Simple-shear conjugate rift margins of the Argentine Precordillera and the Ouachita embayment of Laurentia

William A. Thomas* *Department of Geological Sciences, University of Kentucky, Lexington, Kentucky 40506-0053*

Ricardo A. Astini† *Cátedra de Estratigrafía y Geología Histórica, Facultad de Ciencias Exactas, Físicas, y Naturales, Universidad Nacional de Córdoba, Avenida Vélez Sársfield 299 C.C. 395, 5000 Córdoba, Argentina*

ABSTRACT

The Argentine Precordillera was rifted from the Ouachita embayment of Laurentia during Cambrian time. The Ouachita rifted margin along the Texas promontory of Laurentia exhibits a narrow zone of transitional crust, a lack of synrift rocks, and a thin passive-margin succession, indicating slow and limited postrift subsidence. In contrast, data from the western margin of the Precordillera suggest more extensive synrift sediment accumulations and document a thick passive-margin succession, indicating more rapid and relatively greater postrift subsidence than along the Ouachita margin of Laurentia. Passive-margin deposition began in latest Early Cambrian time around the Precordillera, but it did not begin before latest Middle Cambrian time around the Ouachita embayment. The contrasts in structure and stratigraphy are best explained by an asymmetric rift system in the context of simple-shear, low-angle–detachment models for continental rifting. Differences in subsidence rates and inferred crustal structure suggest that the rifted margin of the Ouachita embayment represents an upper-plate configuration, whereas the conjugate margin on the western Precordillera represents a lower-plate configuration.

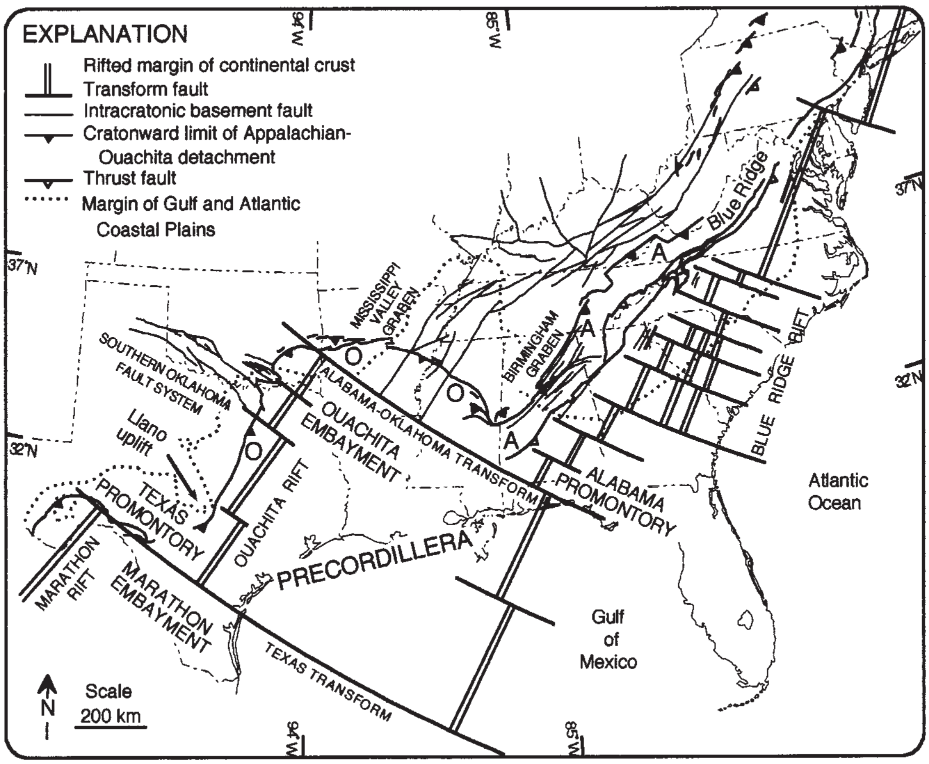

Figure 1. Map of southeastern North America showing the location of the Ouachita embayment of Laurentia, the restored location of the Argentine Precordillera, the general outline of the late Precambrian–Cambrian rifted margin of Laurentia and related structures (after Thomas and Astini, 1996), and the outline of the Appalachian (A) and Ouachita (O) allochthon.

INTRODUCTION

The Argentine Precordillera is recognized as a continental fragment that was rifted from the Ouachita embayment of the margin of Laurentia (present southeastern North America) during Cambrian time (Fig. 1) and subsequently accreted to the western margin of Gondwana (present western South America) during Ordovician time (Astini et al., 1995a, 1996; Thomas and Astini, 1996). Several independent lines of evidence document the original Laurentian site of the Precordillera. Precambrian basement rocks of the Precordillera (sampled from xenoliths in Tertiary plutons) are similar in age and geochemistry to basement rocks of the Llano region of Laurentia (Ramos et al., 1986; Abbruzzi et al., 1993; Kay et al., 1996). Shallow-marine shelf faunas of Cambrian age in the Precordillera are dominated by Laurentian forms (Borrello, 1971; Vaccari, 1994), but successive Ordovician faunas of the Precordillera show increasing endemism and, ultimately, mixing of Gondwanan elements (e.g., Benedetto, 1993; Astini et al., 1995a). Cambrian

*E-mail: geowat@pop.uky.edu.
†E-mail: rastini@satlink.com.

GSA Bulletin; July 1999; v. 111; no. 7; p. 1069–1079; 5 figures.

and Lower Ordovician carbonate successions, sedimentary facies, and faunas in both the Precordillera and southern Laurentia record the evolution of similar passive-margin shelves in approximately the same paleolatitudinal belt, and numerous examples exhibit similarities in specific lithologic details (Barnes, 1959; Johnson et al., 1988; M. Keller et al., 1989; Astini, 1995; Astini et al., 1995a, 1995b, 1996; Cañas, 1995; Thomas and Astini, 1996). The Ouachita embayment has dimensions comparable to those of the Precordillera, and a compatible kinematic history links the Precordillera to Laurentia (summarized in Thomas and Astini, 1996). A recently obtained Early Cambrian paleomagnetic pole for the northern Precordillera corresponds to the coeval Laurentian pole in a reconstruction that places the Precordillera in the Ouachita embayment of Laurentia (Rapalini and Astini, 1998).

Distributions and ages of synrift rocks and structures of southeastern (all directions in present coordinates) Laurentia indicate diachronous rifting during latest Precambrian and Cambrian time (Thomas, 1991). A block of continental crust (the Precordillera), bounded by the northeast-striking Ouachita rift and the northwest-striking Alabama-Oklahoma transform fault, was removed from the Ouachita embayment of southern Laurentia as the Ouachita rift opened during Cambrian time (Fig. 1) (Thomas, 1991; Astini et al., 1995a; Thomas and Astini, 1996; for an alternative view that does not recognize Cambrian rifting, see Dalziel, 1997). In this context, the Ouachita rift margin of the Ouachita embayment and Texas promontory of Laurentia is conjugate to the western margin of the Precordillera, and the Alabama-Oklahoma transform margin of the Ouachita embayment and Alabama promontory was originally contiguous with the northern margin of the Precordillera (Figs. 1 and 2).

Strong similarities in lithology, stratigraphic succession, and general thickness specifically link redbeds of the Lower Cambrian Cerro Totora Formation of the northernmost Precordillera with the temporally equivalent Rome Formation of the Alabama promontory of southeastern Laurentia (Astini et al., 1995b). The Lower and Middle Cambrian stratigraphic succession of the Birmingham graben within the Alabama promontory is similar to that of the northernmost Precordillera, suggesting similar tectonic evolution on opposite sides of the Alabama-Oklahoma transform fault (Fig. 1). In contrast, the Cambrian-Ordovician passive-margin stratigraphy on the Texas promontory of Laurentia differs markedly from that of the Precordillera. The base of the passive-margin succession on the Texas promontory contains no strata older than latest Middle Cambrian, whereas the succession on the Precordillera includes beds as old as Early Cambrian age. The succession on the Precordillera is more than three times as thick as that on the Texas promontory (Fig. 2). These substantial differences between the stratigraphic successions might seem to be inconsistent with the interpretation that the Texas promontory and the Precordillera are the opposite sides of the Ouachita rift (Fig. 2) (Thomas and Astini, 1996). Substantial differences in late synrift and passive-margin (postrift) stratigraphy on opposite sides of a rift, as well as similarities across a transform margin, however, are predictable within the context of mechanical and thermal models for continental rifting.

The purpose of this article is to compare the synrift and postrift stratigraphy of the Precordillera with that of the Ouachita rifted margin of Laurentia in order to place the style of rifting in the context of available mechanical and thermal models for continental rifting. Sedimentologic data indicate similar depositional conditions on the passive margins (summarized in Astini et al., 1995a; Thomas and Astini, 1996); therefore, the cause(s) of the differences in thickness and time of initiation of passive-margin deposition must be sought in the structural and thermal history of the rift and postrift margins. Subsidence profiles from stratigraphic successions can be used to document the history of thermal uplift and subsidence of rifted margins (Bond et al., 1984). Available data are not abundant; however, stratigraphic successions for comparison of subsidence history can be assembled in key locations for both the Precordillera and Texas promontory. The results of this work will help to focus future acquisition of data.

BACKGROUND

Current models for continental rifting comprise two general end members: pure-shear, symmetrical-rift models; and simple-shear, asymmetrical-rift, low-angle–detachment models (e.g., Lister et al., 1986; Buck et al., 1988). These alternatives for mechanical extension and heat flow predict distinctive sedimentary accumulations both in synrift grabens and on passive-margin continental shelves. Because of specific implications for synrift and postrift structures and sediment accumulation, the overall geometry of a rifted margin can be inferred from structure and stratigraphy (e.g., Issler et al., 1989; Osleger and Read, 1993; Thomas, 1993; Walker et al., 1994).

Pure-shear models of continental stretching imply symmetrical rift structures, including oppositely facing half-grabens on opposite sides of the rift (e.g., McKenzie, 1978; Lister et al., 1986). Continental crust thins at similar gradients from both sides toward the rift. Heat-flow models yield similar patterns of synrift uplift and postrift subsidence on both margins of the rift (Buck et al., 1988), implying similar times, rates, and thicknesses of passive-margin sediment accumulation on both sides of the rift (i.e., symmetrical distribution of thickness and stratigraphic ages).

