carter and Tsenn (1987) (Table 1). Flow laws are for Aheim dunite in the mantle and wet quartz diorite in the Laurentian crust north of the Ouachita orogen and the lower half of the crust in the accreted arc terrane. A wet Westerly granite flow law is used in the upper crust in the arc terrane, in keeping with granitic rocks encountered in drill holes south of the Ouachita Mountains in Mississippi, on the Sabine Uplift and Wiggins arch, and on the conjugate Yucatan Peninsula (Neathery and Thomas, 1975; Harrelson and Bicker, 1979; Viele and Thomas, 1989; Harrelson et al., 1992; Molina-Garza et al., 1992). A depth-dependent limit on the yield stress is applied to simulate plastic failure (e.g., Dunbar and Sawyer, 1989). The maximum yield stress at the surface is 60 MPa in the Laurentian crust and 45 MPa (25% weaker) in the accreted terrane, and increases 4 MPa km<sup>-1</sup>



**Figure 6.** General structure of the best-fitting finite element model prior to the onset of extension. Key features include dioritic cratonic crust north of the Ouachita orogen, thin crust and shallow mantle beneath the Ouachita orogen, and a magmatic arc south of the Ouachita orogen composed of a granitic upper crust and dioritic lower crust. The model lithosphere is initially 125 km thick. The prerift crust is 42 km thick beneath the craton, 25 km thick beneath the orogen (including the preorogenic crust and the metasedimentary rocks emplaced during the orogeny), and 40 km thick beneath the arc. The strength of the lithosphere varies across the region in response to these variations in rheology and thermal structure. In the accreted arc region, the warm geotherm and weak rock type result in a relatively weak lithosphere, while in the region of the Ouachita orogen the shallow mantle results in a relatively strong lithosphere.

with depth (Byerlee, 1968, 1978). The thermal parameters in the model (Table 2) are chosen to produce a prerift geotherm in the region south of the Ouachita orogen (in the accreted Wiggins terrane) that is typical of mature magmatic arcs (Furukawa and Uyeda, 1989), and a geotherm north of the Ouachita orogen that is typical of stable cratons (Sclater et al., 1980; Pollack et al., 1993; Mareschal and Jaupart, 2004). Additional details of the modeling method and rheological behavior are given in Dunbar and Sawyer (1989).

This combination of variations in crustal rheology, thermal properties, and crustal thickness results in a lithosphere that is weakest in the arc terrane (which is slightly warmer than the craton) and strongest in the orogen (where the crust is thinnest) (Fig. 6). Thus, extensional deformation is primarily accommodated within the weak arc terrane, while the Ouachita orogen acts as a buttress against extensional deformation.

To simulate the extensional evolution of the Gulf of Mexico, the model is subjected to a constant extension rate of  $7.25 \text{ km m.y.}^{-1}$ . This extension rate is chosen to produce  $\sim 400 \text{ km}$  of extension during a 55 m.y. period, in accord with the estimated duration of rifting and the amount of extension discussed previously. Minor extension occurs on the northern flank of the orogen during the first  $\sim 1 \text{ m.y.}$  of extension ( $\sim 250 \text{ km}$  in the model), but this is short-lived and contributes little to the total extension on the margin (Figs. 7A and 8A). For the remainder of the evolution of the model, all extension is accommodated south of the Ouachita orogen (within the accreted terrane). The zone of extension terminates abruptly on the southern flank of the orogen.

During the first 30 m.y. of extension, the lithosphere south of the Ouachita orogen undergoes substantial, relatively uniform thinning over a broad region (Figs. 7B, 7C, 8B, and 8C). Minor extension occurs during this period in the model on the southern flank of the Ouachita orogen above the subducted Paleozoic oceanic crust (the southward-thickening wedge of crust between 450 and 575 km in the model), corresponding to the location of the Interior Salt Basin on the Gulf of Mexico coastal plain. A region of relatively thick crust is situated between this location and the main region of extension further south, in a position comparable to that of the Wiggins arch. By 45 m.y., strain rates begin to decrease in the areas corresponding to the Interior Salt Basin, the Wiggins arch, and areas immediately to the south (Figs. 7D and 8D). The northern and central Gulf of Mexico coastal plain becomes inactive, and extension becomes progressively more concentrated toward the seaward end of the model (Fig. 8D). By 55 m.y., immediately prior

