Early Paleozoic transform-margin structure beneath the Mississippi coastal plain, southeast United States

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ABSTRACT
A geophysical transect across the central Gulf of Mexico coastal plain shows that the early Paleozoic continental margin of southern Laurentia is preserved in a nearly pristine state beneath younger strata that were emplaced during the late Paleozoic Ouachita orogeny and formation of the modern Gulf of Mexico coastal plain. The thickness of the crystalline crust decreases abruptly across the margin over a distance of ~50 km, from 35 km beneath the Black Warrior foreland basin to 10 km beneath the Ouachita fold-and-thrust belt. This abrupt decrease in crustal thickness is similar to modern transform margins, but very different from most rifted margins, which display much more gradual transitions in crustal thickness. The geophysical data indicate an absence of synrift intrusive and volcanic rocks, underplated mafic rocks at the base of the crust, and abnormally thick oceanic crust adjacent to the margin. The lack of these features is also characteristic of modern transform margins. Combined with transects across the margin farther west, the data confirm previous suggestions that the central Gulf of Mexico coastal plain overlies an ~800-km-long transform segment of the late Proterozoic–early Paleozoic southern Laurentian continental margin that extends continuously from western Arkansas to southeast Alabama.

Keywords: Gulf of Mexico, North America, rifting, Ouachita orogeny.

INTRODUCTION
The North American Gulf of Mexico coastal plain is underlain by an early to middle Paleozoic passive continental margin that developed following Late Proterozoic rifting along the southern Laurentian continent. The margin structure is obscured by younger events that include the late Paleozoic Ouachita Appalacian orogeny, Mesozoic opening of the Gulf of Mexico, and formation of the modern passive continental margin. However, the broad-scale geometry of the margin can be inferred from the strike of the Ouachita Appalacian orogen and the distribution of synrift sedimentary and volcanic rocks (Cebull et al., 1976; Thomas, 1976, 1991; Viele and Thomas, 1989). These observations suggest that Laurentia moved west-northwest during Proterozoic rifting, creating a passive continental margin consisting of distinct north-northeast–striking rift segments and east-southeast–striking transform segments (Fig. 1). The central Gulf of Mexico coastal plain overlies the proposed Alabama-Oklahoma transform segment, which extends ~800 km from southwestern Arkansas into southeastern Alabama.

Geophysical data and studies of lithospheric flexure in central Texas and western Arkansas confirm the proposed margin segmentation in these areas (Kruger and Keller, 1986; Keller et al., 1989; Culotta et al., 1992; Mickus and Keller, 1992; Harry and Mickus, 1998; Mickus, 1999), but few data constrain the structure of the Alabama-Oklahoma transform margin. In this paper geophysical data are used to constrain the structure and history of the central part of the Alabama-Oklahoma transform margin. Comparison of these results with modern rift and transform margins indicates that the subsurface geology closely matches that of modern transform margins.

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GEOPHYSICAL CONSTRAINTS ON MARGIN STRUCTURE

A transect across the Mississippi coastal plain is shown in Figure 2. Petroleum industry well and seismic data constrain the upper 10 km in the transect and the thickness of the upper Paleozoic clastic sequence in the northern and central Black Warrior basin (Harry and Londono, 2004). The thickness of the crust, depth to mid-crustal interfaces south of the Ouachita fold-and-thrust belt, and thickness of Mesozoic and Cenozoic sedimentary rocks in the Mississippi Interior Salt basin are constrained by seismic refraction data (Warren et al., 1966). Other features are constrained primarily by forward modeling of gravity data, including the depth to the base of the Ouachita fold-and-thrust belt, its southern extent, and the geometry of the late Paleozoic Ouachita suture. Densities in the gravity model are based on empirical relations to seismic velocity for the appropriate lithologies (Christensen, 1989) and comparison to previous gravity models in the region (Kruger and Keller, 1986; Mickus and Keller, 1992). These initial density estimates were revised as needed during the forward-modeling process.

MARGIN STRUCTURE

The Mississippi transect (Fig. 2), like similar transects in Louisiana and Texas (Kruger and Keller, 1986; Mickus and Keller, 1992), reveals a buried Paleozoic passive continental margin that was not affected by subsequent tectonic events. The Ouachita fold-and-thrust belt is a thin-skinned orogen that was thrust northward over the passive margin, but it did not result in significant shortening or crustal thickening on the margin. Mesozoic extension was focused south of the orogen, and also did not significantly modify the Paleozoic passive-margin structure. Consequently, the deep crust in this area preserves the structure of the Paleozoic passive margin at the time of its formation.

The thickness of the Proterozoic crust decreases abruptly across the margin, from 35 km in the northern Black Warrior basin to ∼10 km north of the Ouachita fold-and-thrust belt 50 km farther south. The thickness of the Proterozoic crust in the Black Warrior basin is constrained by seismic refraction and reflection data, which constrain the depths to the base of the crust and top of the Paleozoic carbonate-shelf sequence, respectively (Harry and Londono, 2004). Refraction data also constrain the depth to the base of the crust beneath the Ouachita fold-and-thrust belt (Warren et al., 1966). The depth to the top of the Paleozoic crust (and, hence, the thickness of the Paleozoic crust) beneath the Ouachita orogen and central Black Warrior basin is constrained primarily by the gravity model.

