Southern-Central Appalachians-Ouachitas Orogen

William A Thomas, Department of Earth and Environmental Sciences, University of Kentucky, Lexington, KY, United States; Geological Survey of Alabama, Tuscaloosa, AL, United States
Robert D Hatcher Jr, Department of Earth and Planetary Sciences, University of Tennessee, Knoxville, TN, United States

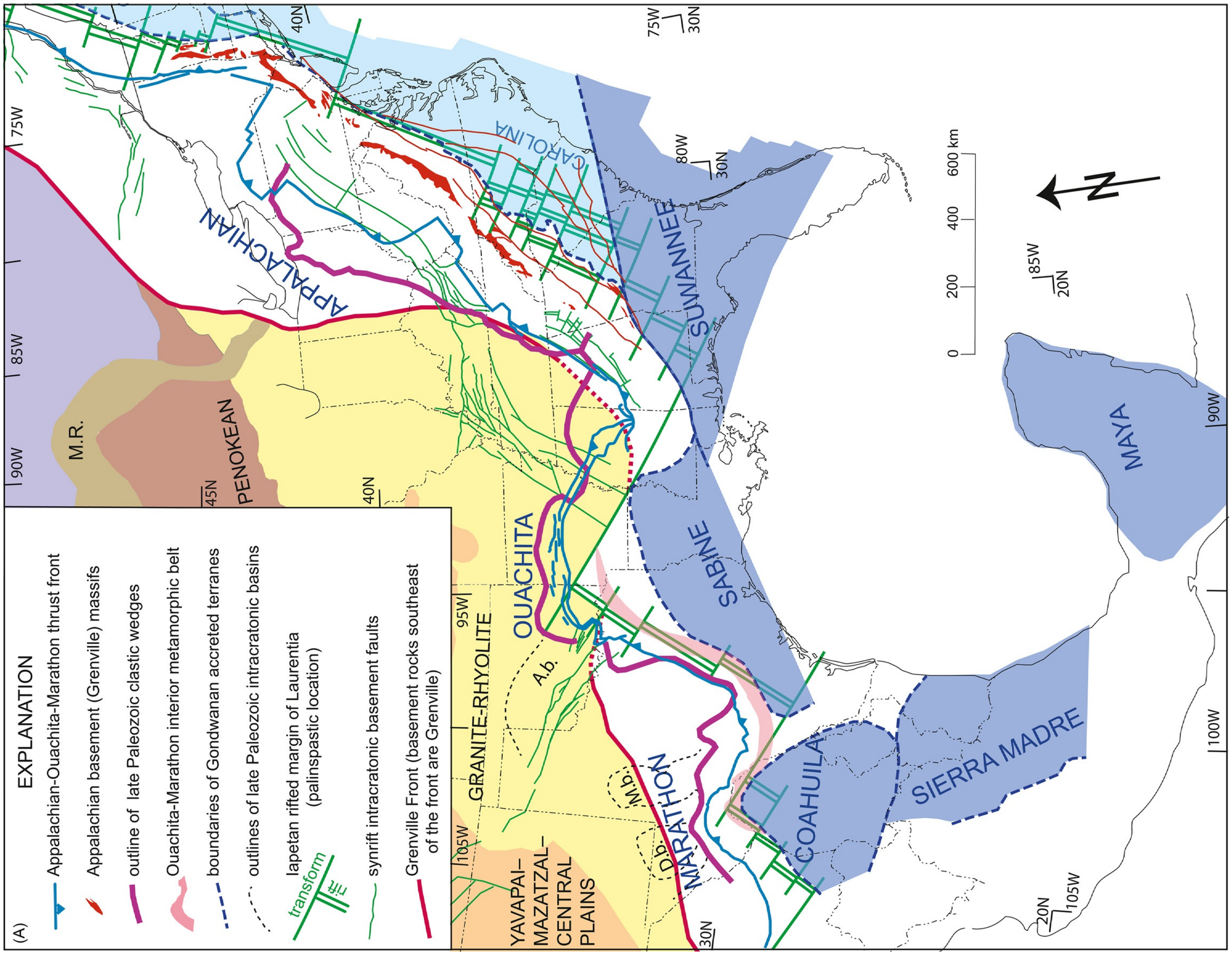
Introduction

The Appalachians are the dominant physiographic feature in eastern North America, extending from Newfoundland in eastern Canada to Alabama and Georgia in the southern United States. Although the physiographic mountains end southwestward at the Gulf Coastal Plain in Alabama, the orogenic system continues westward beneath post-orogenic Mesozoic strata of the Gulf Coastal Plain into the State of Coahuila in northern Mexico but is exposed only in the Ouachita Mountains in Arkansas and Oklahoma and in the Marathon region of western Texas (Fig. 1). The trace of the orogenic belt, which is exposed in the mountains and revealed by drilling beneath the Coastal Plain, follows a sinuously curved path around salients (convex toward the craton in the direction of thrust translation) and recesses (concave toward the craton). This article considers the Pennsylvania, Tennessee, Ouachita, and Marathon salients and the associated New York, Virginia, Alabama, and Texas recesses, the shapes of which reflect tectonic inheritance from the outline of the pre-orogenic rifted margin of Laurentia (Fig. 1) (Thomas, 1977, 2006). Across strike, the orogenic belt encompasses an array of distinctive components: synorogenic foreland basins, foreland sedimentary thrust belt, and crystalline interior of the orogen, consisting of external basement massifs, metasedimentary rocks from the Laurentian margin, internal basement massifs, accreted arc terranes, sutures marking closed oceans or remnant oceans, and accreted non-Laurentian Peri-Gondwanan and Gondwanan terranes. The various elements of the orogenic belt vary significantly in continuity or discontinuity along strike, and the various tectonic processes vary diachronously through time. In general, the contractional events that constructed the orogenic belt may be grouped into three overarching time bundles—Taconic, Acadian, and Alleghanian-Ouachita (Fig. 2); however, only the latter is expressed along the entire length of the orogen from Canada to Mexico.

Pre-Orogenic Foundations

Supercontinent Rodinia

The foundations of the Appalachian-Ouachita orogen were laid when the assembly of supercontinent Rodinia was completed (e.g., Hoffman, 1988; Van Schmus et al., 1993; Whitmeyer and Karlstrom, 2007; Bickford et al., 2015). The collisional events were accompanied by high-grade metamorphism and magmatism during the Grenville orogeny in the time span of 1300–950 Ma (Hatcher et al., 2004). Grenville rocks form the basement to nearly all of the Appalachian-Ouachita structures with two exceptions:


(A)
EXPLANATION
Appalachian-Ouachita-Marathon thrust front
Appalachian basement (Grenville) massifs
outline of late Paleozoic clastic wedges
Ouachita-Marathon interior metamorphic belt
boundaries of Gondwanan accreted terranes
outlines of late Paleozoic intracratonic basins
Iapetan rifted margin of Laurentia (palinspastic location)
transform
synrift intracratonic basement faults
Grenville Front (basement rocks southeast of the front are Grenville)
APPALACHIAN
CAROLINA
SUWANNEE
SABINE
OUACHITA
MARATHON
COAHUILA
SIERRA MADRE
MAYA
M.R.
PENOKEAN
GRANITE-RHYOLITE
YAVAPAI–MAZATZAL–CENTRAL PLAINS
A.b.
M.b.
D.b.
0
200
400
600 km
75W
85W
90W
95W
100W
105W
80W
45N
40N
30N
20N