Simple-shear (low-angle–detachment) models for continental rifting imply asymmetrical rift structures and include contrasting structural configurations that distinguish upper and lower plates (Fig. 3) (e.g., Wernicke, 1985; Lister et al., 1986, 1991; Etheridge et al., 1989; Wernicke and Tilke, 1989). On the lower plate, rotated blocks are bounded by listric faults that sole into an oceanward-dipping low-angle detachment fault (Lister et al., 1991), and continental crust thins gradually across a wide zone of transition to oceanic crust. Sedimentary accumulations on lower-plate margins include locally thick, fault-rotated, synrift graben-fill deposits, as well as thick, late synrift and early postrift (passive margin) deposits unconformably (locally conformably) overlying the graben-fill rocks and associated crustal horsts. The upper plate, in contrast, generally is characterized by a relatively narrow, broadly arched zone of transition from full-thickness continental crust to oceanic crust and by a few steep oceanward-dipping normal faults (Lister et al., 1991). Because of thermal uplift (Fig. 3), accumulations of synrift rocks along the upper-plate margin are limited in extent and thickness; and postrift, passive-margin shelf successions are relatively thin. In contrast, as the lower plate moves away from the heat-flow maximum (Buck et al., 1988), crustal subsidence begins earlier and reaches greater magnitude than on the upper plate (Fig. 3). Therefore, simple-shear models predict contrasting synrift and passive-margin shelf successions on the opposite conjugate margins (i.e., asymmetrical distribution of thickness and stratigraphic ages), a defining principle for reconstruction of rifted margins. Off-shelf passive-margin deposits on both upper and lower plates represent deep-water deposition on thinned continental (transitional) crust to oceanic crust and are not directly sensitive to thermal uplift and subsidence of the shelf.

Abrupt changes in structural style along the strike of a rift are localized at transform faults, which function as offsets of the rift and as boundaries between domains of opposite dip of the detachment (Lister et al., 1986; Rosendahl, 1987). Transform margins are distinct from rift margins because of an abrupt transition from full-thickness continental crust to oceanic crust (Keen, 1982; Scrutton, 1982; Keen and Haworth, 1985; Keen et al., 1990; Reid and Jackson, 1997). Steep faults parallel some transform fault systems (e.g., Mascle and Blarez, 1987; Sylvester, 1988; Keen et al., 1990), providing conduits for deep-source magmas. During the opening of an ocean adjacent to a transform continental margin, the end of

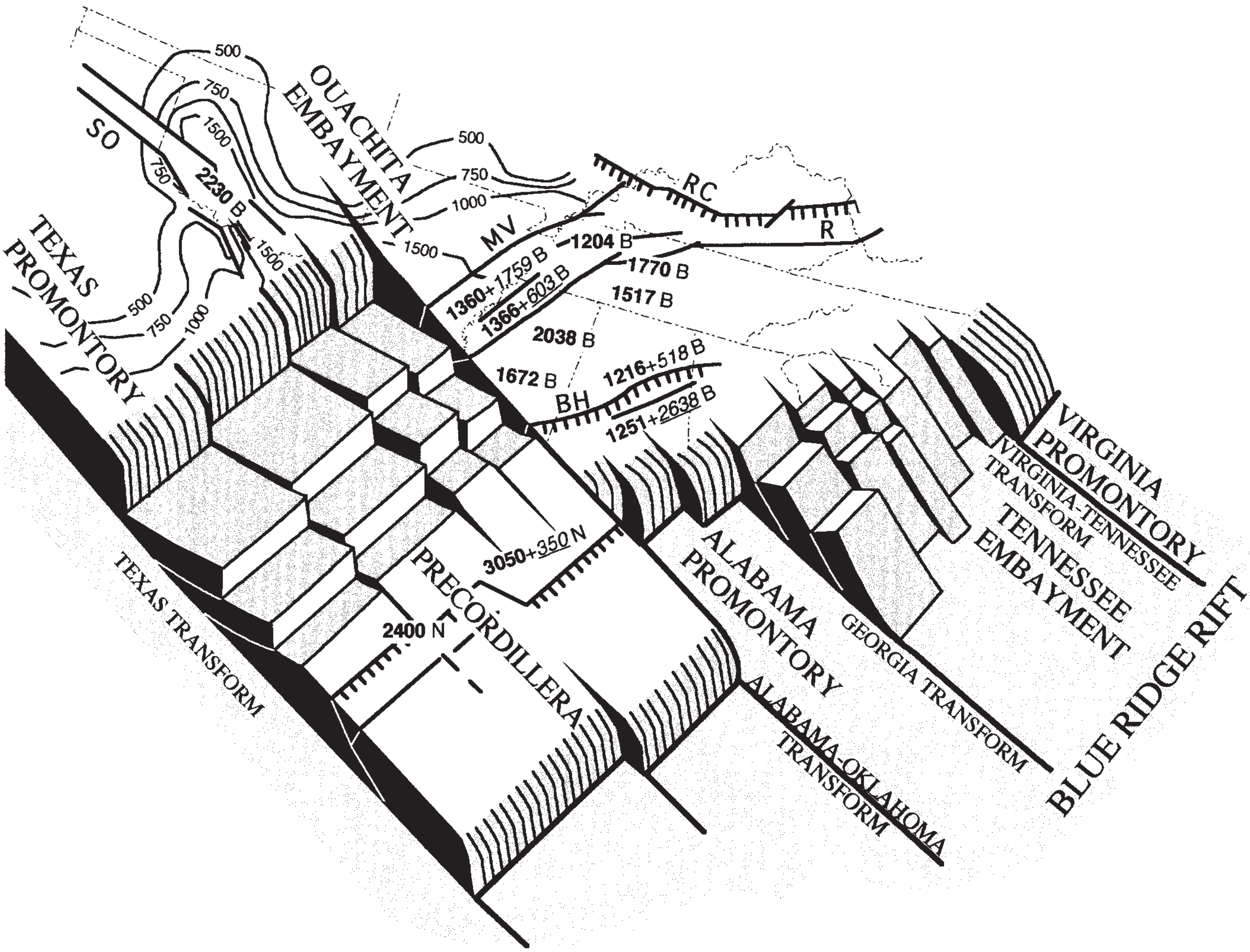

Figure 2. Schematic block diagram of the rifted margin and rift-related intracratonic fault systems around the Ouachita embayment of southern Laurentia (modified from Thomas, 1993) and the Precordillera fragment of Laurentia at the time of continental breakup (ca. 525 Ma). Abbreviations: BH—Birmingham graben; MV—Mississippi Valley graben; RC—Rough Creek graben; R—Rome trough; SO—Southern Oklahoma fault system. The Ouachita rifted margins of both Laurentia and the Precordillera have been deformed and partly covered by allochthonous rocks and sedimentary deposits. The isopach map (thickness in meters) of the Cambrian–Lower Ordovician passive-margin succession for the Texas promontory and Ouachita embayment is compiled from Barnes (1959) and Johnson et al. (1988). The stratigraphic thickness of the Cambrian–Lower Ordovician passive-margin succession is shown at specific localities on the Alabama promontory of Laurentia, along the Southern Oklahoma fault system, and in the Precordillera (bold numerals—thickness in meters of entire Cambrian–Lower Ordovician passive-margin carbonate succession; bold numerals plus italicized numerals—thickness of Cambrian–Lower Ordovician passive-margin carbonate succession plus thickness of underlying synrift succession; underlined italicized numerals—section containing evaporites; B—sedimentary succession resting directly on basement; N—lower part of sedimentary cover and basement not documented). Sources of data for wells and measured stratigraphic sections on the Alabama promontory were summarized in Thomas (1988, 1991) and Thomas and Whiting (1995). The stratigraphic section for the Southern Oklahoma fault system is from Johnson et al. (1988) and Osleger and Read (1993). The measured stratigraphic sections in the Precordillera are compiled from Furque (1972), Baldis and Bordonaro (1981, 1984), Astini (1991), Keller et al. (1994), Vaccari (1994), Lehnert (1995), and unpublished data (Astini).

the spreading ridge migrates along the active continent-ocean transform within a continental embayment, and a corresponding thermal uplift migrates along the transform margin of continental crust (Todd and Keen, 1989). Possible synrift accumulations along a transform margin include thick, local graben fills; however, the diachronous ridge-end uplift may result in erosion of the graben-fill accumulations and associated basement horsts. Therefore, transform margins are likely to be characterized by either a lack of preserved synrift rocks or local accumulations in narrow fault-bounded basins, and by restricted early postrift passive-margin deposits. The width of thermal uplift is ~80 km (Todd and Keen, 1989), beyond which passive-margin deposition on continental crust apparently is unaffected.

Subsidence history as determined from backstripping of stratigraphic successions on passive margins records the mechanical and thermal evolution of the rift (e.g., Bond et al., 1984, 1995). An exponential decay curve characterizes postrift thermal subsidence of stretched continental lithosphere (McKenzie, 1978). In this article, subsidence history is used to characterize tectonic history along both sides of the Ouachita rift and to compare the conjugate margins of the Ouachita embayment and the Precordillera.

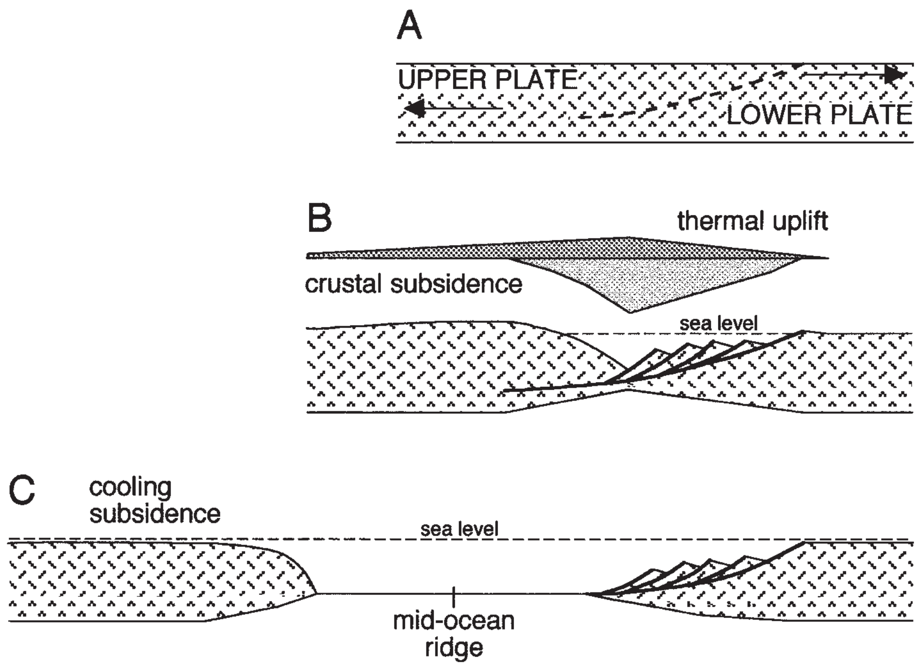

Figure 3. Sequential, schematic cross sections depicting the interaction of thermal uplift and isostatic crustal subsidence on opposite blocks of a low-angle detachment during continental rifting and breakup in simple shear (designed to illustrate concepts from Wernicke, 1985; Lister et al., 1986, 1991; Buck et al., 1988; Etheridge et al., 1989; Issler et al., 1989). (A) Trajectory of low-angle detachment (dashed line) prior to initial stretching. (B) Extended crust prior to breakup (geometry of faults from Lister et al., 1986). Maximum heat flow is at the intersection of the low-angle detachment with the surface (Buck et al., 1988). Isostatic subsidence of thinned crust counteracts thermal uplift (proportions and distribution of thermal uplift, crustal subsidence, and topography from Buck et al., 1988). Maximum topographic elevation of thermal uplift is at the edge of full-thickness continental crust on the upper plate. Subsidence of thinned crust exceeds thermal uplift. (C) Following breakup and drift away from mid-ocean ridge. Cooling (thermal decay) subsidence leads to transgression and initiation of passive-margin–shelf deposition on the upper plate. Crustal subsidence and shelf deposition continue on the lower plate.