TABLE 1. RHEOLOGICAL PROPERTIES USED IN THE MODELS

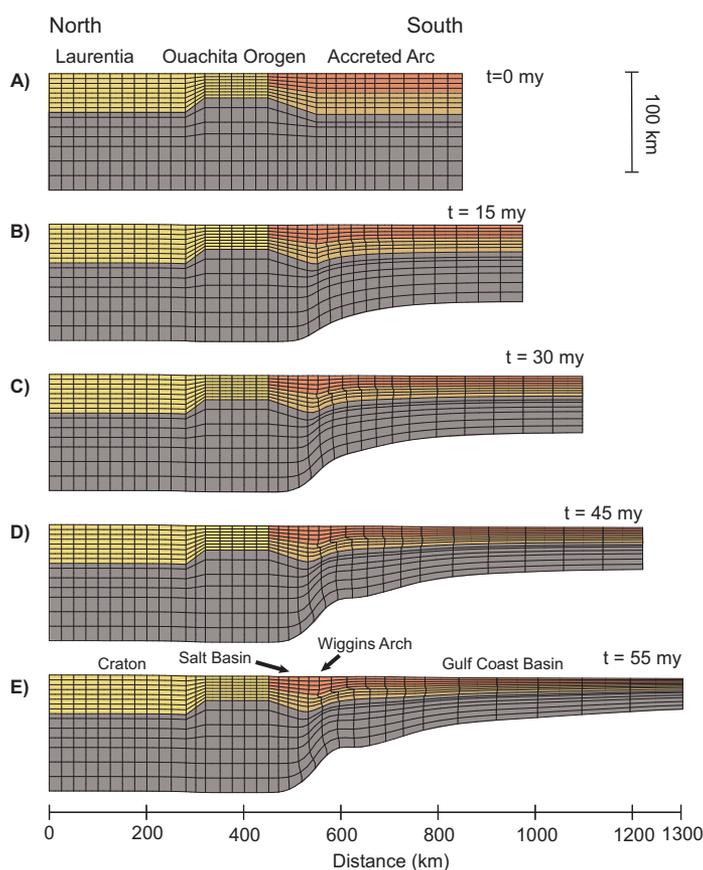
	n	A (Pa <sup>-n</sup> s <sup>-1</sup> )	Q <sub>c</sub> (J/mol)
Aheim dunite	3.4	$3.5 \times 10^{-25}$	$498 \times 10^3$
Quartz diorite	2.4	$5.0 \times 10^{-18}$	$219 \times 10^3$
Gabbro	3.1	$3.2 \times 10^{-20}$	$276 \times 10^3$
Westerly granite	1.9	$7.9 \times 10^{-16}$	$141 \times 10^3$

Note: ductile flow laws are of the form  $\dot{\epsilon} = A \sigma^n e^{-Q_c/RT}$ , where n is the creep exponent, A is the preexponential creep constant, Q<sub>c</sub> is the activation energy,  $\dot{\epsilon}$  is strain rate,  $\sigma$  is stress, R is the universal gas constant, and T is temperature. All values are from Carter and Tsenn (1987).

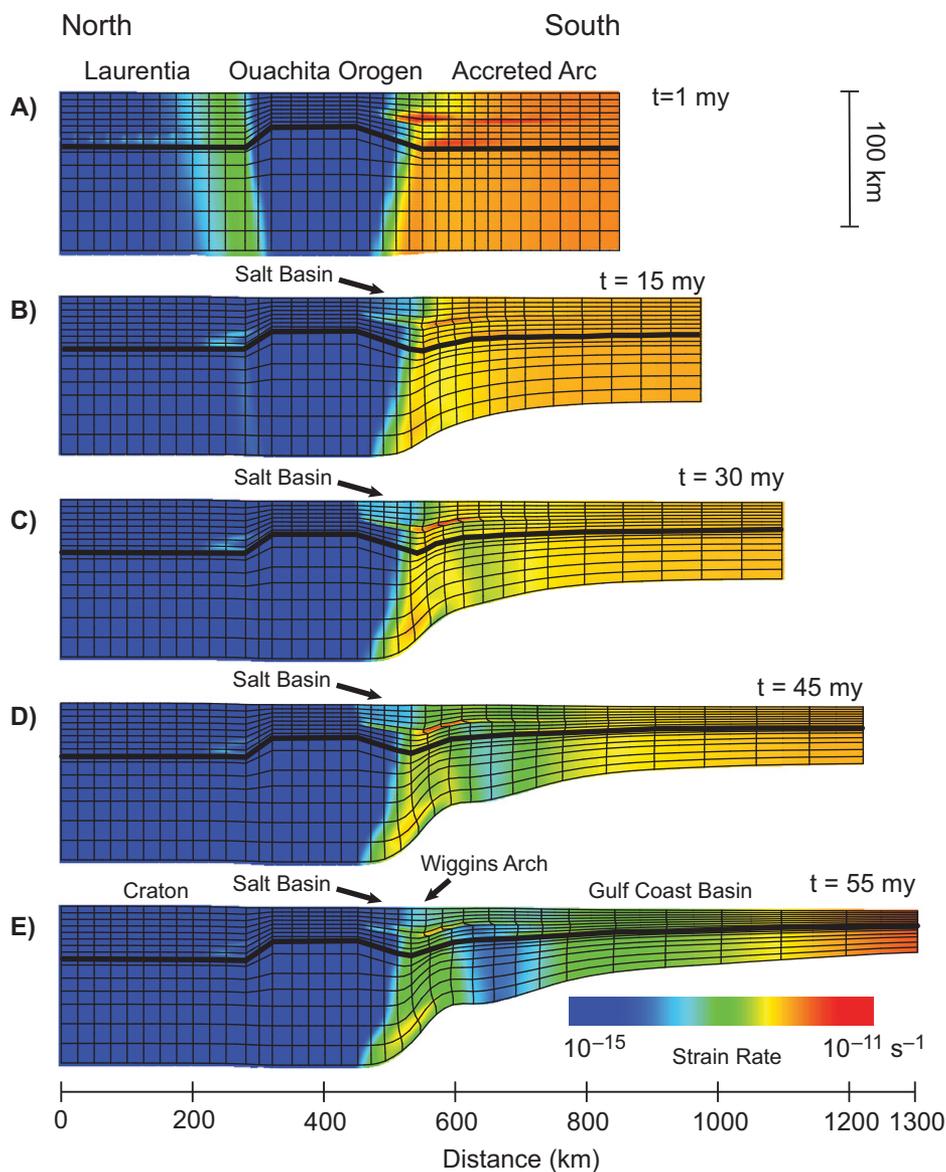
TABLE 2. THERMAL PARAMETERS USED IN THE MODELS