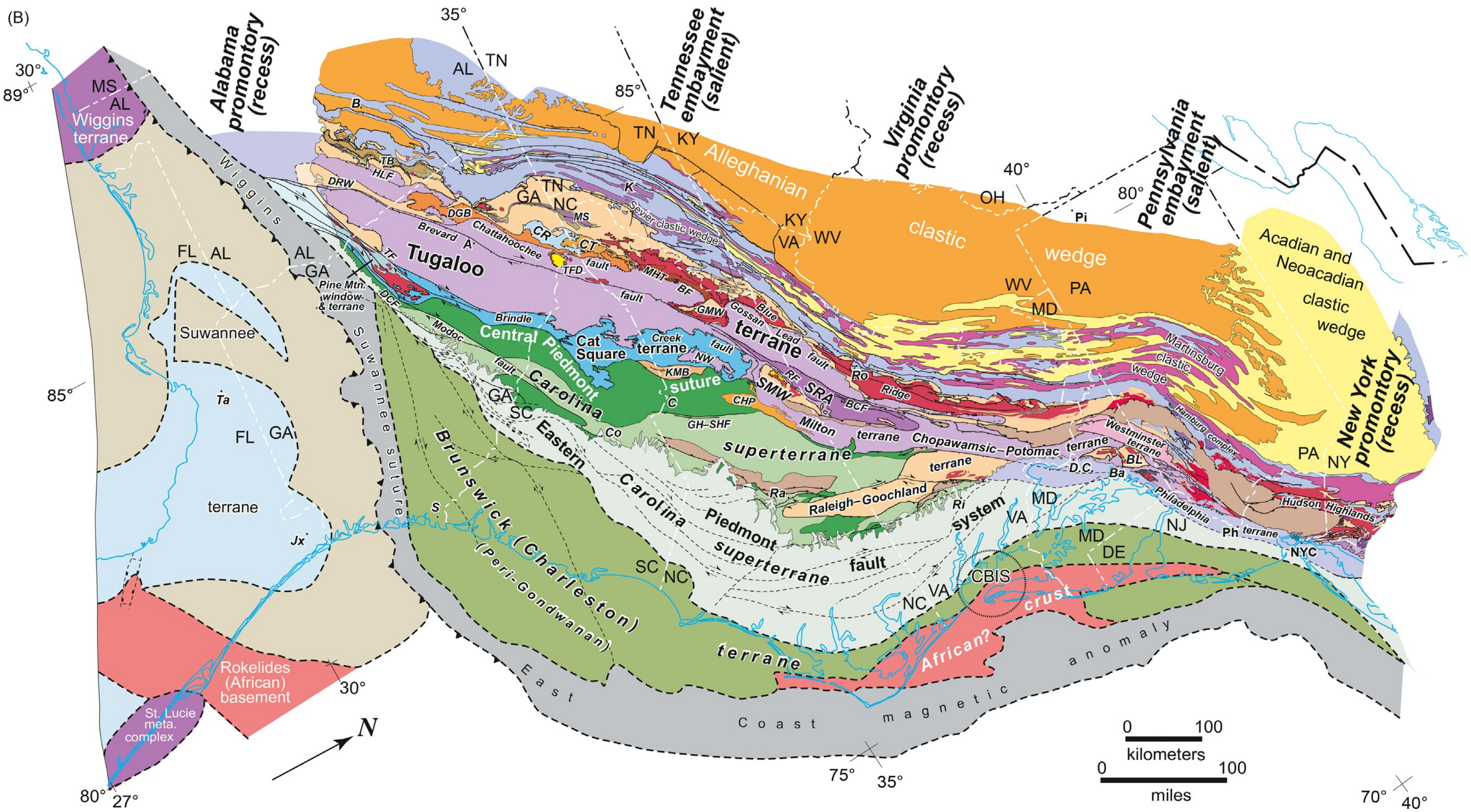


Fig. 1 (A) Regional outline map of Appalachian-Ouachita orogen. Abbreviations: M.R.—Midcontinent rift; D.b.—Delaware basin; M.b.—Midland basin; A.b.—Anadarko basin. (B) Tectonic map simplified from Plate 1, showing the distribution of major tectonic units in the southern and central Appalachians, as well as the location of the foreland fold-thrust belt, major boundaries, and the names of several structures. Explanation of tectonic units not identified on the map: Medium blue from Alabama to New York-Laurentian platform. Dark purple in the Valley and Ridge from Georgia to Virginia-Middle Ordovician clastic wedge. Lighter purple in the Valley and Ridge from Tennessee to New York-Martinsburg clastic wedge (mostly Upper Ordovician). Dark purple in the SE Pennsylvania Valley and Ridge—Hamburg complex. Tan in the Blue Ridge, Alabama Inner Piedmont, and Goochland terrane—rifted margin succession. Pink in the Alabama Blue Ridge—Wedowee Group. Brown in the western Alabama Blue Ridge—Talladega belt. Dark purple and brown in the Georgia and North Carolina Blue Ridge—Murphy syncline sequence. Red—Grenvilian basement. Maroon-brown in the North Carolina and Tennessee Blue Ridge—Mars Hill terrane. Light blue in the Georgia and North Carolina Blue Ridge—Cowrock terrane. Burnt orange NE of the Cowrock terrrane in North Carolina and Georgia—Cartoogechaye terrane. Bright orange in the Georgia and North Carolina Blue Ridge—Dahlonega gold belt. Light green in Virginia to Maryland Blue Ridge—Catoctin Greenstone. GMW—Grandfather Mountain window. Light yellow in NE Georgia along the NW South Carolina state line—Tallulah Falls Quartzite. Brown—Mesozoic (Triassic-Jurassic) basins. Subsurface Mesozoic basins indicated by a conglomerate pattern. Orange unit west of the Carolina superterrane along the South Carolina-North Carolina border—Kings Mountain belt. Light tan unit NE of the Kings Mountain belt in North Carolina—Churchland stitching pluton. CBIS—Chesapeake Bay impact structure. Medium-dark green in the exposed Piedmont is the higher-grade parts of the Carolina superterrane (Charlotte terane); lighter green represents the lower-grade portions (Carolina slate belt, or Carolina terrane). Pale green bebeath the Coastal Plain is the Carolina superterrane, undivided. Olive green represents the Brunswick-Charleston (peri-Gondwanan) terrane and possible equivalents to the northeast. (A) From Thomas WA, Gehrels GE, Lawton TF, Satterfield JI, Romero MC, and Sundell KE (2019) Detrital zircons and sediment dispersal from the Coahuila terrane of northern Mexico into the Marathon foreland of the southern Midcontinent. *Geosphere* 15: 1101–1127. https://doi.org/10.1130/GES02033.1; (B) from Hatcher RD Jr., Bream BR and Merschat AJ (2007b). Tectonic map of the southern and Central Appalachians, USA, Plate 1. In: Hatcher RD Jr., Carlson MP, McBride JH, and Martínez Catalán JR (eds.) *The 4-D Framework of Continental Crust, Scale 1:2,000,000.* Boulder, CO: Geological Society of America. Memoir, 200. Plate 1.

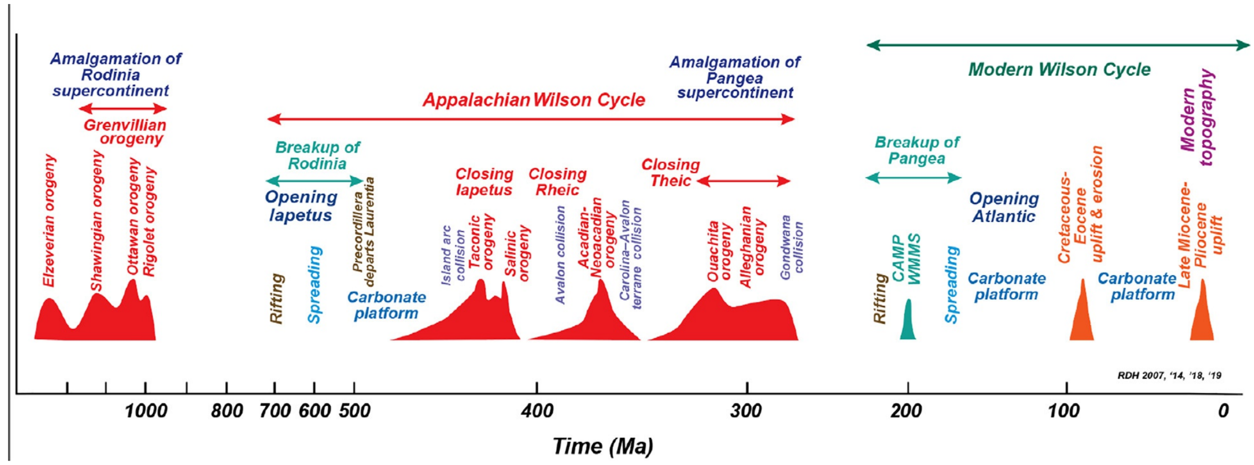


Fig. 2 Appalachians-Ouachitas timeline.

(1) beneath the Ouachita salient of the allochthon, where rifting away of the Argentine Precordillera terrane left part of the Granite-Rhyolite province at the rifted continental margin (Fig. 1A) (Thomas and Astini, 1996; Thomas et al., 2012, 2015); and (2) beneath accreted suspect terranes accreted outboard of the rifted margin of continental and oceanic crust, exposed as small bodies in the Appalachian Inner Piedmont and Pine Mountain window (Fig. 1B) (Hatcher et al., 2004).

Grenville basement in external and internal massifs from the Hudson Highlands (Fig. 1B), and all exposed basement to the southwest, has a Gondwanan (Amazonian) provenance, on the basis of Pb isotope studies (summarized in Fisher et al., 2010). This requires a suture within the Grenville orogen beneath the late Paleozoic allochthonous Blue Ridge-Piedmont megathrust sheet (Fig. 3).

Iapetan Rifted and Passive Margin of Laurentia

While the assembly of Rodinia formed the Appalachian basement rocks, it was the continental rifting and breakup of Rodinia that framed the location and trace of the future orogenic belt. Diachronous rifting events during the time span of >765 to about 530 Ma produced an orthogonally zigzag rifted margin of Laurentia by early Paleozoic time (Fig. 1A) (Thomas, 2014). Along the rifted margin, northeast-trending (present coordinates) rift segments were offset by northwest-trending transform faults (Thomas, 1977, 1993, 2006). The palinspastic locations of the rift segments and transform faults are documented by palinspastic reconstructions of rift-stage rocks (both synrift igneous rocks and rift-fill sedimentary rocks) and by palinspastic reconstructions of the passive-margin shelf edge as defined by sedimentary facies now thrust-displaced in the orogenic belt (Thomas, 1991), as well as by geophysical resolution of the undeformed Laurentian margin of continental crust beneath the allochthon (Keller et al., 1989a; Mickus and Keller, 1992; Harry et al., 2003; Harry and Londoño, 2004). The resulting outline of the rifted margin describes embayments (concave toward the opening ocean) and promontories (convex toward the opening ocean). The structure of the rifted continental margin varies along strike (Fig. 4), depending on the polarity of the basal low-angle detachment fault (Thomas, 1993). On the lower plate, the low-angle detachment dips oceanward beneath an array of listric-fault-bounded half-graben blocks, forming a wide extent of thinned crust, which subsides isostatically (Thomas and Astini, 1999). The upper plate bends down onto the detachment, leaving a relatively steep and narrow zone of thinned crust, which is thermally uplifted to sometimes create "passive-margin mountains." In contrast to rift margins, transform margins are generally steep and crust penetrating (e.g., Harry et al., 2003; Harry and Londoño, 2004).

Intracratonic fault systems inboard from the rifted margin of Laurentia show that rift extension affected the crust for some distance inboard from the rifted margin. Intracratonic fault systems parallel with the rift margin indicate rift extension, whereas those parallel with transform faults indicate transform motion in the crust (Fig. 4) (Thomas, 2014). Rift-parallel faults reflect brittle extension of the crust (inboard from the rifted margin) in response to ductile extension of the underlying mantle lithosphere; ductile extension of the mantle lithosphere may lead to exhumation of the asthenosphere along parts of the rifted margin (e.g., Lavier and Manatschal, 2006). Transform-parallel intracratonic faults show a brittle crustal response to a zone of distributed ductile shear in the underlying mantle lithosphere where rift-sense ductile extension is offset along strike (e.g., Baldock and Stern, 2005; Thomas, 2014).

Synrift igneous rocks are scattered along the rifted margin and include plutonic and volcanic rocks. Crystallization ages from U-Pb analyses of zircon range from 765 to 530 Ma (Fig. 5) (compilation in Thomas, 2014). No systematic distribution of ages is evident. The oldest documented ages include 765 Ma in the Tennessee embayment and 706 Ma in the Marathon embayment. The youngest ages include 564 Ma along the Blue Ridge rift zone on the Virginia promontory and 530 Ma along the Southern Oklahoma transform-parallel intracratonic fault system (Thomas, 2014).