OUACHITA RIFTED MARGIN OF LAURENTIA

Trace of the Margin

The intersection of the Alabama-Oklahoma transform fault and the Ouachita rift outlines the Ouachita embayment of Laurentia (Fig. 1) (Thomas, 1991). The Alabama-Oklahoma transform also intersects the southern Blue Ridge rift to outline the Alabama promontory, and the intersection of the Ouachita rift with the Texas transform outlines the Texas promontory (Fig. 1).

Alabama-Oklahoma Transform Margin

Seismic velocity and gravity models define a narrow zone of transition (~25 km wide) along the edge of Laurentian continental crust at the location of the Alabama-Oklahoma transform in the Ouachita embayment beneath the southern part of the Ouachita thrust belt in Arkansas (G. Keller et al., 1989a; Mickus and Keller, 1992). A boundary between regions of contrasting magnetic signatures trends northwest-southeast (Hinze and Braile, 1988) from the seismically defined edge of continental crust, marking the trace of the transform (Fig. 1) (Thomas, 1991).

Passive-margin cover and late synrift rocks are exposed in the Appalachian thrust belt (A, Fig. 1) on the Alabama promontory and, along with underlying basement, have been drilled in deep wells. These data document a shallow-marine carbonate platform across the Alabama promontory of southeastern Laurentia. Seismic reflection data and a few deep wells show that an autochthonous passive-margin carbonate-shelf facies around the Ouachita embayment extends southward beneath the Ouachita allochthon (O, Fig. 1), which includes off-shelf passive-margin rocks of Late Cambrian to Early Mississippian age (Viele and Thomas, 1989). Shelf-edge facies have not been identified along the Alabama-Oklahoma transform, but the tectonic juxtaposition of temporally equivalent shelf and off-shelf facies restricts the location of the shelf edge (Thomas, 1989).

Synrift sedimentary rocks adjacent to the Alabama-Oklahoma transform are restricted to the northeast-striking (rift-parallel) Birmingham and Mississippi Valley intracratonic graben systems (Figs. 1 and 2) (Thomas, 1991). The Birmingham graben fill was dismembered and displaced by late Paleozoic Appalachian thrusting, but deep wells and seismic reflection profiles enable reconstruction of the graben-fill stratigraphy, as well as the rift-stage basement structure (Thomas, 1985, 1991; Thomas and Whiting, 1995). Lower Cambrian sandstone at the base of the succession is overlain by a transgressive dolostone, above which fine-grained siliciclastic rocks compose most of the graben fill. Drill samples document anhydrite within the clastic succession (Raymond, 1991); however, no evaporites are preserved in outcrops. The biostratigraphic range of the Birmingham graben fill is from Early Cambrian at the base to early Late Cambrian (Dresbachian) at the top (Palmer, 1962, 1971). Irregular distribution of Middle Cambrian carbonate facies and coeval fine siliciclastic rocks (Thomas and Drahovzal, 1973) suggests synsedimentary reactivation of faults along the Birmingham graben and possibly reflects initiation of shelf-carbonate deposition on upthrown blocks. Facies variations in Middle Cambrian strata indicate nonuniform subsidence and instability of the eastern shelf of Laurentia as far north as the Tennessee embayment (Rankey et al., 1994).

Westward across the Alabama promontory on the regional horst between the Birmingham and Mississippi Valley graben systems, relatively thick carbonate successions overlie the basement rocks, suggesting initiation of passive-margin deposition as early as Middle Cambrian time (Fig. 2). Thickness variations in the Cambrian carbonates and a basal sandstone suggest additional, currently unmapped basement faults, which are also suggested by gravity and magnetic data (Johnson et al., 1994).

The sedimentary fill of the Mississippi Valley graben includes a basal sandstone, a transgressive carbonate unit, and a relatively thick, dark mudstone (summaries in Thomas, 1988, 1991). Locally the graben-fill succession includes anhydrite (Mellen, 1977). The upper part of the Mississippi Valley graben fill contains trilobites of early Late Cambrian (Dresbachian) age (Resser, 1938; Grohskopf, 1955; Palmer, 1962, 1971); however, the age of the base of the succession is not defined biostratigraphically.

The Southern Oklahoma fault system extends northwestward from the Ouachita rift into the Laurentian craton in a direction parallel to the Alabama-Oklahoma transform (Fig. 1). Igneous rocks (gabbros, basalts, granites, rhyolites) within the transform-parallel fault system range in age from 552 ± 7 Ma (U-Pb), to 539 ± 2 Ma (Ar-Ar), to 525 ± 25 Ma (Rb-Sr)(Lambert et al., 1988; Hogan et al., 1996). Linear gravity and magnetic anomalies show that the igneous rocks are restricted to a steeply bounded zone ~65 km wide (Fig. 1) (Gilbert, 1983; Coffman et al., 1986; Thomas, 1991; Denison, 1995). The Southern Oklahoma (transform) fault system is kinematically linked to rifting (Thomas, 1991, 1993), and the ages of the igneous rocks define the time of transform faulting, which tapped deep sources of magma.

The synrift rocks, both sedimentary and igneous, are overlapped by carbonate-shelf strata of middle Late Cambrian (Franconian) age, indicating initiation of widespread passive-margin deposition (Thomas, 1991). The Upper Cambrian–Lower Ordovician carbonate-shelf succession is >1200 m thick from the Alabama promontory westward to the Ouachita embayment (Thomas, 1988). Between the Birmingham and Mississippi Valley graben systems, where the carbonate succession probably includes Middle Cambrian strata, the total thickness of carbonate rocks is greater than in the graben systems (Fig. 2). The Lower Ordovician part of the carbonate succession thickens locally in a narrow, linear area along the Southern Oklahoma fault system, where the entire Upper Cambrian–Lower Ordovician succession is >2000 m thick (Denison, *in* Johnson et al., 1988).

Ouachita Rift Margin

Along the Ouachita rifted margin of the Texas promontory of Laurentia, wells and seismic reflection profiles document a steep eastward descent of the top of crystalline basement rocks (Nicholas and Rozendal, 1975; Nicholas and Waddell, 1989; Culotta et al., 1992). Gravity models illustrate thick continental crust (~43 km) on the promontory and a relatively narrow zone of transitional crust (<75 km wide) along the rifted margin (Kruger and Keller, 1986; G. Keller et al., 1989b). Subsurface and geophysical data indicate an extensive, gently east-dipping shelf bordered by a steep east-facing slope.

Basement and passive-margin cover strata are exposed around the Llano uplift on the Texas promontory (Fig. 1), and the passive-margin carbonate succession has been penetrated in numerous wells north and east of the Llano uplift. No synrift rocks have been recognized on the Texas promontory, and the transgressive passive-margin shelf succession unconformably overlies Precambrian basement rocks. An extensive Upper Cambrian–Lower Ordovician passive-margin carbonate-shelf succession is generally <1000 m thick on the Texas promontory (Fig. 2) (Barnes, 1959; Denison, *in* Johnson et al., 1988). At the base of the passive-margin succession in exposures around the Llano uplift, uppermost Middle Cambrian sandstones directly overlie crystalline basement rocks, and local paleotopographic relief on the sub-Cambrian unconformity is >200 m (Barnes et al., 1972; Krause, 1996). The passive-margin succession thickens gradually southeastward toward the trace of the rifted margin, and regional isopach lines (Barnes, 1959) parallel the strike of the Ouachita rifted margin between the Southern Oklahoma (transform) fault system and the Texas transform (Fig. 2).

In a structural configuration like that along the Alabama-Oklahoma transform, seismic data show that the passive-margin carbonate succession on the Texas promontory dips southeastward beneath the Ouachita allochthon (O, Fig. 1) (Nicholas and Waddell, 1989). The Ouachita allochthon consists of off-shelf passive-margin facies, and as it is along the Alabama-Oklahoma transform, the shelf edge is covered by the allochthon (Viele and Thomas, 1989).

Time of Rifting

Ages of synrift rocks of the Birmingham, Mississippi Valley, and Southern Oklahoma systems consistently indicate initiation of rifting at about the beginning of Cambrian time (545 Ma, using the time scale of Tucker and McKerrow, 1995) and continuation of crustal extension through early Late Cambrian time (ca. 503 Ma) (Thomas, 1991; Thomas and Astini, 1996). The age of the carbonate-shelf succession, overlapping Precambrian basement and synrift rocks, documents establishment of a passive margin on the Texas promontory by latest Middle Cambrian time (ca. 510 Ma) and entirely around the Ouachita embayment by middle Late Cambrian time (ca. 503 Ma) (Thomas, 1991). Coeval, passive-margin off-shelf rocks now in the Ouachita allochthon are no older than Late Cambrian age (Ethington et al., 1989; Viele and Thomas, 1989).

Rifting around the Ouachita embayment of Laurentia is younger than that along the Blue Ridge rifted margin of Laurentia (Fig. 1), where the youngest synrift volcanic rocks are 564 ± 9 Ma (Aleinikoff et al., 1995) and the transition from late synrift to passive-margin sediment deposition is earliest Cambrian (ca. 544 Ma) (Simpson and Sundberg, 1987; Simpson and Eriksson, 1989). The diachroneity of active rifting indicates a shift of the spreading center from the southern part of the Blue Ridge rift to the Ouachita rift at the beginning of Cambrian time (Thomas, 1991). The successive ages of active rifting encompass establishment of a passive margin along the Blue Ridge rift (margin of Laurentia including the Precordillera) followed by rifting of the Precordillera from Laurentia (Thomas and Astini, 1996).