	Mantle	Oceanic crust	Diorite crust	Granite crust
Thermal conductivity (W m <sup>-1</sup> K <sup>-1</sup> )	3.4	3.4	2.5	2.5
Specific heat (J kg <sup>-1</sup> K <sup>-1</sup> )	1250	1250	875	875
Surface heat production A <sub>0</sub> (μW m <sup>-3</sup> )	0	0	2.0	3.0
Thermal decay rate D (km)	—	—	10	15
Thermal expansion coefficient (K <sup>-1</sup> × 10 <sup>-5</sup> )	3.1	3.1	3.1	3.1

Note: Heat production decays exponentially with depth according to  $A(z) = A_0 E^{-z/D}$ .



**Figure 7. Deformation of the best-fitting finite element model during extension. Ages indicate the time elapsed since the onset of extension. See Animations 1 and 2 for time-lapse videos showing evolution of the net strength and temperature in the model lithosphere during rifting. Animations can be viewed with any mp4 viewer. If you are viewing the PDF of this paper or reading it offline, please visit the full-text article on [www.gsapubs.org](http://www.gsapubs.org) or <http://dx.doi.org/10.1130/GES00725.S1> to view Animation 1 and <http://dx.doi.org/10.1130/GES00725.S2> to view Animation 2.**



**Figure 8.** Strain rate in the best-fitting finite element model during extension. Solid line shows crust-mantle boundary. (A) Immediately after the onset of extension, strain is distributed throughout the accreted arc terrane and in a narrow band focused at the northern edge of the Ouachita orogen. (B) 15 m.y. after the onset of extension, strain occurs only in the region of the developing Gulf Coast Basin, south of the Wiggins arch. (C) 30 m.y. after the onset of extension, strain includes the Gulf Coast Basin, Wiggins arch, and the Interior Salt Basin on the southern flank of the Ouachita orogen. (D) 45 m.y. after the onset of extension, strain rates begin to decrease in the Interior Salt Basin and on the Wiggins arch and begin to focus in the central coastal plain and regions farther south. (E) 55 m.y. after the onset of extension, immediately prior to the onset of seafloor spreading, strain rates have declined within the Gulf Coast Basin and are concentrated near the incipient seafloor spreading center at the southern edge of the model.

to the onset of seafloor spreading, extension in the Interior Salt Basin and northern coastal plain has ceased and the most rapid rates of extension are focused in a relatively narrow 100-km-wide area adjacent to the incipient spreading center (Figs. 7E and 8E).

The simulation predicts extensional evolution, final crustal thickness, and final strain pattern that agree well with the geologic evolution and present-day structure of the modern Mississippi margin (exclusive of postrift sedimentation). The simulation recreates major features of

the region (Fig. 9), including: (1) a broad zone of highly thinned and extended crust in the Gulf of Mexico coast basin of the central and southern coastal plain, shelf, and slope (700–1300 km in the model), (2) a region of relatively thick crust beneath the Wiggins arch, (3) thin and relatively unextended crust beneath the Ouachita orogen, and (4) thick unextended crust beneath the craton.