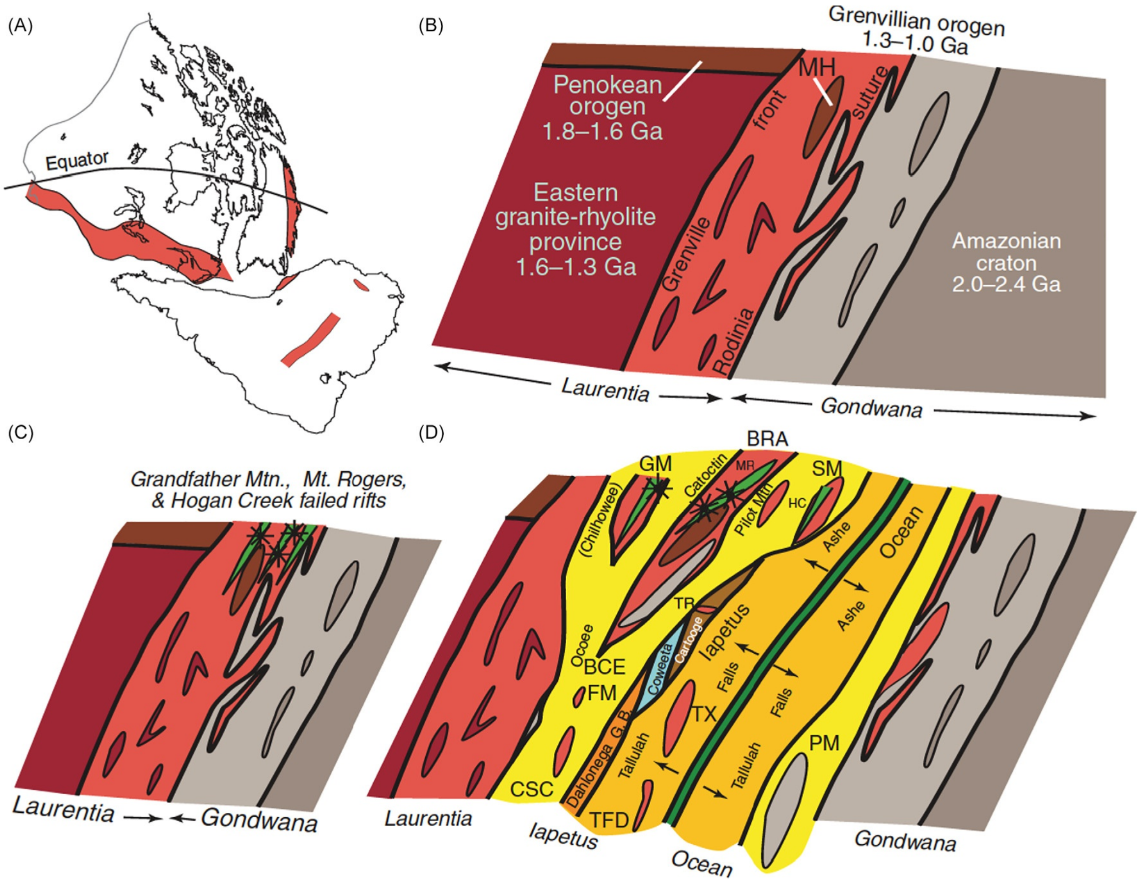


Fig. 3 Diagrammatic representation of Laurentian margin evolution from the Grenville orogeny forming Rodinia ~1 Ga to Neoproterozoic–early Paleozoic successful rifting and formation of the Iapetus ocean on the Laurentian margin. (A) Possible configuration of Laurentian and Gondwanan cratons at the end of the Proterozoic, showing Grenvillian belts (shaded). (B) Representation of likely components of Rodinia and the Grenville orogen along the suture between the Laurentian and Amazonian/Rio de la Plata cratons at the end of the Grenvillian orogenies. Recycled components of the cratons on both sides of the suture are shown as outliers on both sides of the suture and new Grenville crust is shown in lighter shades. MH—Mars Hill terrane (here presumably derived from the Penokean orogen). (C) Failed rifting and bimodal volcanism (asterisks) in "southeastern" Rodinia at 750–720 Ma produced the Grandfather Mountain, Mt. Rogers, and Hogan Creek and Robertson River assemblage (not shown), farther north in Virginia rift facies sedimentary-volcanic and alkali plutonic (e.g., Crossnore) assemblages. (D) Successful rifting and opening of Iapetus 572–564 Ma provided the rifted margin for deposition of the proximal to distal sedimentary sequences off the Laurentian margin. Several of the more distal units (e.g., Tallulah Falls-Ashe) are probably time transgressive and are likely to be much younger than the more proximal deposits. More proximal assemblages were probably deposited on continental or attenuated continental crust, whereas the more distal assemblages were probably deposited on oceanic crust and basement fragments. The configuration of both failed rift deposits shown in (C), and synrift to postrift deposits, and rifted blocks of Grenvillian crust is based on their relative spatial positions in the thrust sheets where they are found today. BCE—Bryson City and Ela domes, and Ravensford anticline; BRA—Blue Ridge anticlinorium; Cartooge—Metasedimentary, metavolcanic, and ultramafic rocks of the Cartoogechaye terrane; CSC—Corbin-Salem Church basement fragment; Dahlonega G.B.—Dahlonega gold belt metasedimentary sequence (could be as young as Ordovician; C. W. Thomas, 2001; Bream, 2003); FM—Fort Mountain basement fragment; GM—Grandfather Mountain window basement block and cover metasedimentary and meta-volcanic rocks; HC—Hogan Creek Formation failed rift sequence (Sauratown Mountains, SM, outer window); MR—Mount Rogers failed rift sequence and basement rocks; PM—Pine Mountain basement fragment and cover metasedimentary rocks (had to have been located close to Gondwana to receive Gondwanan detrital zircons, but is kinematically difficult to get back to its present position); TFD—Tallulah Falls dome basement fragment(s) and cover metasedimentary rocks; TR—Trimont Ridge basement fragment(s); TX—Toxaway dome basement fragment(s). Chilhowee Group is shown in parentheses because it was deposited later, but either directly on basement or on rifted-margin cover (e.g., Hardeman, 1966). Note that rock units depicted in (C) and (D) comprise part of the Iapetan margin preserved today in the Blue Ridge-Piedmont megathrust sheet. (Modified from Hatcher RD Jr. (1978) Tectonics of the western Piedmont and Blue Ridge: Review and speculation. *American Journal of Science* 278: 276–304, his Fig. 7, and Bartholomew MJ and Lewis SE (1992) Appalachian Grenville massifs: Pre-Appalachian translational tectonics. In: Mason R (ed.) *Basement Tectonics*, vol. 7, pp. 363–374. Dordrecht, The Netherlands: Kluwer Academic Publishers, their Fig. 4); Modified from Hatcher RD Jr., Bream BR, Miller CL, Eckert JO Jr., Fullagar PD, and Carrigan CW (2004) Paleozoic Structure of Southern Appalachian Blue Ridge Grenvillian Internal Basement Massifs. In: Tollo RP, Corriveau L, McLelland J, and Bartholomew MJ (eds.) *Proterozoic Evolution of the Grenville Orogen in North America*, pp. 525–547. Boulder, CO: Geological Society of America. Memoir 197, their Fig. 14.

Synrift sedimentation varied along the rifted margin in concert with the distinctly different structures on upper-plate and lower-plate segments. On the Texas promontory, a classic passive-margin transgressive succession of quartzose sandstone and shallow-marine limestone unconformably overlies basement rocks; the basal beds of the sandstone are late Middle Cambrian age. A similar passive-margin succession, with a basal sandstone of Late Cambrian age, overlies basement and synrift igneous rocks along the

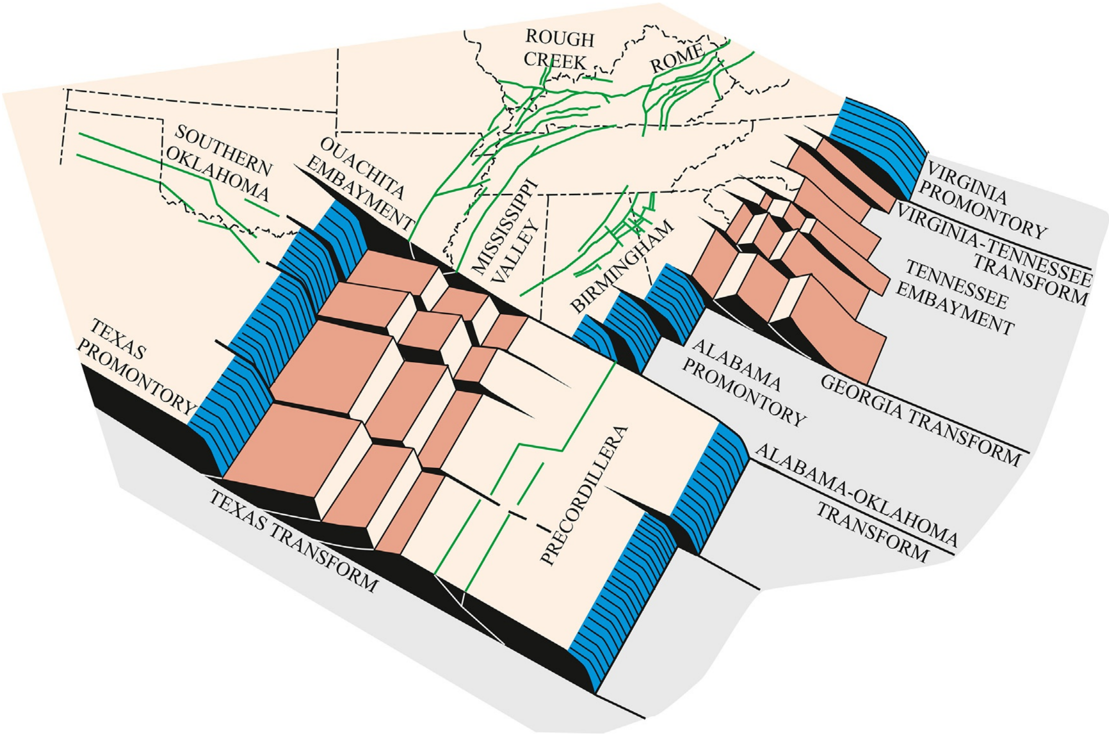


Fig. 4 Block diagram of southern Laurentian rifted margin. From Thomas WA (2011) The Iapetan rifted margin of southern Laurentia. *Geosphere* 7: 97–120.