RIFTED MARGIN OF THE PRECORDILLERA TERRANE

In the Precordillera, neither the structure of the top of Precambrian basement rocks nor the distribution of synrift sedimentary rocks beneath Andean thrust sheets (Cenozoic thrusting) is known (e.g., Cominguez and Ramos, 1991; Zapata and Allmendinger, 1996). An abrupt down-to-the-west offset of basement rocks beneath the western Precordillera is implied by eastward shallowing of the basal décollement (Allmendinger et al., 1990; Gosen, 1992; Astini et al., 1995a); gravity data are consistent with that interpretation (Introcaso et al., 1992; Gimenez et al., 1997). The inferred configuration of the top of basement rocks may reflect faults associated with Ouachita rifting (Astini et al., 1995a).

The oldest part of the exposed stratigraphic succession in Andean thrust sheets of the Precordillera consists of Early Cambrian evaporites and red siliciclastic rocks exposed only in the northern Precordillera (Astini et al., 1995a, 1995b; Astini and Vaccari, 1996). The basal anhydrite-gypsum succession (>250 m) is interbedded with dolomitized cryptomicrobial and oolitic tabular limestones. The redbed succession includes abundant halite-hopper-crystal casts and intrasedimentary gypsum crystals, which indicate extensive evaporation in arid, supratidal environments (as shown by modern analogs; e.g., Shinn, 1983; Handford, 1991; Warren, 1991). Layers of wave-reworked detrital gypsum, mud-cracked beds, stromatolites, and brecciated beds with tepee structures are also common, suggesting cyclical subaerially exposed mud flats and salt flats (e.g., Kendall and Warren, 1987; Demicco and Hardie, 1994). The association of evaporites and marginal-marine redbeds represents restricted circulation that is commonly associated with early stages of continental rifting in low-latitude, arid-climate settings (Kinsman, 1975; Rona, 1982; Miall, 1984; Warren, 1989). The Lower Cambrian evaporite-redbed succession suggests synrift graben-filling deposition (Astini and Vaccari, 1996), either in the main (Ouachita) rift or in a Precordilleran intracratonic synrift graben similar to the Mississippi Valley and Birmingham graben systems on Laurentia adjacent to the Alabama-Oklahoma transform margin (Fig. 1).

Initiation of the passive-margin stage is recorded by upward gradation from the evaporite-redbed succession to a thick carbonate succession in the uppermost part of the Lower Cambrian Series (Astini et al., 1995a; Astini and Vaccari, 1996). Between the synrift evaporite-redbed succession and the limestone-dominated passive-margin succession, a thin transitional interval (~50 m) consists of reddish arkosic silty shales and minor quartzose to subfeldspathic sandstones with sparse evaporite and carbonate interbeds that grade upward to quartz arenites and intercalated olive-green glauconitic shales and sandstones. The stratigraphic transition at the top of the graben fill is interpreted to indicate transgression associated with cessation of rifting. *Bonnia-Olenellus* Zone trilobites (Vaccari, 1990) in the green shales and dolomitized grainstones at the top of the transitional interval define a minimum age of Early Cambrian for active rifting.

Overstepping of the graben-fill succession by passive-margin carbonates marks the end of brittle stretching during the rifting stage and the beginning of thermotectonic subsidence during the drifting stage by late Early Cambrian time. New data from mafic rocks in the western Precordillera further constrain the time of rifting from Laurentia. A preliminary U-Pb zircon age of 565 ± 45 Ma from microgabbros exposed in a thrust sheet in the southwestern Precordillera is interpreted as the crystallization age of the mafic rocks in the earliest stages of ocean spreading (Davis et al., 1997). Within the range of uncertainty, this age for initial ocean spreading is consistent with the Early Cambrian age of rifting indicated by the upper Lower Cambrian stratigraphic transition from synrift rocks upward to passive-margin carbonates, as well as with the rifting age of the Precordillera determined from subsidence curves (Bond et al., 1984).

The Middle Cambrian–Lower Ordovician passive-margin succession in the Precordillera ranges from ~2400 to ~3100 m thick, approximately three times as great as that on the Texas promontory of Laurentia (Fig. 2). A north-to-south polarity of facies in Lower Cambrian rocks is replaced by an east-to-west polarity in the Middle Cambrian and younger passive-margin facies. Lower Cambrian marginal-marine siliciclastic rocks to the north are probably equivalent to shallow-marine, thin siliciclastic intervals within the lower part of a cyclic carbonate succession to the south (Astini and Vaccari, 1996). The uppermost Lower Cambrian succession includes shallower marine facies (laminated and massive dolostones) to the north and progressively deeper water facies (inner-platform limestones) toward the south. Lower Middle Cambrian dolostones on the north are replaced southward by ramp limestones, and farther south by outer shelf-slope facies represented in olistoliths (Bordonaro, 1985). Through most of the Middle Cambrian succession, however, shallow-water limestones and dolostones on the east and coeval outer shelf-slope deep-water carbonates in olistoliths in the western Precordillera indicate distinct east-to-west polarity. East-west polarity has been further documented throughout the later stages of evolution of the Precordillera passive margin (Astini et al., 1995a, 1996).

West of the Precordillera carbonate shelf, a west-facing slope facies of Ordovician mudstone turbidite contains olistoliths of both the shelf facies and the slope facies (Astini, 1988; Astini et al., 1995a). The oldest strata of redeposited slope facies are of late Early Cambrian age (Benedetto et al., 1986; Vaccari and Bordonaro, 1993; Bordonaro and Liñán, 1994; Palmer et al., 1996). The slope deposits also contain olistoliths of quartz-pebble conglomerate, conglomeratic sandstone, and coarse lithic conglomerate, the composition of which indicates a provenance of continental basement rocks (Banchig et al., 1990; Astini, 1991, 1996; Mendoza et al., 1997). Such conglomerates have not been seen in stratigraphic position; however, the olistoliths in the slope deposits suggest graben-filling synrift rocks along the western rifted margin of the Precordillera, the margin that was formed by the Ouachita rift (Figs. 1 and 2) (Thomas and Astini, 1996). Paleomagnetic data indicate no significant rotation of the Precordillera block after Early Cambrian time (Rapalini and Astini, 1998), further suggesting that the west-facing slope of the Precordillera is the margin that faced the Ouachita rift of the Texas promontory.

SUBSIDENCE HISTORY

Comparison of subsidence histories for key locations on Laurentia and the Precordillera documents a range of responses to postrift thermal subsidence along the rifted margin. The subsidence history is presented here in profiles of the depth to top of crystalline basement rocks as a function of time (Fig. 4).

Backstripping of two stratigraphic sections from the Precordillera yields subsidence profiles (Fig. 4A) that are typical of passive-margin thermal subsidence. Each of the sections is truncated at the base by an Andean thrust fault; the thickness and lithology of the initial deposits above basement are unknown. The section from the central Precordillera is based on stratigraphic data that have been used for two previously published profiles (Bond et al., 1984; González Bonorino and González Bonorino, 1991). Allowing for changes in calibration of the geologic time scale, the profile in Figure 4A for the central Precordillera is identical to that of Bond et al. (1984). The section from the northern Precordillera includes older beds at the base, specifically the Lower Cambrian synrift evaporite-redbed succession (Astini and Vaccari, 1996), and the passive-margin succession in the northern Precordillera is significantly thicker than that in the central Precordillera (Fig. 2). The sections are incomplete at the base; however, projection of the profiles backward in time is compatible with initiation of rifting ca. 545 Ma and continental breakup ca. 525 Ma (Fig. 4A). An artifact of backstripping sections with missing bases distorts the profile of early subsidence history. Compaction of the original (noncompacted) thickness of the exposed evaporite-redbed succession in the northern Precordillera accommodates part of the thickness of the lowermost passive-margin carbonates, thereby reducing the computed subsidence of basement beneath that section. In contrast, because of the lack of preserved basal evaporite-redbed succession in the section from the central Precordillera, the entire thickness of the lowermost passive-margin carbonate is computed to be a result of basement subsidence, thereby relatively increasing computed basement subsidence beneath that section. Coincidentally, basement subsidence (reduced by evaporite-redbed compaction) computed for the thicker passive-margin succession in the northern Precordillera is approximately equal to that computed for the thinner passive-margin succession (without a known underlying evaporite mudstone succession) in the central Precordillera. Therefore, these profiles are useful to illustrate the general form of subsidence history, but they depict the minimum magnitude of basement subsidence for each section. The distortion of the profiles by nonuniformly preserved and exposed basal strata disappears in the later part of the subsidence computation, and the profiles for the northern and central Precordillera are similar. Allowing for shortening of present dimensions by Cenozoic Andean thrusting, the stratigraphic sections in the Precordillera represent a position ~60 km east of the shelf edge (as defined by the location of the slope facies).