The nature of the crystalline crust beneath the southern Black Warrior basin and Ouachita orogen is problematic. Figure 2 depicts this as oceanic crust emplaced in a southward-verging subduction complex beneath the allochthonous terrane that collided with Laurentia during the Ouachita orogeny. However, the data allow for a variety of interpretations, including (1) complete absence of subducted oceanic crust beneath the Ouachita fold-and-thrust belt, (2) presence of ∼7-km-thick oceanic crust (typical of modern oceanic crustal thicknesses) as shown in Figure 2, or (3) oceanic crust to ∼12 km thick, indicating excessive volcanism during margin formation. The latter alternative is similar to interpretations of margin structure in western Arkansas and Louisiana (Keller et al., 1989; Mickus and Keller, 1992), but it is deemed unlikely in Mississippi because it requires an unusually shallow detachment (<10 km) and low densities in the Ouachita orogen compared to the model of Mickus and Keller (1992) to compensate for the high-density oceanic crust (Harry and Londono, 2004). The first alternative is also unlikely because the absence of oceanic crust would require a shallower high-density basement in the Mississippi Interior.
Salt basin that is not consistent with the seismic refraction data (Warren et al., 1966).

Thus, the favored interpretation involves ∼7-km-thick oceanic crust preserved in the relict subduction system. The northern extent of the oceanic crust is poorly constrained. Figure 2 places the ocean-continent transition beneath the central Ouachita orogen, but it may be as far north as the southern Black Warrior basin. To be consistent with the gravity data, the presence of high-density oceanic crust beneath the northern Ouachita orogen and southern Black Warrior basin would require a slightly thicker upper Paleozoic sequence and thinner crystalline crust in these areas than shown in Figure 2, but this is permissible given the available data.

**COMPARISON TO MODERN CONTINENTAL MARGINS**

Three aspects of the geophysical transect indicate that the Paleozoic continental margin beneath the Mississippi coastal plain is a transform rather than a rift margin. First, the steep crustal thickness gradient seaward of the basement hinge zone and the abrupt transition from thick to thin crust are strikingly similar to modern transform margins (Fig. 3). Rift margins typically have much wider regions of transitional crust thickness and lack the steep monotonous gradient. In addition, horsts and grabens produce large-amplitude short-wavelength variations in crustal thickness near the basement hinge zone on most rift margins. The Mississippi Paleozoic margin, like most transform margins, shows relatively subdued topography near the hinge zone.

Second, the seismic velocity and density structures of the margin show no indication of synrift volcanism, plutonism, or mafic underplating of the crust. This lack of synrift magmatism is another characteristic of transform margins. Although amagmatic rift margins exist (e.g., the Iberia margin), they are rare. The majority of modern rift margins are associated with widespread synrift magmatism and mafic underplating (White et al., 1987; Whittmarsh et al., 2001). Gravity modeling of the Mississippi Valley graben to the northeast, the Gulf of Mexico farther south, and the Cretaceous Monroe volcanic province near the Louisiana-Mississippi border demonstrates that magmatic underplating and volcanic features should be resolved if they are present (Harry and Londono, 2004), so their absence cannot be attributed to an inability of the data to resolve these features.

Third, the Paleozoic oceanic crust adjacent to the margin does not appear to be anomalously thick (see preceding discussion). Oceanic crust adjacent to modern rift margins is commonly thicker than the global average as a result of excess transitory magmatism immediately after continental breakup (White et al., 1987). In contrast, oceanic crust adjacent to transform margins is formed at mature spreading centers in steady-state thermal conditions. This process typically results in either normal-thickness crust or, if significant heat is conducted away from the ridge system and into the adjacent continental lithosphere, crust that is slightly thinner than the global average (Bird, 2001).

**SUMMARY AND CONCLUSIONS**

The late Proterozoic through middle Paleozoic Laurentian passive continental margin beneath the central North American Gulf of Mexico coastal plain is preserved in a nearly pristine state beneath upper Paleozoic through Cenozoic rocks emplaced during the Ouachita orogeny, opening of the Gulf of Mexico, and formation of the modern Gulf of Mexico coastal plain. The thickness of the crust on the margin changes abruptly over a distance of ∼50 km, from ∼35 km beneath the northern Black Warrior basin to ∼10 km beneath the Ouachita orogen. The abrupt change in crustal thickness and the steep crustal thickness gradient seaward of the basement hinge zone are similar to modern transform margins and contrast with the more gradual crustal attenuation that is typical of rifted continental margins. The lack of synrift magmatism and normal faulting on the margin is also characteristic of modern transform margins, and is unusual on rift margins. The data are inconclusive in regard to the position of the ocean-continent transition and thickness of the Paleozoic oceanic crust, but favor an interpretation that places ∼7-km-thick oceanic crust adjacent to the margin beneath the central Ouachita fold-and-thrust belt. The volume of postrift magmatism is similar to modern transform margins.

Thus, the structure and magmatic history of
the margin are strikingly similar to modern transform margins and quite different from most rift margins. The margin beneath the Mississippi coastal plain appears to be an along-strike continuation of a similar transform-margin structure in western Arkansas and Louisiana, supporting the contention that the Paleozoic passive margin beneath the central Gulf of Mexico coastal plain developed along a continuous transform segment of a late Proterozoic rift system that extended from western Arkansas to western Alabama (e.g., Thomason, 1976).

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