Southern Oklahoma fault system; the passive-margin succession is exceptionally thick because of a great magnitude of post-rift thermal subsidence related to synrift igneous rocks along the fault system (Thomas and Astini, 1999). The passive-margin succession on the Alabama promontory overlies basement along an upper-plate margin, which extends northeastward to the Georgia transform (Fig. 4). The detachment flips to southeast dip northeast of the Georgia transform (Tull and Holm, 2005), and a lower-plate rift margin extends northeastward to the Virginia-Tennessee transform (Fig. 4). A thick succession of late Neoproterozoic to earliest Cambrian coarse clastic sediment (Ocoee Supergroup, etc.) accumulated within the system of graben and horst blocks (Rast and Kohles, 1986) on the lower plate within the Tennessee embayment (Fig. 4). The synrift sedimentary accumulations have a range of sources as indicated by detrital-zircon populations, generally from proximal basement rocks but some from the more distant Laurentian craton (summary in Thomas et al., 2017). The fault systems and the thick synrift sediment end abruptly along strike at transform faults. The passive-margin sandstone-carbonate succession overlies the synrift clastic sediment on lower-plate settings and laps across the transform faults onto eroded basement rocks on upper-plate settings; here the oldest sandstones in the passive-margin cover are Early Cambrian. Northeast of the Virginia-Tennessee transform, the detachment flips to northwest dip beneath an upper plate on the Virginia promontory (Thomas, 1991). Northeast of the corner of the Virginia promontory, the passive-margin succession overlaps synrift volcanic rocks (565 Ma Catoctin Formation). Another thick accumulation of synrift sedimentary rocks (Peters Creek Formation) is localized in the Pennsylvania embayment, indicating anomalous subsidence adjacent to the New Jersey transform.

On the Alabama promontory, the rift-parallel intracratonic late synrift Birmingham graben (Fig. 4) is generally filled with a thick succession of dark-colored fine-grained clastic sediment and subordinate carbonate rocks (Middle Cambrian Conasauga Formation), and the graben boundaries are overlapped by Upper Cambrian and younger carbonate rocks of the passive-margin succession (Thomas et al., 2000). The thick Conasauga muddy facies in the Birmingham graben is coeval with a thinner shallow-marine carbonate succession, indicating that synsedimentary fault movement maintained a deeper water setting in the graben. Detrital-zircon populations in the Rome Formation below the Conasauga Formation indicate sediment dispersal from the various Precambrian provinces of the Laurentian craton (Thomas et al., 2004). In contrast to the sediment-filled rift-parallel graben, the Southern Oklahoma transform-parallel fault system provided conduits for an enormous volume of synrift magma largely between 539 and 530 Ma (Hanson et al., 2013) inboard from the corner of the Ouachita embayment (Fig. 5). Similar facies and thickness distributions suggest similar depositional conditions along other intracratonic grabens. Northeastward along the Appalachians, the Middle Cambrian succession consists of varying amounts of shale and limestone, depending on siliciclastic mud supply from the craton, local intracratonic fault-bounded basins, and proximity to the Iapetan margin.

From Late Cambrian to earliest Middle Ordovician time, carbonate deposition transgressed across the entire Iapetan margin into the central interior of North America, extending westward as far as present-day California and northward into western and northern Canada as the younger part of the Sauk sequence (Sloss, 1963). This formed the first known extensive carbonate platform across interior Laurentia. Deposition of coeval carbonate platform deposits on other continents, as well as North America, was followed by

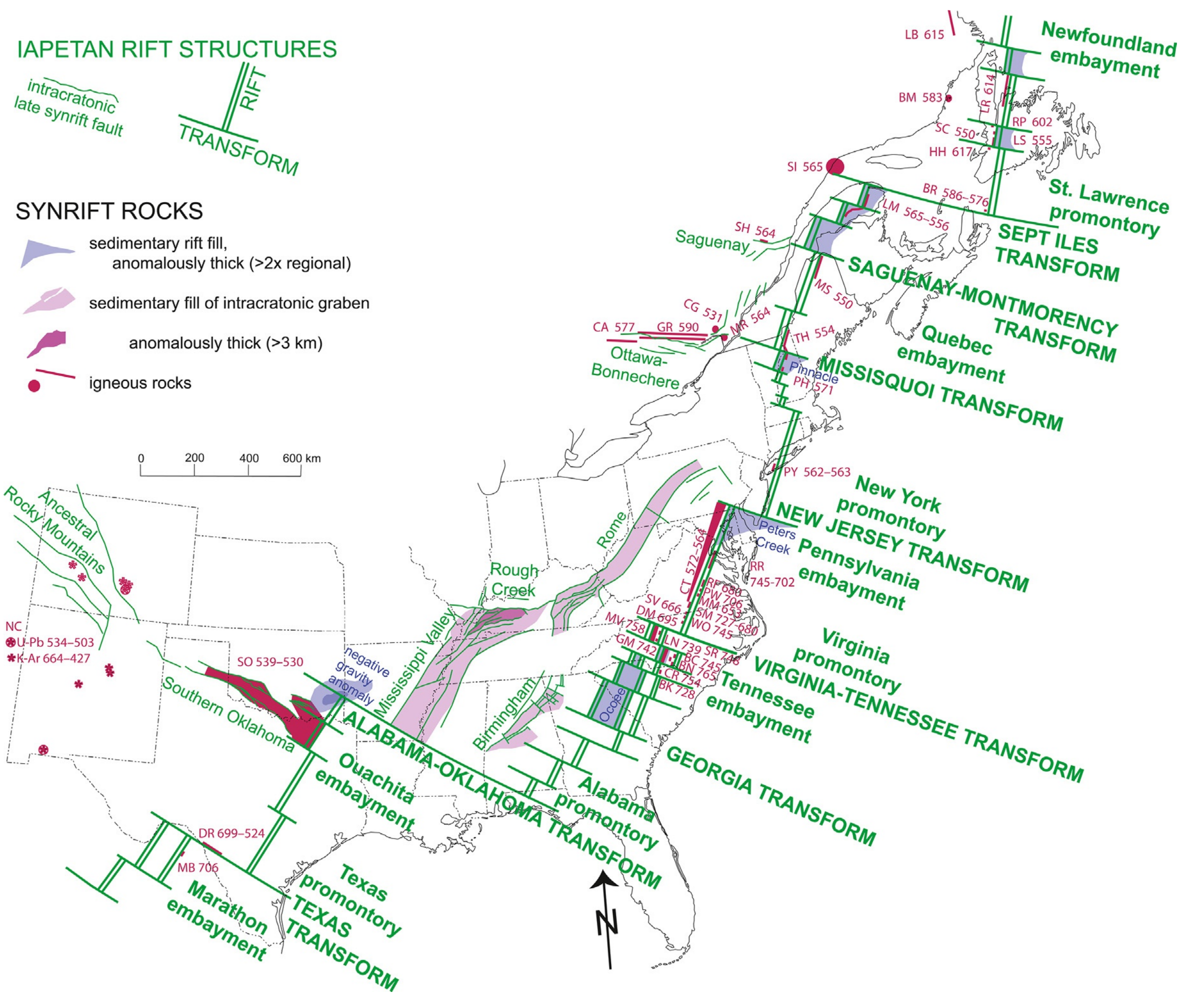


Fig. 5 Outline map of palinspastically restored Iapetan rifted margin of Laurentia, late synrift intracratonic fault systems, and distribution of synrift rocks. The ages of synrift rocks are shown to illustrate the time frame of Iapetan rifting. Reported ages of synrift igneous rocks (references to sources of age data are described in Thomas, 2014) are from U-Pb zircon analyses, except as noted in the following list, which also explains the abbreviations used on the map: BM—Baie des Moutons syenite (^{40}Ar-^{39}Ar, McCausland et al., 2011), BR—Blair River dikes (Miller and Barr, 2004), CA—Callander complex [Ottawa-Bonnechere graben] (Kamo et al., 1995), CG—Chatham-Grenville stock [Ottawa-Bonnechere graben] (^{40}Ar-^{39}Ar, McCausland et al., 2007), CR—Crossnore pluton (Su et al., 1994), CT—Catoctin volcanics and dikes (Aleinikoff et al., 1995), DR—Devils River uplift volcanics (Rb-Sr, Nicholas and Rozendal, 1975; Denison et al., 1977; Nicholas and Waddell, 1989), GR—Grenville dike swarm [Ottawa-Bonnechere graben] (Kamo et al., 1995) HH—Hare Hill granite (van Berkel and Currie, 1988), LB—Labrador dikes (Kamo et al., 1989), LM—Lac Matapedia volcanics (Hodych and Cox, 2007), LR—Long Range dikes (^{40}Ar-^{39}Ar, Stukas and Reynolds, 1974; Kamo et al., 1989), LS—Lady Slipper pluton (Cawood et al., 1996), MB—Marathon igneous boulder in the Ordovician Ft. Peña Formation [palinspastic location of source not known] (Hanson et al., 2016), MV—Mount Rogers volcanics (Aleinikoff et al., 1995), MR—Mont Rigaud stock [Ottawa-Bonnechere graben] (Malka et al., 2000), MS—Mount St. Anselme volcanics (Hodych and Cox, 2007), NC—scattered plutons in New Mexico and Colorado (compilation in McMillan and McLemore, 2004), pH—Pinney Hollow metavolcanics (Walsh and Aleinikoff, 1999), PW—Polly Wright Cove pluton (Tollo et al., 2004), PY—Pound Ridge granite and Yonkers gneiss (Tollo et al., 2004), RP—Round Pond granite (Williams et al., 1985), RR—Robertson River batholith (Lukert and Banks, 1984), SC—Skinner Cove volcanics (Cawood et al., 2001), SH—St. Honoré carbonatite complex [Saguenay graben] (K-Ar, Doig and Barton, 1968), SI—Sept Isles layered intrusion (Higgins and van Breemen, 1998), SM—Suck Mountain pluton (Tollo et al., 2004), SO—Southern Oklahoma volcanic-plutonic complex (Wright et al., 1996; Thomas et al., 2012; Hanson et al., 2013), TH—Tibbit Hill metavolcanics (Kumarapeli et al., 1989). From Thomas WA (2014) A mechanism for tectonic inheritance at transform faults of the Iapetan margin of Laurentia. *Geoscience Canada* 41: 321–344. [also in Hibbard JP, Pollock JC, van Staal CR, and Greenough JD (eds.) *Reeltime Geological Synthesis: Remembering Harold 'Hank' Williams*. Geoscience Canada Reprint Series, vol. 10, pp. 143–166].

withdrawal of the seas, forming the extensive Middle Ordovician post-Sauk (post-Knox) unconformity, and indicating that this large-scale inundation of and simultaneous withdrawal from the continental platforms was a product of a large-scale rise and subsequent fall of sea level rather than local processes (Hatcher and Repetski, 2007).

Although the post-Sauk unconformity is expressed across the continent (as well as on other continents), in two places (along the Alabama-Oklahoma transform margin, and along the rift south of the New Jersey transform) the hiatus is either very minor or null, suggesting that these places represent anomalous subsidence of part of the rifted margin. Transgression over the post-Sauk unconformity re-established shallow-marine carbonate deposition, but Appalachian orogenic processes soon began to interfere with the eustatic effects because of tectonic loading and flexural subsidence of the lithosphere, as well as the influx of clastic sediments from the rising orogen on the east.