Three profiles are shown here to represent the subsidence history of the thick continental crust of the Texas promontory (Fig. 4B). The exposed stratigraphic section and unconformable contact with basement rocks in the Llano uplift are thoroughly documented (Barnes et al., 1972) as the basis for one subsidence profile. Extensive subsurface data compiled in regional isopach maps (Fig. 2) (Barnes, 1959; Johnson et al., 1988) for

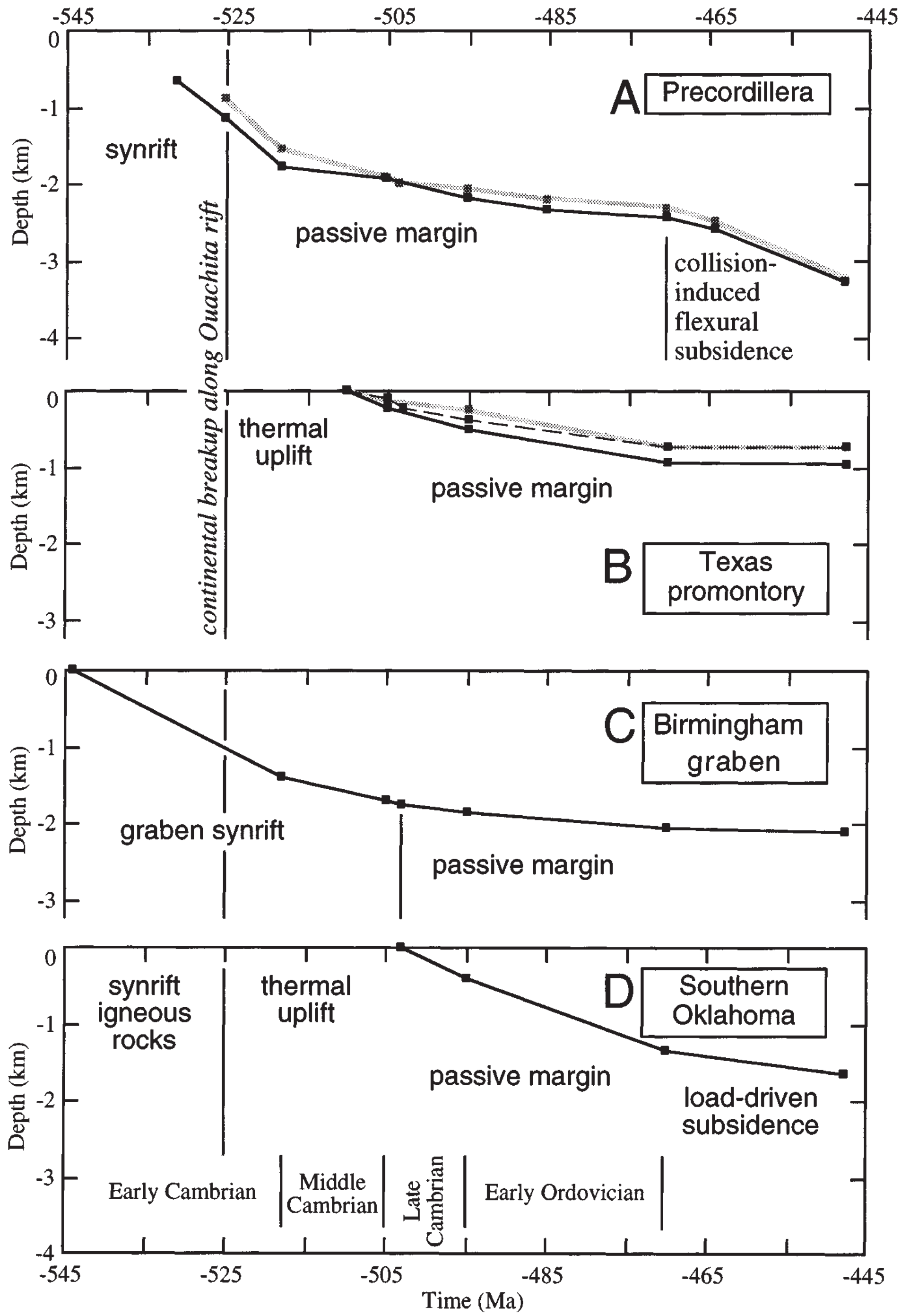

Figure 4. Tectonic subsidence profiles for top of basement rocks derived from lithology-dependent decompaction and backstripping calculations (program by Wilkerson and Hsui, 1989; using porosity/depth data from Sclater and Christie, 1980, and Schmoker and Halley, 1982). The profiles use the time scale of Tucker and McKerrow (1995). (A) Passive-margin successions at locations in the northern Precordillera (black line) and central Precordillera (gray line). Stratigraphic data are from Furque (1972), Baldis and Bordonaro (1981, 1984), Astini (1991), Keller et al. (1994), Vaccari (1994), Lehnert (1995), and unpublished data (Astini). No contact of the synrift or passive-margin succession with basement is exposed in these sections in the Precordillera; therefore, the age of zero subsidence (initial deposition on basement) and the depth of tectonic subsidence of the top of basement at the time of deposition of the oldest exposed rocks are estimated. See text for discussion of effects on subsidence curves of a lack of a complete succession down to basement. (B) Passive-margin successions from three locations on the Texas promontory of Laurentia (dashed line—Llano uplift; gray line—location ~60 km from shelf edge and midway between Alabama-Oklahoma and Texas transform faults; black line—maximum thickness shown by isopach maps on margin of Texas promontory). Stratigraphic data are from Barnes (1959), Barnes et al. (1972), and Johnson et al. (1988). Passive-margin sedimentary rocks unconformably overlie basement rocks on the Texas promontory, and the top of basement is defined at zero depth at the beginning of deposition. (C) Synrift and passive-margin succession from the palinspastic location of the Birmingham graben. Palinspastic reconstruction is based on cross sections modified from Thomas (1985). Stratigraphic data are from Butts (1926), Mack (1980), Raymond (1991), Osborne (1992), and interpretation of seismic reflection profiles across the graben. The contact of the synrift succession with basement is imaged in seismic reflection profiles. (D) Carbonate-shelf succession from the Southern Oklahoma fault system. Stratigraphic data are from Johnson et al. (1988), Osleger and Read (1993), and Denison (1997). The exposed base of the carbonate-shelf succession overlaps synrift igneous rocks and older Precambrian basement.

the Texas promontory provide an opportunity to use regionally smoothed values for thickness, rather than to rely on a possibly anomalous thickness from a single well. Furthermore, in order to compare subsidence history at sites approximately equidistant from the shelf edge, values were selected from the isopach maps to represent a location ~60 km west of the shelf edge (comparable to the restored distance from the shelf edge to stratigraphic sections in the Precordillera). An additional section was compiled from the isopach maps to represent the maximum thickness of the carbonate-shelf facies on the Texas promontory. The three subsidence profiles for the Texas promontory indicate postrift thermal subsidence and initiation of passive-margin shelf deposition in late Middle Cambrian time, somewhat after the time of continental breakup as estimated from the ages of synrift rocks. The subsidence of the Texas promontory differs from that of the Precordillera, both in later time of initial subsidence below sea level and in lesser magnitude of subsidence (cf. Fig. 4, A and B). The subsidence profiles for the Texas promontory and the Precordillera are similar in that they show an exponential decrease of subsidence rate through time. Following more rapid initial subsidence in the Precordillera, the subsidence rates are similar.

Stratigraphic data indicate a complex subsidence history for the region of the Birmingham graben (Fig. 4C), including the effects of both Blue Ridge postrift thermal subsidence beginning ca. 544 Ma and Birmingham graben extension continuing until ca. 503 Ma (Thomas, 1991). Passive-margin carbonate facies overlap the Birmingham graben fill, and the postrift Late Cambrian–Early Ordovician subsidence history of the Birmingham graben is similar to the stratigraphically recorded subsidence history of the Texas promontory (cf. Fig. 4, C and B), as well as to the late stage of passive-margin subsidence of the Precordillera (cf. Fig. 4, C and A).

The subsidence profile for the Southern Oklahoma fault system is unique in the region and does not conform to a simple exponential thermal decay curve (Fig. 4D) (cf. Feinstein, 1981). Carbonate-shelf deposition over the synrift igneous rocks and associated Precambrian basement did not begin until middle Late Cambrian time (ca. 503 Ma), indicating persistent thermal uplift along the trend of the Cambrian igneous rocks. Thermal subsidence accompanied by transgression is recorded in the carbonate-shelf succession and is depicted in the subsidence profile for Late Cambrian time (Fig. 4D). A continuing high rate of subsidence rather than exponential decrease in subsidence rate after Late Cambrian time (Fig. 4D) may reflect modification of thermal subsidence by load-driven subsidence. Dense mafic rocks at shallow crustal levels provide an isostatic mechanism for continued subsidence. Load-driven subsidence is restricted to a narrow linear area along the Southern Oklahoma fault system, corresponding to the distribution of synrift mafic rocks (Feinstein, 1981). Hence, the locally thick carbonate-shelf succession evidently reflects a transform-related subsidence anomaly.

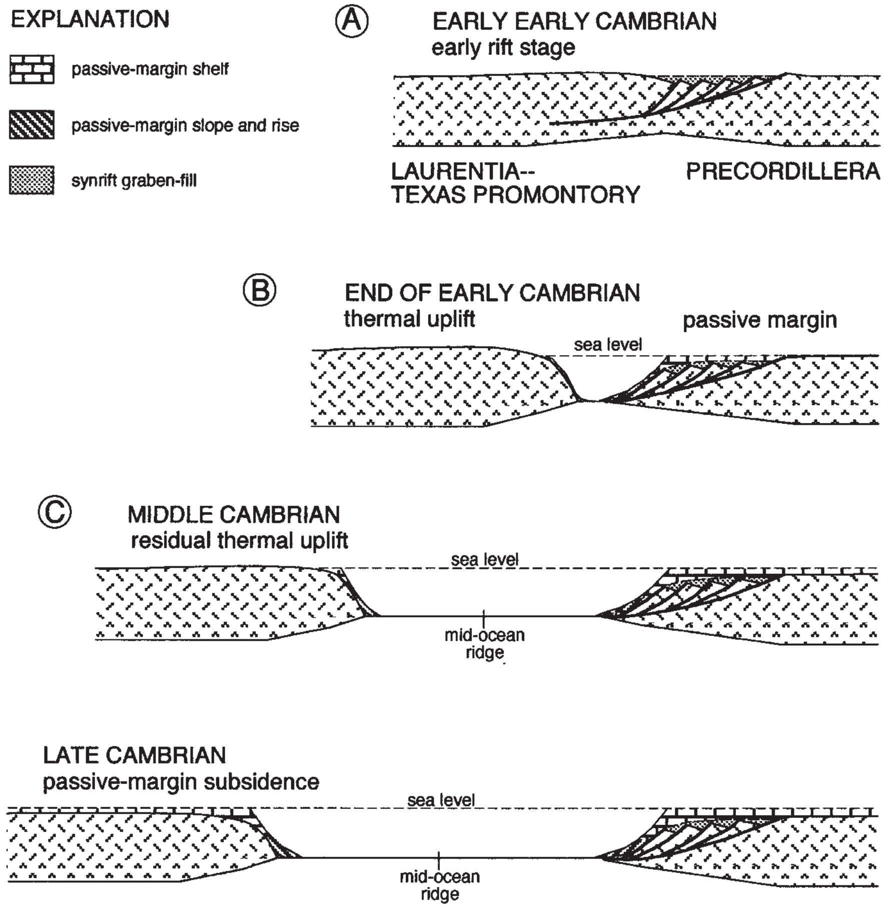

Figure 5. Sequential, schematic cross sections of continental rifting and breakup along the Ouachita rift. Cross sections are proportional, vertically exaggerated, and not to scale. Proportional scale and rates of thermal uplift follow the models of Buck et al. (1988). (A) Early Early Cambrian, ca. 540 Ma. Initial rifting and synrift graben filling. (B) End of Early Cambrian, ca. 518 Ma. After continental breakup; transition from synrift graben filling to initial passive-margin deposition on lower plate (Precordillera); thermal uplift of margin of upper plate (Laurentia). (C) Middle Cambrian, ca. 512 Ma. Passive-margin carbonate-shelf deposition on subsiding lower plate (Precordillera); residual thermal uplift of passive margin on upper plate (Laurentia). (D) Late Cambrian, ca. 500 Ma. Continuation of shelf deposition on lower plate (Precordillera); initial transgression and deposition of passive-margin shelf facies during thermal subsidence of upper plate (Laurentia).