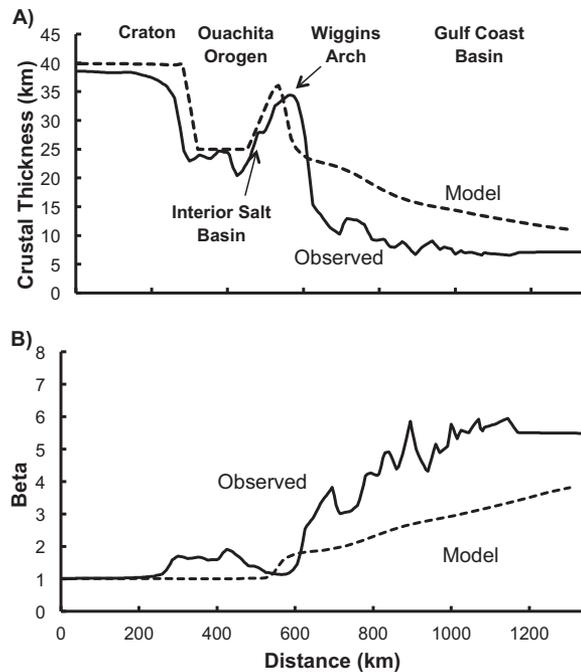
## MODEL ROBUSTNESS

In order to test for robustness of model behavior, additional families of models were run (Table 3). The first family of alternative models examined different extension rates, ranging from 5 to 15 mm yr<sup>-1</sup>. The behavior of all of these models was similar to that shown in Figures 7–9, with very similar extensional evolutions and final geometries. The primary difference between simulations was the time at which the various features in the models develop. Faster extension rates lead to more rapid cessation of extension within the interior of the model and focusing of extension at the southern edge of the model. Conversely, slower extension rates delay the development of these characteristics. In all of the models, however, the same essential features are observed, including minor extension on the southern flank of the Ouachita orogen accompanied by broadly distributed extension within the Gulf of Mexico coast basin, later transition to progressively more focused extension in the southern portion of the basin, the presence of relatively unextended crust on the Wiggins arch, and a lack of extension within the central and northern Ouachita orogen and on the craton.

The second family of alternative models considered the presence of a gabbroic layer in the lower crust beneath the southern Ouachita orogen to simulate the presence of remnant subducted Paleozoic oceanic crust within the deep Ouachita suture (Fig. 4) (e.g., Keller et al., 1989; Mickus and Keller, 1992; Harry and Londono, 2004). The presence or absence of a gabbroic layer had no effect on model behavior, indicating that it is the shallow mantle rather than the rheology of the crust in this region that is the key factor that keeps this portion of the model strong.

The third family of alternative models considered a simplified arc structure, with the crust consisting of only a single diorite layer (Fig. 10). In general, simulations with a single layer arc crust behave similarly to the models shown in Figures 7–9. Extension develops over a broad region in the Gulf of Mexico coast basin, becoming progressively more focused at the southern edge of the model with time. Minor amounts of

**Figure 9. Model crust 55 m.y. after the onset of extension in the best fitting model, compared to crustal structure determined immediately prior to the onset of seafloor spreading determined from Figure 4. (A) Thickness of the crust. (B) Extension factor  $\beta$  (ratio of final to initial crust thickness).**



crustal thinning occur during the early stages of extension on the Wiggins arch and the southern flank of the Ouachita orogen, but these are abandoned after ~45 m.y. The major difference between the behavior of this model and the two-layer crust model shown in Figures 7–9 is that extension focuses at the southern edge of the model relatively early, leading to rapid necking in this region, an earlier onset of continental breakup (45 m.y. instead of 55 m.y.), and comparatively less extension within the coastal plain and Interior Salt Basin.

The fourth family of alternative models varied the heat production rate in the crust of the arc terrane between 2 and 4  $\mu\text{W m}^{-3}$  (Fig. 11). Models with relatively low rates of crustal heat production have a cooler (and stronger) arc terrane. In these models the crust beneath the Interior Salt

Basin and coastal plain is less affected by extension than in the preferred model, with strain occurring primarily in regions further south where the accreted arc crust is thickest (i.e., within the Gulf of Mexico coast basin). Models with crustal heat production values in the arc similar to those of the coolest models examined (which have arc geotherms similar to that of the craton), behave similarly to the 1-layer arc model shown in Figure 10. Minimal extension occurs within the Gulf of Mexico coast basin in these models. Extension rapidly becomes focused in a region of necking at the southern edge of the model, leading to relatively early onset of continental breakup at this location (Fig. 11A). Models with higher heat production than the preferred model (warmer arc crust) behave as in Figures 7–9 for the first ~30–40 m.y. of exten-

sion. However, with continued extension, a lithospheric neck and zone of focused crustal thinning develop immediately south of the Wiggins arch (850 km in the model) (Fig. 11B). Extension to the north and south of this position ceases once the neck begins to develop, and the model behaves as a narrow rift, as described by Buck (1991). All hot arc models behave as that shown in Figure 11B, with the timing at which the lithospheric necking develops being dependent upon the initial thermal structure (hotter arcs lead to earlier onset of necking).