Generation of the Carolina, Avalon, Gander, and Meguma Superterranes

Coeval with the rifting of Rodinia, numerous peri-Gondwanan terranes, consisting mostly of island arcs, were isolated in the intervening oceans separating Laurentia from Gondwana (Figs. 6 and 7). All of these terranes evolved proximal to Gondwana, amalgamated to form composite superterranes, and subsequently were accreted to the Laurentian assemblage during the early to mid-Paleozoic (e.g., Rast and Skehan, 1983; van Staal et al., 2007), except Meguma, which was accreted to Avalon (in present-day Nova Scotia) during the Alleghanian (Schenk, 1997). The peri-Gondwanan component in the southern and central Appalachians consists of the Carolina superterrane (or Carolinia) (Fig. 1B). These superterranes also contain the basic components of most of the

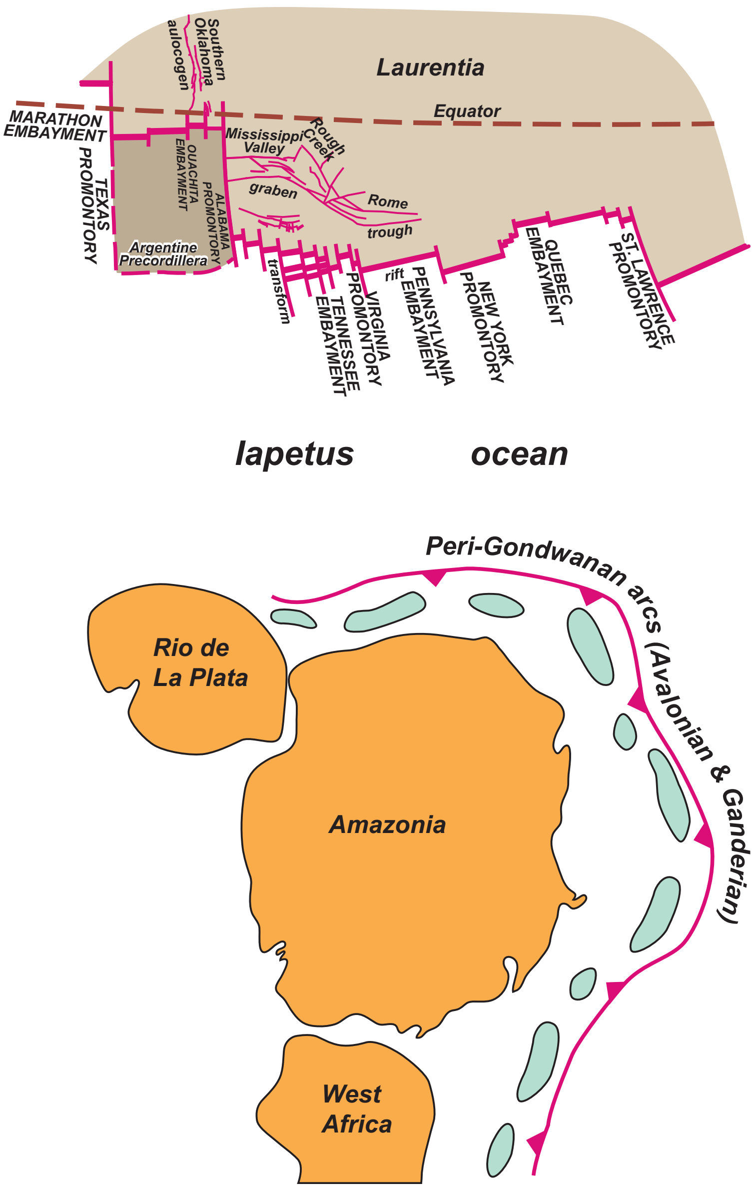


Fig. 6 Possible late Neoproterozoic to Early Cambrian paleogeography showing possible relationships among Laurentia, the irregular Laurentian margin, Gondwanan components, departure of the Argentine Precordillera from Laurentia, and peri-Gondwanan arc terranes. The configurations depicted in this and Figs. 8–10 are consistent with available data. From Hatcher RD Jr. (2010) The Appalachian orogen: A brief summary. In: Tollo RP, Bartholomew MJ, Hibbard JP, and Karabinos P (eds.) *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*, pp. 1–19. Boulder, Colorado: Geological Society of America. Memoir 206.

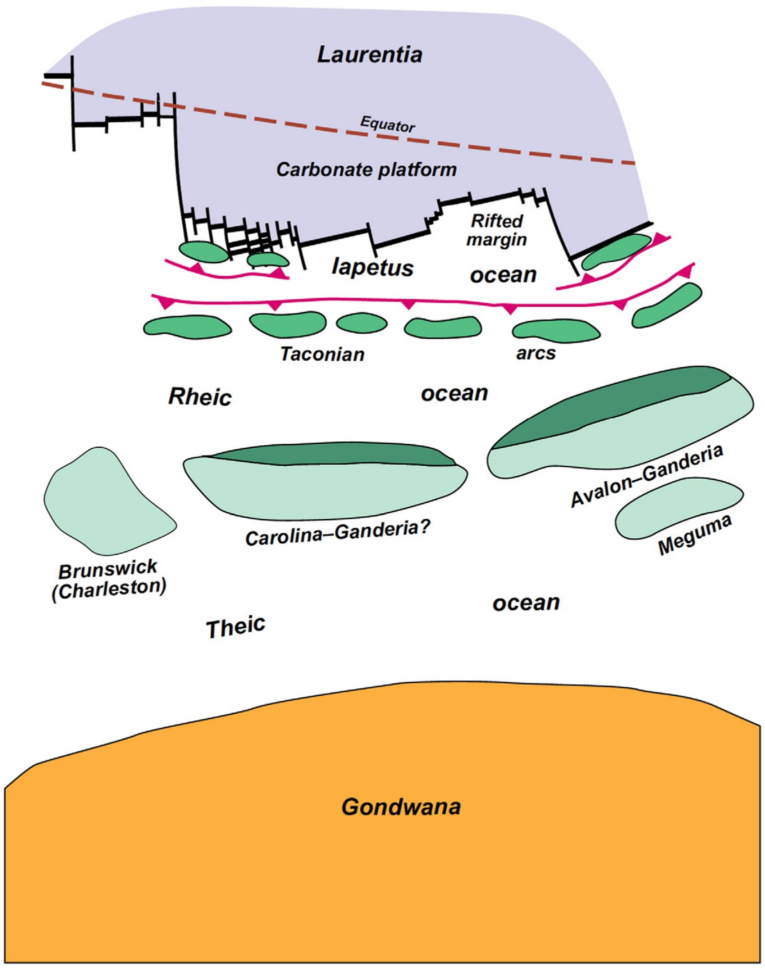


Fig. 7 Possible configuration of Laurentia, Gondwana, peri-Gondwanan terranes ("ribbon" microcontinents), Theic and Rheic oceans, and the soon-to-close Iapetus ocean during the early Middle Ordovician (late Arenig). A west-dipping subduction zone may have existed along the entire Laurentian margin that was subducted by the east-dipping subduction during the main-phase Taconic orogeny. From Hatcher RD Jr. (2010) The Appalachian orogen: A brief summary. In: Tollo RP, Bartholomew MJ, Hibbard JP, and Karabinos P (eds.) *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*, pp. 1–19. Boulder, Colorado: Geological Society of America. Memoir 206.

coeval Pan-African terranes: dominance of 625–550 Ma volcanic arcs and associated volcanogenic sediments, subarc plutonic complexes, and rare basement massifs. Basement from which the arc materials in the Carolina superterrane were derived appears to have been evolved continental crust on the basis of inherited zircons at 2.5, 2.1, and 1.0 Ga, and Sm-Nd whole-rock isotopic data (Samson, 1995).

The Neoproterozoic component of the Carolina superterrane consists of a mafic to felsic volcanic arc assemblage and associated volcaniclastic sedimentary rocks. Numerous plutons in the range of 618–550 Ma intruded the underpinning of the arc complex (Hibbard et al., 2002; Ingle et al., 2003). This assemblage was metamorphosed during the Cambrian, because 530 Ma plutons cut upper amphibolite- to greenschist-facies metamorphic rocks (Dennis and Wright, 1997; Barker et al., 1998). Neoproterozoic Ediacaran metazoan fossils have been identified on bedding planes in low-grade felsic volcanic and sedimentary rocks in two places in the Carolina terrane in North Carolina (Cloud et al., 1976; Hibbard et al., 2006a; Weaver et al., 2006). Unconformably overlying the arc complex in the Carolina superterrane is a sequence of Middle Cambrian and possibly Ordovician clastic sedimentary rocks. A Middle Cambrian Acado-Baltic (*Paradoxides*) fauna occurs in these sedimentary rocks in South Carolina (Secor et al., 1983), and Ordovician conodonts have also been reported in another part of the sequence in North Carolina (Koeppen et al., 1995). Hibbard et al. (2006b,c), however, reported Ediacaran fossils from at least one of the same localities, and their Neoproterozoic age is corroborated by U-Pb radiometric ages, casting doubt on the age of the reported conodonts.

High-grade components of the western Carolina superterrane in the southern Appalachians (excluding the more easterly Alleghanian high-grade zones) were deformed and metamorphosed prior to ~530 Ma, following termination of arc magmatism (Barker et al., 1998). This is principally the Charlotte terrane of Hibbard et al. (2002). If the subsurface Brunswick (Charleston) terrane in South Carolina and Georgia has a peri-Gondwanan origin, as the one age date might suggest (Mueller et al., 2005), and became part of the Carolina superterrane either during the 530 Ma event or possibly the Alleghanian, it is simply another component of the superterrane.