DISCUSSION

Deposition of a thin passive-margin succession beginning in late Middle Cambrian time along the Ouachita rifted margin of the Texas promontory of Laurentia indicates limited postrift subsidence of a broad uplift of the rift shoulder (Fig. 5). The passive-margin stratigraphy and local paleotopographic relief on the underlying Precambrian basement are consistent with thermal buoyancy of the upper plate above a low-angle detachment (Buck et al., 1988). The narrow zone of transitional crust and the lack of synrift rocks further suggest an upper plate structural configuration for the Ouachita rifted margin. Although the unusually thin succession on the Llano uplift suggests a stable cratonic setting (Osleger and Read, 1993), it is within ~100 km of the rifted margin (as defined by the geophysically documented edge of continental crust). The subsidence profiles for the

Texas promontory indicate postrift cooling, and the delay in subsidence below sea level is consistent with thermal uplift of an upper plate (Fig. 5). In contrast, the locally thick carbonate succession along the Southern Oklahoma (transform) fault system evidently reflects an initial local thermal anomaly along the transform fault followed by load-induced subsidence in response to dense synrift mafic rocks at shallow crustal levels.

In the Precordillera, the basal evaporite-redbed succession and the basement-derived clasts within olistoliths in slope deposits represent synrift sediment accumulations, which probably were associated with large-scale basement faults. The passive-margin succession of the Precordillera documents significantly greater subsidence and sediment accumulation than along the Ouachita rifted margin of Laurentia (Fig. 5). Passive-margin deposition around the Precordillera began in latest Early Cambrian time, earlier than initiation of passive-margin deposition along the Texas promontory of Laurentia (Fig. 5). The earlier beginning and greater magnitude of postrift subsidence of the Precordillera are consistent with a thinner, more extended continental crust characteristic of a lower-plate margin (Fig. 5); the subsidence history of the Precordillera indicates early cooling as a result of separation from the synrift heat-flow maximum.

The contrasts between the subsidence history of the Precordillera and that of the Texas promontory are consistent with the contrasts in subsidence history of opposite plates predicted in simple-shear rift models. Similarities between the subsidence history and stratigraphic record of the northern Precordillera and the Birmingham graben are consistent with locations on opposite sides of a transform fault. The change from north-south to east-west stratigraphic polarity in the Precordillera carbonate shelf may reflect an initial north-to-south gradient away from a thermal anomaly and associated doming along the northern transform boundary followed by an east-to-west gradient generated by more rapid subsidence over the most highly extended crust nearest the rifted margin of a lower plate (western margin of the Precordillera).

CONCLUSIONS

Previous interpretations of rifting of the Argentine Precordillera from the Ouachita embayment of southeastern Laurentia are further supported by compatible subsidence histories on opposite rifted margins. The distinct differences in postrift subsidence history, as well as contrasts in synrift accumulations and crustal structure, demonstrate asymmetry of the Ouachita rift between the Texas promontory of Laurentia and the Precordillera. Such complementary asymmetry of rifted margins is characteristic of simple-shear rift models. A lower-plate configuration of the western rifted margin of the Precordillera is conjugate to an upper-plate configuration on the Ouachita rifted margin of Laurentia.

ACKNOWLEDGMENTS

This research was supported in part by U.S. National Science Foundation grant EAR-9706735 to Thomas, a Fulbright Research Award to Astini, and a grant from the National Geographic Society (6090-97) to Thomas and Astini. Thomas acknowledges research support in the form of a sabbatical leave from the University of Kentucky. Astini acknowledges research support from Consejo Nacional de Investigaciones Científicas y Técnicas and from Fundación Antorchas (Argentina). Earlier drafts of this manuscript were constructively reviewed by Victor A. Ramos, Sarah M. Roeske, and Paul D. Howell. Reviews by Gerard C. Bond and John D. Cooper are gratefully acknowledged.

REFERENCES CITED

Abbruzzi, J., Kay, S. M., and Bickford, M. E., 1993, Implications for the nature of the Precordilleran basement from Precambrian xenoliths in Miocene volcanic rocks, San Juan Province, Argentina: 12th Congreso Geologico Argentino y 2nd Congreso de Exploracion de Hidrocarburos, v. 3, p. 331–339.

Aleinikoff, J. N., Zartman, R. E., Walter, M., Rankin, D. W., Lyttle, P. T., and Burton, W. C., 1995, U-Pb ages of metarhyolites of the Catoctin and Mount Rogers Formations, central and southern Appalachians: Evidence for two pulses of Iapetan rifting: American Journal of Science, v. 295, p. 428–454.

Allmendinger, R. W., Figueroa, D., Snyder, D., Beer, J., Mpodozis, C., and Isacks, B. L., 1990, Foreland shortening and crustal balancing in the Andes at 30° S latitude: Tectonics, v. 9, p. 789–809.

Astini, R. A., 1988, Yerba Loca Formation: An Ordovician clastic wedge in western Argentina: Newfoundland, Canada, 5th International Symposium on the Ordovician System, Abstracts, p. 3.

Astini, R. A., 1991, Paleoambientes sedimentarios y secuencias depositacionales del Ordovícico clástico de la Precordillera Argentina [Ph.D. thesis]: Córdoba, Argentina, Universidad Nacional de Córdoba, 851 p.

Astini, R. A., 1995, Paleoclimates and paleogeographic paths of the Argentine Precordillera during the Ordovician: Evidence from climatically sensitive lithofacies, *in* Cooper, J. D., Droser, M. L., and Finney, S. C., eds., Ordovician odyssey: 7th International Symposium on the Ordovician System: Pacific Section, SEPM (Society for Sedimentary Geology) Book 77, p. 177–180.

Astini, R. A., 1996, The Argentine Precordillera—Lower plate of the Ouachita conjugate-pair rift: A suitable explanation for their stratigraphic differences: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 2.

Astini, R. A., and Vaccari, N. E., 1996, Sucesión evaporítica del Cámbrico Inferior de la Precordillera: Significado geológico: Revista de la Asociación Geológica Argentina, v. 51, p. 97–106.

Astini, R. A., Benedetto, J. L., and Vaccari, N. E., 1995a, The early Paleozoic evolution of the Argentine Precordillera as a Laurentian rifted, drifted, and collided terrane: A geodynamic model: Geological Society of America Bulletin, v. 107, p. 253–273.

Astini, R. A., Vaccari, N. C., Thomas, W. A., Raymond, D. E., and Osborne, W. E., 1995b, Shared evolution of the Argentine Precordillera and the southern Appalachians during the Early Cambrian: Geological Society of America Abstracts with Programs, v. 27, no. 6, p. A-458.

Astini, R. A., Ramos, V. A., Benedetto, J. L., Vaccari, N. E., and Cañas, F. L., 1996, La Precordillera: Un terreno exótico a Gondwana: 13th Congreso Geológico Argentino y 3rd Congreso de Exploración de Hidrocarburos, Actas, v. 5, p. 293–324.

Baldis, B. A., and Bordonaro, O., 1981, Evolución de las facies carbonáticas en la cuenca Cámbrica de la Precordillera de San Juan: 8th Congreso Geológico Argentino, v. 2, p. 385–397.

Baldis, B. A., and Bordonaro, O., 1984, Cámbrico y Ordovícico en la Sierra Chica de Zonda y cerro Pedernal, provincia de San Juan. Génesis del margen continental en la Precordillera: 9th Congreso Geológico Argentino, v. 4, p. 190–207.

Banchig, A. L., Milana, J. P., and Bordonaro, O., 1990, Litofacies clásticas de la Formación Los Sombreros (Cámbrico Medio) en la Quebrada Ojos de Agua, Sa. del Tontal, San Juan: Tercera Reunión Argentina de Sedimentología, v. 1, p. 25–30.

Barnes, V. E., 1959, Stratigraphy of the pre-Simpson Paleozoic subsurface rocks of Texas and southeast New Mexico: Volume 1: University of Texas Bureau of Economic Geology Publication 5924, p. 11–72.

Barnes, V. E., Bell, W. C., Clabaugh, S. E., Cloud, P. E., Jr., McGehee, R. V., Rodda, P. U., and Young, K., 1972, Geology of the Llano region and Austin area, field excursion: University of Texas Bureau of Economic Geology Guidebook 13, 77 p.

Benedetto, J. L., 1993, La hipótesis de la aloctonía de la Precordillera Argentina: Un test estratigráfico y biogeográfico: 12th Congreso Geológico Argentino y 2nd Congreso de Exploracion de Hidrocarburos, v. 3, p. 375–384.

Benedetto, J. L., Vaccari, N. E., and Herrera, Z. A., 1986, El hallazgo de rocas cámbricas fosilíferas al oesto de Jáchal, Provincia de San Juan: 4th Congreso Argentino de Paleontología y Bioestratografía, v. 1, p. 29–30.

Bond, G. C., Nickeson, P. A., and Kominz, M. A., 1984, Breakup of a supercontinent between 625 Ma and 555 Ma: New evidence and implications for continental histories: Earth and Planetary Science Letters, v. 70, p. 325–345.

Bond, G. C., Kominz, M. A., and Sheridan, R. E., 1995, Continental terraces and rises, *in* Busby, C. J., and Ingersoll, R. V., eds., Tectonics of sedimentary basins: Oxford, Blackwell Science, p. 149–178.

Bordonaro, L. O., 1985, El Cambrico de San Isidro, Mendoza, en facies de borde externo y talud de la plataforma calcarea de Precordillera: San Juan, Primeras Jornadas Sobre Geología de Precordillera, Acta 1, p. 12–17.

Bordonaro, L. O., and Liñán, E., 1994, Some Middle Cambrian agnostoids from the Precordillera Argentina: Revista Española de Paleontología, v. 9, p. 105–114.

Borrello, A. V., 1971, The Cambrian of South America, *in* Holland, C. H., ed., Cambrian of the New World: New York, Wiley-Interscience, p. 385–438.