The fifth family of alternative models examined the effect of the thickness of the crust within the prerift crust in the arc terrane; thickness was varied from 40 to 45 km in different model realizations (Fig. 12). Models in which the arc crust is thinner than the preferred model behave similarly to the cool arc model (Fig. 11A), with relatively minor extension on the coastal plain and rapid onset of focused rifting and continental breakup at the southern edge of the model (Fig. 12A). Models with thicker arc crusts behave similarly to the hot arc model (Fig. 11B), resulting in lithospheric necking immediately south of the Wiggins arch that rapidly leads to focused rifting and continental breakup in this position (Fig. 12B).

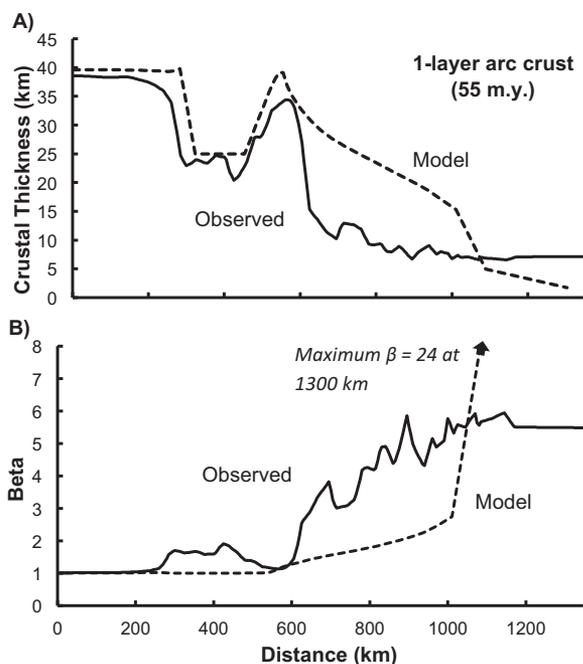
The influence of variations in the thickness of the North American and Wiggins terrane lithospheres prior to extension (i.e., the depth of the 1300 °C isotherm) on model behavior was not explicitly examined in this study. Previous modeling studies have found that a thinner prerift lithosphere (i.e., a shallower 1300 °C isotherm) promotes a longer period of extension prior to the necking, but does not greatly alter the overall structural evolution of the model (e.g., Bassi et al., 1993). Huerta and Harry (2007) used a finite element model similar to those in this study to describe rifting in West Antarctica. Like the northern Gulf of Mexico, rifting in West Antarctica involved extension of a relatively juvenile

TABLE 3. ALTERNATIVE MODEL REALIZATIONS

Model family	Parameter	Parameter range	Best-fitting model	Impact on model
Alternative I	Extension rate	15–15 km/m.y.	7.27 km/m.y.	Same behavior as preferred model, but higher extension rates accelerate the timing of the structural evolution of the margin
Alternative II	Paleozoic subducted crust rheology	Gabbroic slab rheology	Slab rheology same as North American crust	No effect
Alternative III	Accreted Mesozoic arc rheology	Arc is entirely dioritic	Upper arc is granitic, lower arc dioritic	No effect
Alternative IV	Arc heat production	2–4 $\mu\text{Wm}^{-3}$	3 $\mu\text{Wm}^{-3}$	Higher heat production leads to necking on Gulf coastal plain; lower heat production leads to rapid end-necking at distal end of model, producing relatively narrow rifts
Alternative V	Thickness of arc crust	40–45 km	42 km	Similar to alternative IV, with thick crust behaving similarly to the high heat production models and thin crust behaving similarly to the low heat production models

Note: All models used a 40-km-thick crust on the craton, a 25-km-thick crust within the Ouachita orogeny, and an extension rate of 7.25 km/m.y. Other parameters kept fixed in the different model realizations are listed in Tables 1 and 2.