The Charlotte terrane within the Carolina superterrane consists of a high-grade assemblage of metavolcanic and plutonic rocks that were metamorphosed and accreted to the Carolina superterrane before ~530 Ma, long before being accreted to Laurentian components (Barker et al., 1998; Hibbard et al., 2002). Because of the basic similarities of the rocks in each of the exposed Appalachian peri-Gondwanan superterranes (Carolina, Avalon, and Gander), they have been traditionally assumed to be part of a single terrane throughout the orogen (e.g., Williams and Hatcher, 1983). Hibbard et al. (2007b) compared both sequences and isotopic data and concluded that, from several points of view, Carolina superterrane rocks have greater similarities to those of the Gander superterrane than to Avalon. While the volcanogenic sequences are broadly similar, details reveal that there are major dissimilarities with respect to the sequences and their histories. Faunal assemblages similar to those in the Carolina have been described from the northern Appalachians in Rhode Island, New Brunswick, and Newfoundland, but differences in both the faunas and stratigraphic sequences suggest the Carolina superterrane is different from the accreted Gondwanan terranes in the northern Appalachians (Secor et al., 1983; Samson, 1995; Hibbard et al., 2007b). Nevertheless, there is little disagreement that all of these terranes had their origin during Neoproterozoic time close to Gondwana, with a bimodal volcanic-plutonic history beginning just after 700 Ma (Coler et al., 2000; Wortman et al., 2000).

The Paleozoic histories of the accreted terranes diverge, however, as might be expected, because their accretionary histories are quite diachronous along the length of the orogen (see Hibbard et al., 2007b). Moreover, Gander and Avalon (and Carolina-Charlotte) superterranes were amalgamated before 530 Ma (Barker et al., 1998; Hibbard et al., 2007a,b), well before their accretion to Laurentia during the mid-Paleozoic.

The exotic Meguma terrane in Nova Scotia consists of a sequence of Upper Cambrian to Lower Devonian sedimentary rocks that have a peri-Gondwanan affinity, concluded to be deposited off the Gondwanan margin (Schenk, 1997). Sequences consisting of alternating thick, fine-grained, deep-water sandstone and shale units have been related to similar sequences in northwestern Africa. Meguma likely was accreted to the outer parts of the already partially assembled Appalachian orogen in the early Alleghanian (Schenk, 1997).

Taconic Orogen

Taconic Synorogenic Clastic Wedges and Contractional Structures Along the Appalachians

Synorogenic clastic wedges with ages encompassed by the Taconic orogeny are distributed along the Appalachian system from the Alabama promontory northward to Newfoundland (Fig. 8) (Thomas, 1977). In the central and southern Appalachians, Taconic clastic wedges are centered on the Tennessee and Pennsylvania embayments. West of the Alabama promontory, a passive margin persisted along the Iapetan margin of Laurentia (around the Ouachita and Marathon embayments) through the entire time span of the various components of the Taconic orogeny (Viele and Thomas, 1989). In summary, Taconic orogenesis affected the Laurentian margin from the Alabama promontory to Newfoundland, but no orogenic effects are recorded west of the Alabama promontory. Nevertheless, rocks with ages equivalent to those of the Taconic orogeny are documented in several Gondwanan terranes that were accreted to southern Laurentia during the late Paleozoic Alleghanian-Ouachita orogeny.

In the Pennsylvania embayment, the Taconic Martinsburg-Shawangunk clastic wedge (Thomas, 1977) begins with a thick succession of dark-colored mud-dominated deposits (Martinsburg Formation) that overlie shallow-marine carbonate rocks of late Middle Ordovician age (=late Darriwilian Age), approximately 460 Ma. The clastic wedge is thickest (about 4 km) in the Pennsylvania embayment and thins both along strike and toward the craton (Fig. 8). Southwestward along strike on the Virginia promontory, the Martinsburg overlaps part of the northeastward thinning Blount clastic wedge. The Martinsburg gray siliciclastic rocks grade upward into redbeds of the classic "Queenston Delta" in the Upper Ordovician. Extensive Lower Silurian sandstones lap over the redbeds. Eastward into the proximal part of the clastic wedge on the southern part of the New York promontory, an unconformity beneath the Silurian sandstones cuts down through the Ordovician stratigraphic section. In the most proximal outcrops, Silurian sandstones rest with angular unconformity on folded Ordovician strata (the classic Taconic unconformity, Rodgers, 1971); in the Green Pond syncline in New Jersey, the unconformity cuts down through the entire sedimentary succession onto Precambrian crystalline basement rocks (Finks, 1968), indicating significant deformation east of the foreland basin during the orogeny. A late stage of synorogenic red clastic sedimentation and evaporite deposition continued into the Late Silurian. Shallow-marine carbonates in the Upper Silurian and Lower Devonian indicate the end of orogenic topography and establishment of a shallow-marine shelf, separating the Taconic and Acadian orogenies.

In the Tennessee embayment, the Taconic Blount clastic wedge (Thomas, 1977) begins with a thick succession of dark-colored mud-dominated deposits (Blockhouse and Sevier Shales) that overlie shallow-marine carbonate rocks of early Middle Ordovician age (=early Darriwilian Age), approximately 465 Ma. The clastic succession grades upward into coarser facies, including some boulder beds, and ultimately into redbeds in the proximal part of the clastic wedge. An unconformity separates Middle Ordovician strata from Silurian red and gray sandstone and shale, as well as hematitic iron deposits, including the commercial iron ores in central Alabama in the more distal part of the clastic wedge. The magnitude of the unconformity decreases away from the center of the wedge toward the craton, and Upper Ordovician strata also include redbeds. The clastic wedge has a maximum thickness of about 2.5 km; the thickness decreases abruptly toward the craton and more gradually along strike onto the Alabama (southwest) and Virginia (northeast) promontories (Fig. 8).

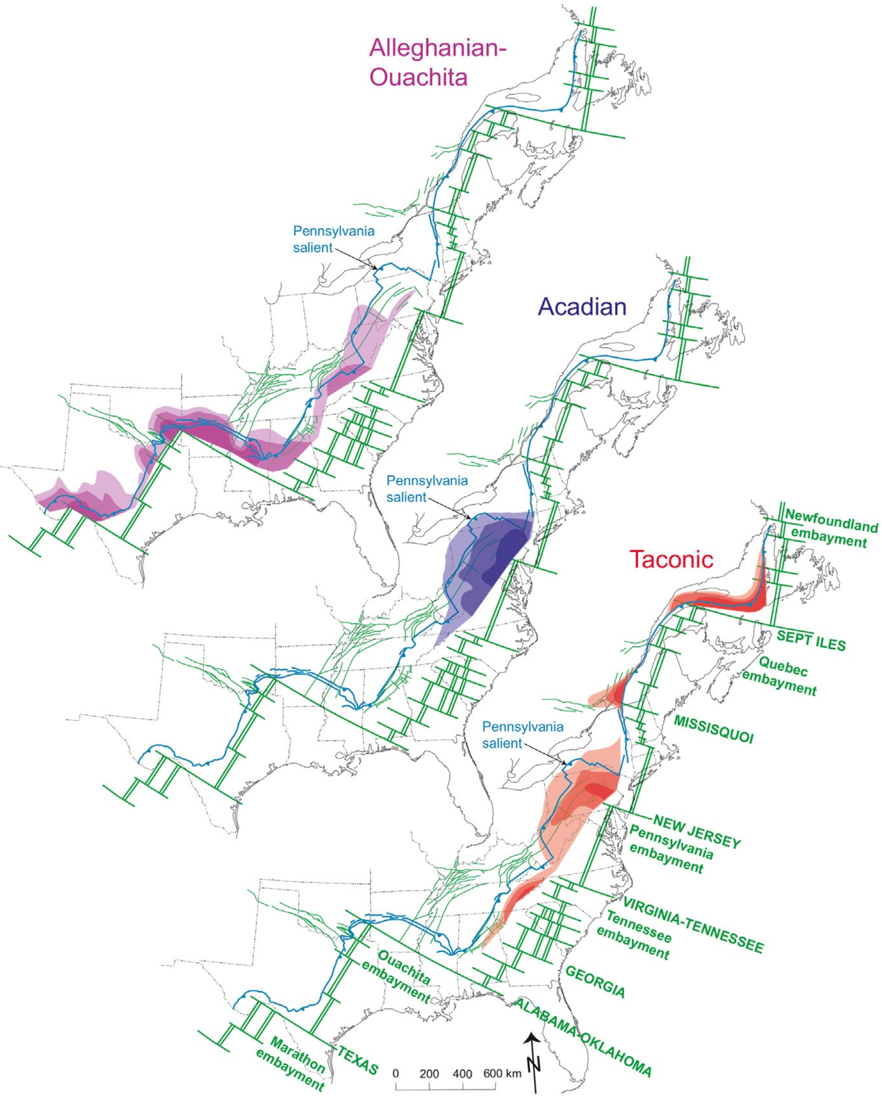


Fig. 8 Maps of the distribution of Appalachian-Ouachita synorogenic clastic wedges. Thomas WA (2019a) Tectonic inheritance at multiple scales during more than two complete Wilson cycles recorded in eastern North America. In: Wilson RW, Houseman GA, McCaffrey KJW, Doré AG, and Buiter SJH (eds.), *Fifty Years of the Wilson Cycle Concept in Plate Tectonics: Geological Society of London Special Publications* 470, p. 337–352. https://doi.org/10.1144/SP470.4.

Sediment composition in the Blount clastic wedge reflects the composition of the Taconic orogenic source east of the foredeep. Clasts in a Middle Ordovician conglomerate near the center of the clastic wedge include all lithologies of the early Middle Ordovician passive margin and older rifted margin and platform sequences, along with some basement rocks (Kellberg and Grant, 1956), consistent with sandstone petrography that indicates a provenance of sedimentary and crystalline rocks, but no volcanic contribution (Mack, 1985; Bayona, 2003; Bayona and Thomas, 2006). Although no volcanic detritus reached the foredeep, widespread bentonite beds in the Ordovician far out into the foreland and craton indicate a volcanic arc within the Taconic orogen (Kolata et al., 1998). A comprehensive interpretation includes an arc complex and a retroarc thrust belt (of basement and passive-margin cover) that both restricted volcanic detritus to the forearc basin and supplied non-volcanic detritus to the foredeep. Other carbonate-boulder beds within the distal foredeep deposits suggest reactivation of intra-foredeep basement faults and uplifts caused by migration of the flexural wave (foredeep and forebulge) during Taconic tectonic loading and flexural subsidence (Bayona, 2003; Bayona and Thomas, 2003). The non-volcanic detritus in the Blount clastic wedge contrasts somewhat in composition with the Martinsburg-Shawangunk clastic wedge, which does contain a component of volcanic lithic grains (McBride, 1962; Mack, 1985), indicating a somewhat different dispersal system through the forearc. Farther north, the Taconic clastic wedge in the Quebec embayment contains ophiolitic debris (Hiscott, 1984), indicating a further contrast in tectonic styles.

The Taconic foreland basins are diachronous, having different times of initiation, filling, and termination (Thomas, 2006). The latest stage consists of molasse deposition, generally including Silurian redbeds and ironores. In general, Taconian foreland deposition reflects accretion of arc terranes, destruction of the Iapetan rifted and passive margin of Laurentia, and closing of the ocean basin.