Buck, W. R., Martinez, F., Steckler, M. S., and Cochran, J. R., 1988, Thermal consequences of lithospheric extension: Pure and simple: Tectonics, v. 7, p. 213–234.

Butts, C., 1926, The Paleozoic rocks, *in* Geology of Alabama: Alabama Geological Survey Special Report 14, p. 41–230.

Cañas, F., 1995, Early Ordovician carbonate platform facies of the Argentine Precordillera: Restricted shelf to open platform evolution, *in* Cooper, J. D., Droser, M. L., and Finney, S. C., eds., Ordovician odyssey: 7th International Symposium on the Ordovician System: Pacific Section, SEPM (Society for Sedimentary Geology) Book 77, p. 221–224.

Coffman, J. D., Gilbert, M. C., and McConnell, D. A., 1986, An interpretation of the crustal structure of the Southern Oklahoma aulacogen satisfying gravity data: Oklahoma Geological Survey Guidebook 23, p. 1–10.

Cominguez, A. H., and Ramos, V. A., 1991, La estructura profunda entre Precordillera y Sierras Pampeanas de la Argentina: Evidencias de la sísmica de reflexión profunda: Revista Geológica de Chile, v. 18, p. 3–14.

Culotta, R., Latham, T., Sydow, M., Oliver, J., Brown, L., and Kaufman, S., 1992, Deep structure of the Texas Gulf passive margin and its Ouachita-Precambrian basement: Results of the COCORP San Marcos arch survey: American Association of Petroleum Geologists Bulletin,

v. 76, p. 270–283.
Dalziel, I. W. D., 1997, Neoproterozoic-Paleozoic geography and tectonics: Review, hypothesis, environmental speculation: Geological Society of America Bulletin, v. 109, p. 16–42.
Davis, J. S., McClelland, W. C., Roeske, S. M., Gerbi, C., and Moores, E. M., 1997, The early to middle Paleozoic tectonic history of the SW Precordillera terrane and Laurentia-Gondwana interactions: Geological Society of America Abstracts with Programs, v. 29, no. 6, p. A-380.
Demicco, R. V., and Hardie, L. A., 1994, Sedimentary structures and early diagenetic features of shallow marine carbonate deposits: SEPM (Society for Sedimentary Geology), Atlas Series 1, 265 p.
Denison, R. E., 1995, Significance of air-photograph linears in the basement rocks of the Arbuckle Mountains, *in* Johnson, K. S., ed., Structural styles in the southern Midcontinent, 1992 symposium: Oklahoma Geological Survey Circular 97, p. 119–131.
Denison, R. E., 1997, Contrasting sedimentation inside and outside the southern Oklahoma aulacogen during the Middle and Late Ordovician, *in* Johnson, K. S., ed., Simpson and Viola Groups in the southern Midcontinent, 1994 symposium: Oklahoma Geological Survey Circular 99, p. 39–47.
Etheridge, M. A., Symonds, P. A., and Lister, G. S., 1989, Application of the detachment model to reconstruction of conjugate passive margins, *in* Tankard, A. J., and Balkwill, H. R., eds., Extensional tectonics and stratigraphy of the North Atlantic margins: American Association of Petroleum Geologists Memoir 46, p. 23–40.
Ethington, R. L., Finney, S. C., and Repetski, J. E., 1989, Biostratigraphy of the Paleozoic rocks of the Ouachita orogen, Arkansas, Oklahoma, west Texas, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 563–574.
Feinstein, S., 1981, Subsidence and thermal history of Southern Oklahoma aulacogen: Implications for petroleum exploration: American Association of Petroleum Geologists Bulletin, v. 65, p. 2521–2533.
Furque, G., 1972, Descripción geológica de la Hoja 16b, Cerro la Bolsa: Servicio Nacional [Argentina] de Minería y Geología, Boletín 125, 69 p.
Gilbert, M. C., 1983, Timing and chemistry of igneous events associated with the Southern Oklahoma aulacogen: Tectonophysics, v. 94, p. 439–455.
Gimenez, M. E., Martínez, M. P., Introcaso, A., Robles, J. A., and Uliarte, E., 1997, Análisis isostático en una sección E-W de la Precordillera andina en la Provincia de San Juan: San Juan, II Jornadas de Geología de la Precordillera, Actas, p. 220–225.
González Bonorino, G., and González Bonorino, F., 1991, Precordillera de Cuyo y Cordillera Frontal en el Paleozoico Temprano: Terrenos "bajo sospecha" de ser autóctonos: Revista Geológia de Chile, v. 18, p. 97–107.
Gosen, W. v., 1992, Structural evolution of the Argentine Precordillera: The Río San Juan section: Journal of Structural Geology, v. 14, p. 643–667.
Grohskopf, J. G., 1955, Subsurface geology of the Mississippi embayment of southeast Missouri: Missouri Geological Survey, 2nd series, v. 37, 133 p.
Handford, C. R., 1991, Marginal marine halite: Sabhkas and salinas, *in* Melvin, J. L., ed., Evaporites, petroleum and mineral resources: Developments in Sedimentology 50: Amsterdam, Elsevier, p. 1–66.
Hinze, W. J., and Braile, L. W., 1988, Geophysical aspects of the craton: U.S., *in* Sloss, L. L., ed., Sedimentary cover—North American craton: U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. D-2, p. 5–24.
Hogan, J. P., Gilbert, M. C., Price, J. D., Wright, J. E., Deggeller, M., and Hames, W. E., 1996, Magmatic evolution of the Southern Oklahoma aulacogen: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 19.
Introcaso, A., Pacino, M. C., and Fraga, H., 1992, Gravity, isostasy and Andean crustal shortening between latitudes 30 and 35° S: Tectonophysics, v. 205, p. 31–48.
Issler, D., McQueen, H., and Beaumont, C., 1989, Thermal and isostatic consequences of simple shear extension of the continental lithosphere: Earth and Planetary Science Letters, v. 91, p. 341–358.
Johnson, K. S., Amsden, T. W., Denison, R. E., Dutton, S. P., Goldstein, A. G., Rascoe, B., Jr., Sutherland, P. K., and Thompson, D. M., 1988, Southern Midcontinent region, *in* Sloss, L. L., ed., Sedimentary cover—North American craton: U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. D-2, p. 307–359.
Johnson, P. R., Zietz, I., and Thomas, W. A., 1994, Possible Neoproterozoic–early Paleozoic grabens in Mississippi, Alabama, and Tennessee: Geology, v. 22, p. 11–14.
Kay, S. M., Orrell, S., and Abbruzzi, J. M., 1996, Zircon and whole rock Nd-Pb isotopic evidence for a Grenville age and a Laurentian origin for the basement of the Precordilleran terrane in Argentina: Journal of Geology, v. 104, p. 637–648.
Keen, C. E., 1982, The continental margins of eastern Canada: A review, *in* Scrutton, R. A., ed., Dynamics of passive margins: American Geophysical Union and Geological Society of America Geodynamics Series, v. 6, p. 45–58.
Keen, C. E., and Haworth, R. T., 1985, D-2 transform margin south of Grand Banks: Offshore eastern Canada: Geological Society of America Centennial Continent/Ocean Transect #2, scale 1:500 000.
Keen, C. E., Kay, W. A., and Roest, W. R., 1990, Crustal anatomy of a transform continental margin: Tectonophysics, v. 173, p. 527–544.
Keller, G. R., Braile, L. W., McMechan, G. A., Thomas, W. A., Harder, S. H., Chang, W.-F., and Jardine, W. G., 1989a, Paleozoic continent-ocean transition in the Ouachita Mountains imaged from PASSCAL wide-angle seismic reflection-refraction data: Geology, v. 17, p. 119–122.
Keller, G. R., Kruger, J. M., Smith, K. J., and Voight, W. M., 1989b, The Ouachita system; a geophysical overview, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 689–694.
Keller, M., Buggisch, W., and Bercowski, F., 1989, Facies and sedimentology of Upper Cambrian shallowing-upward cycles in the La Flecha Formation (Argentine Precordillera): Zentralblatt für Geologie und Paläontologie, v. 1, p. 999–1011.
Keller, M., Cañas, F. L., Lehnert, O., and Vaccari, N. E., 1994, The Upper Cambrian and Lower Ordovician of the Precordillera (western Argentina): Some stratigraphic reconsiderations: Newsletters on Stratigraphy, v. 31, p. 115–132.
Kendall, C. G. St. C., and Warren, J., 1987, A review of the origin and setting of tepees and their associated fabrics: Sedimentology, v. 34, p.1007–1027.
Kinsman, D. J. J., 1975, Rift valley basins and sedimentary history of trailing continental margins, *in* Fischer, A. G., and Sheldon, J., eds., Petroleum and global tectonics: Princeton, New Jersey, Princeton University Press, p. 83–126.
Krause, S. J., 1996, Stratigraphic framework, facies analysis, and depositional history of the Middle to Late Cambrian Riley Formation, central Texas [M.A. thesis]: Austin, University of Texas, 172 p.
Kruger, J. M., and Keller, G. R., 1986, Interpretation of crustal structure from regional gravity anomalies, Ouachita Mountains area and adjacent Gulf Coastal Plain: American Association of Petroleum Geologists Bulletin, v. 70, p. 667–689.
Lambert, D. D., Unruh, D. M., and Gilbert, M. C., 1988, Rb-Sr and Sm-Nd isotopic study of the Glen Mountains layered complex: Initiation of rifting within the southern Oklahoma aulacogen: Geology, v. 16, p. 13–17.
Lehnert, O., 1995, Ordovizische Conodonten aus der Präkordillere Westargentiniens: Ihre Bedeutung für Stratigraphie und Palaogeographie [Ph.D. thesis]: Erlanger Geologische Abhandlungen, v. 125, 193 p.
Lister, G. S., Etheridge, M. A., and Symonds, P. A., 1986, Detachment faulting and the evolution of passive continental margins: Geology, v. 14, p. 246–250.
Lister, G. S., Etheridge, M. A., and Symonds, P. A., 1991, Detachment models for the formation of passive continental margins: Tectonics, v. 10, p. 1038–1064.
Mack, G. H., 1980, Stratigraphy and depositional environments of the Chilhowee Group (Cambrian) in Georgia and Alabama: American Journal of Science, v. 280, p. 497–517.
Mascle, J., and Blarez, E., 1987, Evidence for transform margin evolution from the Ivory Coast–Ghana continental margin: Nature, v. 326, p. 378–381.
McKenzie, D. P., 1978, Some remarks on the development of sedimentary basins: Earth and Planetary Science Letters, v. 40, p. 25–32.
Mellen, F. F., 1977, Cambrian System in Black Warrior basin: American Association of Petroleum Geologists Bulletin, v. 61, p.1897–1900.
Mendoza, N., Banchig, A., and Bordonaro, O., 1997, Petrografía de los clastos de las psefítas Ordovícicas de la Sierra Tontal y su vinculación con la Sierra de Pie de Palo, San Juan: San Juan, Jornadas de Geología de Precordillera, Actas, v. 2, p. 42–46.
Miall, A. D., 1984, Principles of sedimentary basin analysis: New York, Springer-Verlag, 490 p.
Mickus, K. L., and Keller, G. R., 1992, Lithospheric structure of the south-central United States: Geology, v. 20, p. 335–338.
Nicholas, R. L., and Rozendal, R. A., 1975, Subsurface positive elements within Ouachita foldbelt in Texas and their relation to Paleozoic cratonic margin: American Association of Petroleum Geologists Bulletin, v. 59, p. 193–216.
Nicholas, R. L., and Waddell, D. E., 1989, The Ouachita system in the subsurface of Texas, Arkansas, and Louisiana, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 661–672.
Osborne, W. E., 1992, Bedrock geology of the Cahaba Valley area between Helena and Lake Purdy, Shelby and Jefferson Counties, Alabama: Alabama Geological Survey Bulletin 144, 42 p.
Osleger, D., and Read, J. F., 1993, Comparative analysis of methods used to define eustatic variations in outcrop: Late Cambrian interbasinal sequence development: American Journal of Science, v. 293, p. 157–216.
Palmer, A. R., 1962, *Glyptagnostus* and associated trilobites in the United States: U.S. Geological Survey Professional Paper 374-F, 49 p.
Palmer, A. R., 1971, The Cambrian of the Appalachian and eastern New England regions, eastern United States, *in* Holland, C. H., ed., Cambrian of the New World: New York, Wiley-Interscience, p. 169–217.
Palmer, A. R., Vaccari, N. E., Astini, R. A., Cañas, F. L., and Benedetto, J. L., 1996, Cambrian history of the Argentine Precordillera: Adios Laurentia!: Geological Society of America Abstracts with Programs, v. 28, no. 1, p. 57.
Ramos, V. A., Jordan, T. E., Allmendinger, R. W., Mpodozis, C., Kay, S. M., Cortés, J. M., and Palma, M., 1986, Paleozoic terranes of the central Argentine–Chilean Andes: Tectonics, v. 5, p. 855–880.
Rankey, E. C., Walker, K. R., and Srinivasan, K., 1994, Gradual establishment of Iapetan "passive" margin sedimentation: Stratigraphic consequences of Cambrian episodic tectonism and eustasy, southern Appalachians: Journal of Sedimentary Research, v. B64, p. 298–310.
Rapalini, A. E., and Astini, R. A., 1998, Paleomagnetic confirmation of the Laurentian origin of the Argentine Precordillera: Earth and Planetary Science Letters, v. 155, p. 1–14.
Raymond, D. E., 1991, New subsurface information on Paleozoic stratigraphy of the Alabama fold and thrust belt and the Black Warrior basin: Alabama Geological Survey Bulletin 143, 185 p.
Reid, I. D., and Jackson, H. R., 1997, A review of three transform margins off eastern Canada: Geomarine Letters, v. 17, p. 87–93.
Resser, C. E., 1938, Cambrian System (restricted) of the southern Appalachians: Geological Society of America Special Paper 15, 140 p.
Rona, P. A., 1982, Evaporites at passive margins, *in* Scrutton, R. A., ed., Dynamics of passive margins: American Geophysical Union and Geological Society of America Geodynamics Series, v. 6, p. 116–132.
Rosendahl, B. R., 1987, Architecture of continental rifts with special reference to East Africa: Annual Review of Earth and Planetary Sciences, v. 15, p. 445–503.
Schmoker, J. W., and Halley, R. B., 1982, Carbonate porosity versus depth: A predictable relation for south Florida: American Association of Petroleum Geologists Bulletin, v. 66, p. 2561–2570.
Sclater, J. D., and Christie, P. A. F., 1980, Continental stretching: An explanation of the post-mid-Cretaceous subsidence of the central North Sea basin: Journal of Geophysi-