**Figure 10. Alternative model with single layer arc crust, composed entirely of diorite. (A) Thickness of the crust. (B) Extension factor  $\beta$  (ratio of final to initial crust thickness).**



terrane accreted to the edge of the older East Antarctica craton. The models presented here (initially broad necking within the arc terrane and a later shift to focused necking at the edge of the model) behave similarly to Huerta and Harry's (2007) Class iii model, which they found to be robust behavior over a wide range of lithosphere thicknesses as long as the prerift temperature at the base of the crust was  $< 680^\circ\text{C}$ . At higher temperatures, the models of Huerta and Harry (2007) generally underwent prolonged extension in the arc terrane without ever developing a focused rift axis (their Class ii model) except in a narrow set of circumstances (which lead to formation of a rift neck at the suture between the craton and arc terrane).

## DISCUSSION

The evolution of strain in the preferred simulation agrees well both temporally and spatially with geologic and geophysical observations from the central North American Gulf of Mexico margin (Fig. 4). Modeled strain during the first 45 m.y. is distributed throughout the accreted terrane, from the southern edge of the Ouachita suture to the southern edge of the model, coinciding with the distribution of fault-bounded rift structures that developed on the southern coastal plain, shelf, slope, and rise between Late Triassic and Callovian time (Salvador, 1987, 1991a, 1991b; Driskill et al., 1988; Marton and Buffler, 1994). The spatial extent of this stage of extension terminates on the southern flank of the Ouachita orogen in a

position that coincides with the location of the peripheral fault trend and the northern limit of synrift evaporite and clastic deposits. A region of relatively thick crust in the model south of the Ouachita orogen agrees in location and crustal thickness with the structure of the Wiggins arch (Rhodes and Maxwell, 1993; Montgomery, 2000). After  $\sim 45$  m.y. of modeled extension, strain in the vicinity of the Ouachita suture wanes and becomes progressively more focused further to the south, coinciding with cessation of

extensional tectonism in the Interior Salt Basin and coastal plain and rapid deepening of the central Gulf of Mexico in late Callovian–early Oxfordian time (Salvador, 1987, 1991a, 1991b; Driskill et al., 1988; Marton and Buffler, 1994). After 50 m.y. of modeled extension, lithospheric necking is well established at the southern edge of the model. The crust in this region thins rapidly thereafter as extensional strain becomes progressively more focused. By 55 m.y. after the onset of extension, the thickness of the crust in the rift axis has decreased to 5 km and the thickness of the lithosphere to 25 km, which by comparison to modern ocean spreading ridges and other rift margins is taken to mark breakup and the onset of seafloor spreading. The 55 m.y. period of modeled extension agrees with the timing of rifting in the Gulf of Mexico that began in Late Triassic and ended in latest Callovian–early Oxfordian time (Pindell and Kennan, 2009). The modeled short time span ( $\sim 5$  m.y.) between the formation of a well-developed rift axis and the onset of seafloor spreading is in accord with the short period of time elapsed between widespread deposition of evaporite deposits on the modern coastal plain and shelf during Callovian time and the onset of seafloor spreading in the deep Gulf of Mexico by early Oxfordian time (Salvador, 1987; Buffler and Thomas, 1994; Marton and Buffler, 1994; Pindell and Kennan, 2009).

Alternative simulations (Figs. 10–12) also show a lack of strain within the central Ouachita orogen and positions farther north, demonstrating that the major features of the model are robust under a range of extension rates, rheologies,

**Figure 11. Effect of varying heat production in the arc crust. (A) Cooler arc model. All parameters are the same as in Figure 9, except surface heat production is reduced from 3 to 2  $\text{mW m}^{-3}$ . (B) Warmer arc model. All parameters are the same as in Figure 9, except surface heat production is increased from 3 to 4  $\text{mW m}^{-3}$ .**