Taconic Arcs and Arc Accretion History

In the northern Appalachians in Canada, ophiolites were obducted to load the outer platform (Stevens, 1970; Williams, 1979), and the fill of the foredeep includes ophiolitic debris (Hiscott, 1984). In the New England Appalachians, successive arcs in the time span of 485–442 Ma reflect east-dipping subduction followed by west-dipping subduction beneath a continental-margin arc on the Laurentian margin (Karabinos et al., 1998). The Taconic orogeny on the Virginia promontory and Pennsylvania embayment began at 489–470 Ma with east-dipping subduction of the oceanic crust of the Laurentian plate beneath evolving oceanic arcs (Sinha et al., 2012), but a flip in subduction polarity led to a continental-margin arc associated with west-dipping subduction. The resolution of the nature of the arc systems varies markedly along the orogen, because of the variability of the intensity of transposition and metamorphic grade. A complex arc system was built off Newfoundland during the Ordovician that involved non-coeval west- and east-dipping subduction zones, with accretion of the Dashwoods block (van Staal et al., 2007). A parallel history took place farther south, but it is obscured by Taconian and later polydeformation, and medium- to high-grade metamorphism. The best-preserved ophiolites in the orogen were obducted onto the Laurentian margin in Newfoundland during the Taconian event, along with accretion of several arc terranes (e.g., Stevens, 1970). The only other demonstrable ophiolites in the orogen are in New Brunswick and Québec (St. Julien and Hubert, 1975; van Staal et al., 2008), but these consist of incomplete sections. Ordovician blueschist has been recognized in northern Vermont and southern Québec (Laird, 1988; Robinson et al., 1998), and in New Brunswick, but the New Brunswick occurrence appears to have a Late Ordovician age and emplacement related to the ~425 Ma Silurian Salinic orogeny (van Staal et al., 2008). Farther south, either no ophiolites or blueschists are preserved on the Laurentian margin or they are located in the internides where they are polydeformed and metamorphosed to amphibolite facies or higher grade assemblages, thereby obscuring their origin. Several mafic-ultramafic complexes in the southern Appalachians, however, possess whole-rock and mineral geochemical characteristics that suggest normal mid-ocean-ridge basalt (N-MORB) to arc provenance and ophiolite emplacement (Hatcher et al., 1984; Swanson et al., 2005). They also are frequently associated with amphibolite complexes that have a non-continental origin (Hatcher et al., 1984). Two successive arcs with subduction flip formed in New England (Karabinos et al., 1998) and Virginia (Sinha et al., 2012), along with an arc/backarc system in Alabama-Georgia (Tull and Stow, 1982), although a better explanation may be a continental margin arc and retroarc thrust belt. The 471 Ma arc-related Hillabee Greenstone in Alabama and western Georgia; (McClellan et al., 2007) formed along the southern margin, providing a good record of Ordovician arc formation and accretion along this part of the orogen (Fig. 8).

Taconic allochthons that emplaced deep-water, offshore facies onto the Laurentian margin occur from New York northward (Zen, 1967; Zen, 1972; St. Julien and Hubert, 1975; Rowley et al., 1979). No Taconic allochthons occur farther south, but several nappes were thrust into the Martinsburg basin during the Middle to Late Ordovician and were originally interpreted as a Taconic allochthon, called the "Hamburg klippe" (Stose, 1946; Lash and Drake, 1984; Drake et al., 1989). Recent detailed paleontologic work, however, has revealed that the Cocalico Formation of variegated sandstone and shale that originally was thought to comprise the Hamburg klippe contains olistoliths of older units, but was also thrust into the Martinsburg basin during the Middle to Late Ordovician (Ganis and Wise, 2008; Wise and Ganis, 2009). Wise and Ganis (2009) suggested this group of parautochthonous to allochthonous rocks be called the "Hamburg complex," rather than the Hamburg klippe. Emplacement of the Hamburg complex occurred close to the time of accretion of several smaller more outboard terranes in the central Appalachians, including the Westminster, Potomac, and Philadelphia terranes (Faill, 1997).

The "Taconian suture" consists of a major fault and terrane boundary that is traceable throughout the orogen. It is called the Baie Verte-Brompton Line from Newfoundland to New England, and consists of faults with a variety of names: Whitcomb Summit, Cameron's Line, and several in the central Appalachians, including the Martic Line, and farther south the Gossan Lead-Burnsville-Chattahoochee-Holland Mountain-Hollins Line fault. The Baltimore complex in Maryland and most of the mafic-ultramafic complexes in the southern and central Appalachians (Drake et al., 1989) likely were emplaced as ophiolites during the closing of Iapetus Ocean. The Hayesville fault forms the western boundary of two smaller terranes (Cartoogechaye and Cowrock) located west of the Chattahoochee fault in the southern Appalachians. These faults separate the rifted margin metasedimentary and rift-related volcanic rocks from dismembered ophiolites; but, south of Québec, deformation at high-grade metamorphic conditions prevents structural or stratigraphic resolution of their provenance. Despite this, numerous geochemical studies over the past 25 years have consistently suggested that the mafic and ultramafic rocks have a non-continental, probably ophiolitic origin.

Taconian metamorphism reached upper-amphibolites-facies, or higher, conditions in the southern Appalachian Blue Ridge (Eckert et al., 1989; Moecher et al., 2004). Timing of Taconian metamorphism ranges from 460 to 455 Ma in the southern Appalachians to 480–455 Ma in New England (Robinson et al., 1998; Moecher et al., 2004; Merschat et al., 2017). Timing of deformation and metamorphism in the internides is roughly coeval with the timing of foreland basin development.

A few Ordovician (~460 Ma) granitoid plutons occur in the southern Blue Ridge (e.g., Hatcher et al., 2007b), but many more occur in the Inner Piedmont (Bream, 2003; McClellan et al., 2007), and 470–458 Ma plutons and volcanic rocks occur in the Milton-Chopawamsic-Potomac terrane (e.g., Coler et al., 2000). These continue into the central Appalachian Piedmont of Virginia to Maryland, with the addition of several Silurian (Salinian?) granitoid plutons (Sinha et al., 2012). Taconian felsic plutons are principally I-type granitoids. Most are considered arc-related plutons and volcanic rocks produced during closing of Iapetus. A suite of Late Ordovician to Early Silurian granitoid plutons also intruded the Virginia to Maryland central Appalachians (Sinha et al., 2012).

The central Appalachians contain several small terranes—Westminster, Philadelphia, and others (Fig. 1B)—but these were identified by Faill (1997) as having originated in the Octararo sea located off of the central Appalachians during the Ordovician, so they are likely all related to the large suite of distal terranes that formed prior to the Taconic orogeny in Iapetus off the Laurentian margin (Figs. 6 and 7).

In the southern Appalachians, the Talladega belt, Dahlonega gold belt, Cowrock, Cartoogechaye, and Kings Mountain belts are small terranes consisting of elements of Laurentian affinity (Fig. 1B). The Kings Mountain belt has been considered part of Carolina (Horton et al., 1989).

Acadian-Neoacadian Orogen

Acadian Synorogenic Clastic Wedges and Contractional Structures Along the Appalachians

Deposition of clastic sediments in the central Appalachian foreland in the Pennsylvania embayment derived from the rising Acadian mountains began in the earliest Middle Devonian. Middle Devonian black shale (Marcellus and Millboro Shales) overlies Lower Devonian shallow-marine carbonate rocks (Onondaga Limestone) and progrades cratonward over the carbonate facies (Thomas, 1977). The clastic succession coarsens upward through sandstone-shale (Chemung) to redbeds of the classic Catskill delta (Woodrow and Sevon, 1985). The clastic wedge is thickest (>3.5 km) in the Pennsylvania embayment and is semi-circular in map view (Fig. 8). The Devonian clastic facies thin and prograde southwestward along subsequent Appalachian strike, as well as northwestward onto the craton. Above the Devonian clastic succession, the Lower Mississippian is dominated by relatively clean sandstone (Pocono and Price) with some coal deposits (a molasse deposit). The sandstone is overlain by muddy deposits (Maccrady and Grainger Formations in the distal southwest) and evaporites (Saltville), which are overlain in turn by the transgressive Mississippian Greenbrier (and Loyalhanna) Limestone, marking the end of progradation of the Acadian clastic wedge (Thomas, 1977). Diachroneity of the clastic wedge is well documented, because successive deltaic deposits shift progressively southward, indicating a progressive southward shift of the sediment supply into the orogenic foreland, and implying dextral strike-slip in the orogen (Ferrill and Thomas, 1988).

Paralleling foreland deposition, deformation and metamorphism occurred in the interior of the orogen, reaching granulite-facies assemblages in southern New England and at least sillimanite II in the southern Appalachians. This is the Acadian-Neoacadian orogeny from New England southward. The Acadian orogeny began in the Early Devonian with granitoid plutons that intruded the Cat Square terrane (~407 Ma; Fig. 9), and the Neoacadian ended in the early Mississippian (~345 Ma) (Osberg et al., 1989; Robinson et al., 1998; Merschat et al., 2005; Hatcher et al., 2007b; Merschat and Hatcher, 2007). The Acadian-Neoacadian orogeny was dominated by dextral transpression that closed the small Rheic ocean, where southern New England and Cat Square terranes were deposited, and obducted Carolina superterrane onto Cat Square and Laurentian assemblages (Fig. 9). The Acadian and Neoacadian events overlap to the extent that they are not readily separated (and probably should not be considered separate events).

The Acadian-Neoacadian orogeny is the product of zippered north-to-south closing of the Rheic ocean separating mid-Paleozoic Laurentia and early Paleozoic accreted Taconian terranes from colliding peri-Gondwanan superterranes, Avalon and Carolina, (Fig. 9) (Rast and Skehan, 1983; Barr et al., 1998; Merschat et al., 2005; Hatcher and Merschat, 2006; Hatcher et al., 2007a; Merschat and Hatcher, 2007). The Cat Square remnant ocean accumulated detrital zircons from both Laurentian and Peri-Gondwanan sources, and zircons as young as 430 Ma (Bream, 2003), indicating deposition occurred in the Rheic remnant ocean during the Silurian and Early Devonian. The zircon suite in the Cat Square terrane is nearly identical to that in the Putnam-Nashoba terrane in southern New England. The Cat Square terrane, Merrimack synclinorium, and Putnam-Nashoba terrane rocks, also have a dual source affinity—both Laurentian and peri-Gondwanan detrital zircons (Bream et al., 2004; Wintsch et al., 2007)—along with abundant 430–425 Ma central Appalachians Salinic(?) event-derived zircons (Sinha et al., 2012). This strongly suggests that the Cat Square terrane is a southern continuation of the Merrimac synclinorium, and Cat Square terrane rocks were originally deposited off present-day New Jersey immediately south of southern New England, and were moved southwestward during dextral transpressive collision with Carolina beginning in the Late Devonian (Fig. 9; Merschat et al., 2005; Merschat and Hatcher, 2007, their Fig. 3; Merschat et al., 2010).