cal Research, v. 85, p. 3711–3739.
Scrutton, R. A., 1982, Passive continental margins: A review of observations and mechanisms, *in* Scrutton, R. A., ed., Dynamics of passive margins: American Geophysical Union and Geological Society of America Geodynamics Series, v. 6, p. 5–11.
Shinn, E. A., 1983, Tidal flat environment, *in* Scholle, P. A., Bebout, D. G., and Moore, C. H., eds., Carbonate depositional environments: American Association of Petroleum Geologists Memoir 33, p. 173–210.
Simpson, E. L., and Eriksson, K. A., 1989, Sedimentology of the Unicoi Formation in southern and central Virginia: Evidence for late Proterozoic to Early Cambrian rift-to-passive margin transition: Geological Society of America Bulletin, v. 101, p. 42–54.
Simpson, E. L., and Sundberg, F. A., 1987, Early Cambrian age for synrift deposits of the Chilhowee Group of southwestern Virginia: Geology, v. 12, p. 123–126.
Sylvester, A. G., 1988, Strike-slip faults: Geological Society of America Bulletin, v. 100, p. 1666–1703.
Thomas, W. A., 1985, Northern Alabama sections, *in* Woodward, N. B., ed., Valley and Ridge thrust belt: Balanced structural sections, Pennsylvania to Alabama (Appalachian Basin Industrial Associates): University of Tennessee Department of Geological Sciences Studies in Geology 12, p. 54–61.
Thomas, W. A., 1988, The Black Warrior basin, *in* Sloss, L. L., ed., Sedimentary cover—North American craton: U.S.: Boulder, Colorado, Geological Society of America, Geology of North America, v. D-2, p. 471–492.
Thomas, W. A., 1989, The Appalachian-Ouachita orogen beneath the Gulf Coastal Plain between the outcrops in the Appalachian and Ouachita Mountains, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 537–553.
Thomas, W. A., 1991, The Appalachian-Ouachita rifted margin of southeastern North America: Geological Society of America Bulletin, v. 103, p. 415–431.
Thomas, W. A., 1993, Low-angle detachment geometry of the late Precambrian–Cambrian Appalachian-Ouachita rifted margin of southeastern North America: Geology, v. 21, p. 921–924.
Thomas, W. A., and Astini, R. A., 1996, The Argentine Precordillera: A traveler from the Ouachita embayment of North American Laurentia: Science, v. 273, p. 752–757.
Thomas, W. A., and Drahovzal, J. A., 1973, Regional Paleozoic stratigraphy of Alabama: Alabama Geological Society, 11th Annual Field Trip, Guidebook, p. 66–91.
Thomas, W. A., and Whiting, B. M., 1995, The Alabama promontory: Example of the evolution of an Appalachian-Ouachita thrust-belt recess at a promontory of the rifted continental margin, *in* Hibbard, J. P., van Staal, C. R., and Cawood, P. A., eds., Current perspectives in the Appalachian-Caledonian orogen: Geological Association of Canada Special Paper 41, p. 3–20.
Todd, B. J., and Keen, C. E., 1989, Temperature effects and their geological consequences at transform margins: Canadian Journal of Earth Sciences, v. 26, p. 2591–2603.
Tucker, R. D., and McKerrow, W. S., 1995, Early Paleozoic chronology: A review in light of new U-Pb zircon ages from Newfoundland and Britain: Canadian Journal of Earth Sciences, v. 32, p. 368–379.
Vaccari, N. E., 1990, Primer hallazgo de trilobites del Cámbrico inferior en la Provincia de La Rioja (Precordillera Septentrional): Revista de la Asociación Geológica Argentina, v. 43, p. 558–561.
Vaccari, N. E., 1994, Las faunas de trilobites de las sucesiones carbonáticas del Cámbrico y Ordovícico temprano de la Precordillera Septentrional [Ph.D. thesis]: Córdoba, Argentina, Universidad Nacional de Córdoba, 271 p.
Vaccari, N. E., and Bordonaro, O., 1993, Trilobites en los olistolitos cámbricos de la Formación Los Sombreros (Ordovícico), Precordillera de San Juan, Argentina: Ameghiniana, v. 30, p. 383–393.
Viele, G. W., and Thomas, W. A., 1989, Tectonic synthesis of the Ouachita orogenic belt, *in* Hatcher, R. D., Jr., Thomas, W. A., and Viele, G. W., eds., The Appalachian-Ouachita orogen in the United States: Boulder, Colorado, Geological Society of America, Geology of North America, v. F-2, p. 695–728.
Walker, D., Simpson, E. L., and Driese, S. G., 1994, Paleogeographic influences on sandstone composition along an evolving passive margin: An example from the basal Chilhowee Group (uppermost Proterozoic to Lower Cambrian) of the south-central Appalachians: Journal of Sedimentary Research, v. A64, p. 807–814.
Warren, J. K., 1989, Evaporite sedimentology: Englewood Cliffs, New Jersey, Prentice Hall, 285 p.
Warren, J. K., 1991, Sulphate dominated sea-marginal and platform evaporitic settings: Sabhkas and salinas, mudflats and salterns, *in* Melvin, J. L., ed., Evaporites, petroleum and mineral resources: Developments in Sedimentology 50: Amsterdam, Elsevier, p. 69–187.
Wernicke, B., 1985, Uniform-sense normal simple shear of the continental lithosphere: Canadian Journal of Earth Sciences, v. 22, p. 108–125.
Wernicke, B., and Tilke, P. G., 1989, Extensional tectonic framework of the U.S. central Atlantic passive margin, *in* Tankard, A. J., and Balkwill, H. R., eds., Extensional tectonics and stratigraphy of the North Atlantic margins: American Association of Petroleum Geologists Memoir 46, p. 7–21.
Wilkerson, M. S., and Hsui, A. T.-K., 1989, Application of sediment backstripping corrections for basin analysis using microcomputers: Journal of Geological Education, v. 37, p. 337–340.
Zapata, T. R., and Allmendinger, R. W., 1996, La estructura cortical de la Precordillera oriental y valle del Bermejo a los 30° de latitud sur: 13th Congreso Geológico Argentino y 3rd Congreso de Exploración de Hidrocarburos, v. 2, p. 211–224.

MANUSCRIPT RECEIVED BY THE SOCIETY JANUARY 20, 1998
REVISED MANUSCRIPT RECEIVED AUGUST 11, 1998
MANUSCRIPT ACCEPTED OCTOBER 6, 1998

Printed in U.S.A.