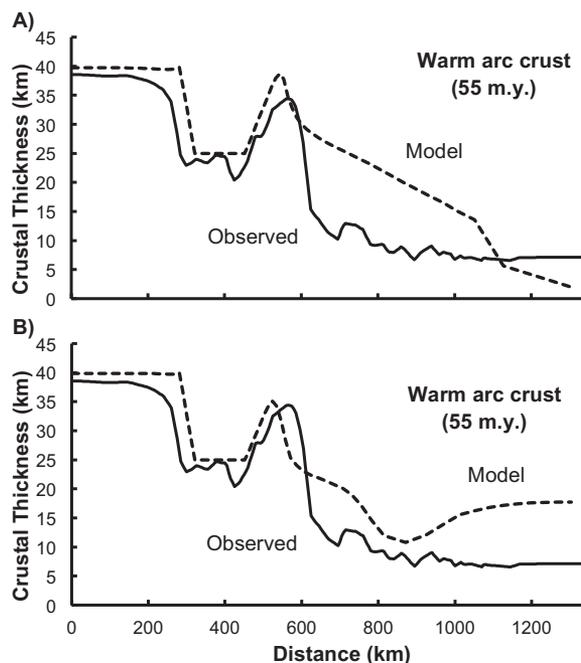
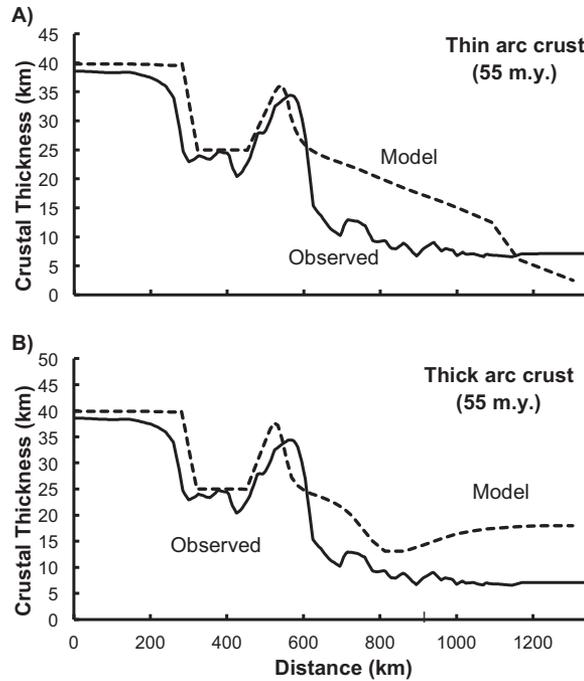


Figure 12. Effect of varying the thickness of the arc crust. (A) Thin arc crust model. All parameters are the same as in Figure 9, except the thickness of the arc crust is decreased from 42 km to 40 km. (B) Thick arc crust model. All parameters are the same as in Figure 9, except the thickness of the arc crust is increased from 42 km to 45 km.



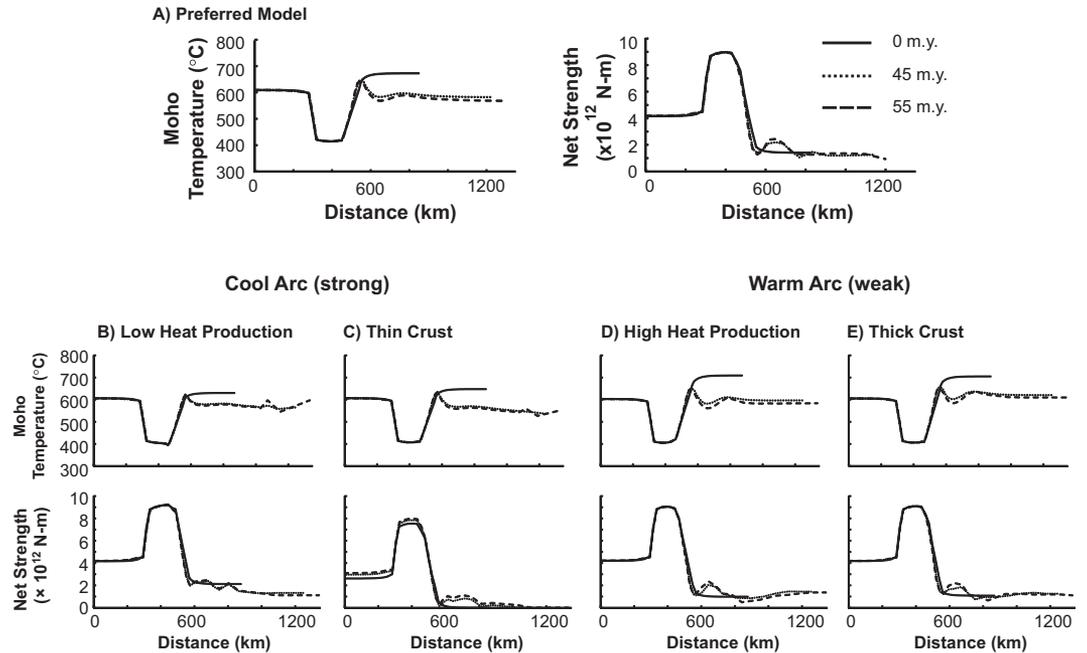
thermal conditions, and assumptions regarding the thickness of the crust on the coastal plain, shelf, slope, and rise prior to extension. Thus, it is the structure of the Ouachita suture (preservation of shallow mantle beneath the fossil Paleozoic convergent margin) that placed fundamental control of the distribution of strain during

the opening of the Gulf of Mexico. The shallow mantle beneath the Ouachita orogen acted as a zone of strength that forced extensional deformation to positions farther south.

The evolution of strain south of the Ouachita orogen depends on the initial thermal state of the arc terrane and the feedback between the

thermal and structural evolution of the model. In general, extensional strain in the model is confined to regions south of the Ouachita suture, within the relatively warm (and therefore weak) arc terrane. Strain is initially uniformly distributed across the width of the arc, but becomes progressively more focused to the south with time, eventually leading to breakup at the far south end of the model (Figs. 7 and 8). This behavior is governed by two competing processes: thinning of the lithosphere, which results in increasingly concentrated deviatoric stress that promotes formation of a narrow rift zone; and cooling of the lithosphere, which results in a strengthening lithosphere that promotes migration of extensional strain into adjacent unextended regions. The extension rate is the primary control over which process dominates, with rapid extension rates promoting narrow rifting and slow extension rates promoting abandonment of early rift basins and migration of extension elsewhere (e.g., Dunbar and Sawyer, 1989; Buck, 1991; Tett and Sawyer, 1996; van Wijk and Cloetingh, 2002). In the preferred model (Figs. 7 and 8), arc crust nearest the Ouachita suture (~600–700 km) is initially slightly cooler (and therefore stronger) than the southern portion of the arc due to its juxtaposition against the relatively cool Ouachita suture and Laurentian craton farther north. Consequently, the northern portion of the arc (between 600 and 700 km in Figs. 7, 8, and 13) extends

Figure 13. Comparison of temperature at the base of the crust and net lithospheric strength in the finite element models. Line weights indicate model state prior to rifting (solid line), 45 m.y. after the onset of rifting (dotted line), and at breakup 55 m.y. after the onset of rifting (dashed line). (A) Preferred model (best fit to Gulf of Mexico geological and geophysical data). Extension results in progressive thinning and cooling of the lithosphere south of the Ouachita suture (~600 km), leading to strengthening of the lithosphere in this region that causes the locus of rifting to shift further southward, ultimately resulting in breakup at the southern edge of the model. (B) Cool arc model with relatively low heat production in the arc crust. (C) Cool arc model with relatively thin arc crust. Model behaves similarly to that shown in B. (D) Warm arc model with relatively high heat production in the arc crust. Note development of comparatively warm and weak region at ~800 km as extension progresses, which leads to focused rifting in this region. (E) Warm arc model with relatively thick arc crust. Model behaves similarly to that shown in D.



slowly in comparison to the rest of the arc. Slow extension promotes cooling and strengthening of the lithosphere in this region, causing the locus of extension to migrate southward, eventually nucleating at the southern edge of the model (Fig. 13A). This behavior is observed in all models, regardless of extension rate, but is accelerated at faster extension rates and in models that have a cooler arc terrane prior to the onset of extension (Figs. 13B, 13C). Models with a warmer arc terrane have a more complex evolution. In these models, extension in the Gulf of Mexico coastal plain initially leads to cooling and strengthening of the lithosphere (Figs. 13D, 13E). The portion of the model immediately south of the Ouachita orogen (~600–800 km in the models), being initially cooler and stronger, undergoes relatively little extension. As extension progresses, the southern part of the model thins and begins to cool and strengthen. The unextended region immediately south of the orogen remains relatively warm, eventually becoming the weakest part of the lithosphere. This results in focusing of extension and rapid lithospheric necking thereafter. The location and time in which necking develops varies depending on the prerift thermal state of the arc terrane.

## SUMMARY AND CONCLUSIONS

The finite element models show that the present-day structure of the North American central Gulf of Mexico continental margin results from inheritance of preexisting tectonic features created during Paleozoic assembly of Pangea. The models confirm that the Ouachita orogen behaved as a strong zone during Mesozoic extension, rather than as a zone of weakness, as is typical of Wilson cycle models of continental rifting. The strength of the Ouachita orogen is responsible for (1) the abrupt northward termination of extensional deformation on the southern flank of the orogenic belt; (2) broadly distributed extension throughout the coastal plain, shelf, slope, and rise between Late Triassic and Callovian time; and (3) the rapid deepening of the distal shelf and rise and onset of seafloor spreading in late Callovian or early Oxfordian time. The results are in marked contrast to similar dynamic models of rifting on the U.S. Atlantic margin (e.g., Harry and Sawyer, 1992) that depict orogens as zones of weakness due to the presence of a thick crustal root beneath the interior of the orogen. In contrast, the Ouachita orogen is underlain by a relatively undeformed subduction system that results in a shallow mantle and strong lithosphere. Modeled behavior of the rift system is robust over a range of geologically reasonable assumptions regarding the strength of the lithosphere, variations in

crustal thickness, and thermal regimes, demonstrating that tectonic structures inherited from Precambrian rifting and the Paleozoic Ouachita orogeny are the dominant controls on the style of rifting on the North American Gulf of Mexico continental margin.

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