From the central Appalachians southward, terranes to the west of Carolina were subducted beneath it after closing the Cat Square remnant ocean basin, producing anatectic melting by 407 Ma (Merschat et al., 2017) and wholesale migmatization of Cat Square and Tugaloo terrane assemblages beneath Carolina generating plutons in these terranes, as well as in the Carolina superterrane. Neoacadian plutons are not as abundant in the Carolina superterrane, but they are present in the Carolinas and Georgia as the arc-related Salisbury plutonic suite and associated mafic plutons in the Carolinas (Butler and Fullagar, 1978; McSween et al., 1991), and the Devonian mafic plutonic suite in central Georgia and the Carolinas (e.g., Huebner and Hatcher, 2017). Evidence supporting the subduction of the Inner Piedmont far beneath Carolina consists of transpressional horses of Carolina superterrane rocks in the Brevard fault zone (farther west of the central Piedmont suture) that could only have been derived from above and not laterally (Hatcher et al., 2017). Although Acadian plutons are not abundant in the southern Appalachians, Acadian plutons are abundant, even dominant, in New England and the Canadian Maritimes. The reason for this difference may be that final emplacement of

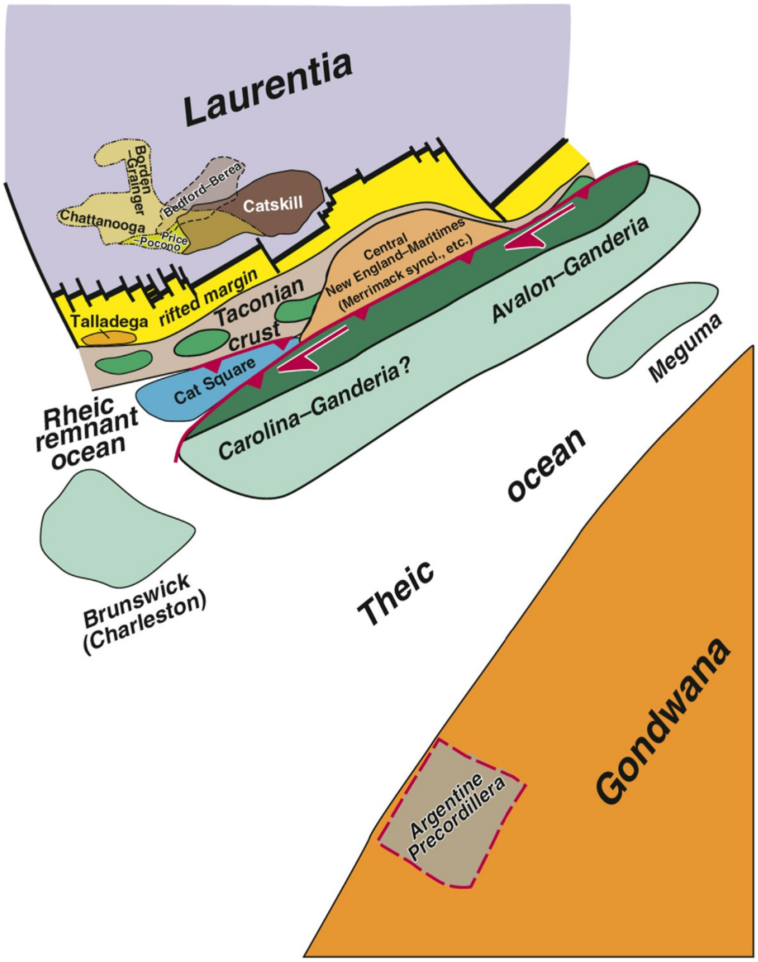


Fig. 9 Possible relationships during Late Devonian to early Mississippian time (~360 Ma) among Laurentia, already formed Taconic crust, and Carolina-Avalon-Gander superterranes that collided transpressionally (southwest-directed) with the Laurentian-Taconian assemblage and subducted these elements beneath them, producing high-grade metamorphism and uplift in southern New England and progressively subducting more of the Laurentian-Taconian terranes, together with sediments deposited in the remnant Rheic ocean, southwestward reaching burial depths of 18–20 km in a relatively short time (1–4 m.y., depending on dip of the subduction zone). The result was a tectonically forced, southwestward escaping, orogenic channel of partially melted Cat Square sediments and Laurentian Taconian crust (Hatcher and Merschat, 2006). Configurations of diachronously prograding deltas on the platform (Ettensohn, 2004) correlate directly with the northeast-to-southwest transpressionally zippered closing of the remnant Rheic ocean. From Hatcher RD Jr. (2010) The Appalachian orogen: A brief summary. In: Tollo RP, Bartholomew MJ, Hibbard JP, and Karabinos P (eds.) *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*, pp. 1–19. Boulder, Colorado: Geological Society of America. Memoir 206.

Avalon was by westward (west-dipping) subduction beneath New England (Phinney, 1986; Robinson et al., 1998), but was eastward (east-dipping) in the southern and central Appalachians. Because of the dextral transpressive nature of collision leaving only a remnant ocean, the amount of ocean crust that was available to be subducted was minimal, thus limiting the ability to generate large numbers of suprasubduction-zone plutons. Once the limited amount of ocean crust was subducted, continental crust began to be subducted from the west, and the ability to generate plutons was shut off analogous to subduction of modern Australian continental crust beneath Indonesia, shutting off arc volcanism (e.g., Hamilton, 1979). The high-grade western Carolina superterrane has a 360–350 Ma metamorphic overprint and numerous younger (Devonian to Carboniferous) granitoids and gabbros (Dallmeyer et al., 1986; McSween et al., 1991; Hibbard et al., 2002; Huebner and Hatcher, 2017) probably related to Late Devonian-Early Mississippian docking of the Carolina superterrane. The Smith River allochthon (Fig. 2) had been identified as a peri-Gondwanan terrane and outlier of the Carolina superterrane based on monazite chemical ages (Hibbard et al., 2003), but detrital zircon data of 1.35–1.0 Ga, 700 Ma, and 469–434 Ma (Carter et al., 2006; Merschat and Hatcher, 2007), do not support this conclusion, and reconfirm that the Smith River allochthon has a Laurentian provenance.

The greenschist-grade and lower-grade central and eastern Carolina superterrane consists mostly of Neoproterozoic to Cambrian volcanic and volcaniclastic rocks interrupted by the Alleghanian Kiokee-Raleigh belt metamorphic core. Southeast of this metamorphic core are more low-grade volcanic and volcaniclastic rocks that have been called different terranes by Hibbard et al. (2002), although the Carolina superterrane was subdivided differently by Horton et al. (1989). The Peri-Gondwanan assemblage in the

Carolina superterrane, and the other Peri-Gondwanan terranes in the eastern Appalachians that also form the pre-Mesozoic basement in central and western Europe and the southern British Isles, are almost identical to the Pan-African terranes in Africa and South America in volcanic arc assemblages, ages of early Paleozoic plutons, and lack of basement.

Evidence supporting mid-Paleozoic accretion of the Carolina superterrane consists of: (1) deposition of Cat Square terrane sediments that occurred subsequent to 430 Ma (Bream, 2003), nearly coeval with deposition of the Silurian-Devonian sediments in New England and the Canadian Maritimes; (2) parallel diachronous timing of metamorphism and deformation (395–340 Ma, Merschat et al., 2017) in the Tugaloo and Cat Square terranes in the southern Appalachian internides (Fig. 1B) with diachronous, southward-younging clastic wedge sedimentation in the foreland, beginning in the north with the Devonian Catskill sediments, and ending in the south with the latest Devonian-Mississippian Chattanooga Shale and coarser equivalents to the east (Fig. 9) (e.g., Ferrill and Thomas, 1988; Ettensohn, 2004; Merschat and Hatcher, 2007); (3) both mafic and felsic magmatism in the overriding Carolina superterrane in North Carolina, South Carolina, and Georgia (Butler and Fullagar, 1978; McSween et al., 1984; Hooper and Hatcher, 1989; Huebner and Hatcher, 2017); and (4) a mid-Paleozoic ~360 Ma thermal overprint recorded in $^{40}Ar/^{39}Ar$ plateau ages in the western Carolina superterrane (Dallmeyer et al., 1986). Hibbard et al. (2012) concluded that Carolina was accreted to Laurentia during the Ordovician based on dated Ordovician deformation within the Carolina superterrane along the Gold Hill-Silver Hill fault system in the Carolinas, and $^{40}Ar/^{39}Ar$ data. These faults have small displacements and their Ordovician deformation in the Carolina superterrane could have occurred while Carolina was far from Laurentia well before mid-Paleozoic accretion, as the overwhelming structural, detrital zircon, and other geochronologic data indicate. In addition, the probability-frequency plot of Ar data (Hibbard et al., 2012, their Fig. 8) contains the greatest frequency of ages in the middle Paleozoic clustered around 370 Ma, consistent with metamorphic ages determined from monazite and zircon rims (Dennis and Wright, 1997; Bream 2003; Merschat et al., 2017). Their few Ordovician ages could be related to localized uplift related to internal deformation in the Carolina superterrane prior to accretion. Moreover, criticism leveled at the abundant data of the mid-Paleozoic docking of Carolina superterrane (Hibbard et al., 2007a) is partly based primarily on paleomagnetic data that place Carolina superterrane at similar paleolatitude with Laurentia in the Ordovician (Vick et al., 1987; Noel et al., 1988), but paleomagnetic data do not indicate paleolongitude, permitting as much as 180 degree of uncertainty in the Ordovician location of Carolina.

Acadian-Neoacadian granitoid and gabbro plutons range in age from 407 to 345 Ma. The suite confined to the Inner Piedmont consists mostly of I- and S-type granitoids, many of which may be anatectic, whereas the Salisbury plutonic suite in the Carolina superterrane contains I-type granitoids. The Concord plutonic suite in the Carolinas and eastern Georgia consists of gabbros with ages ranging from 416 to 372 Ma. The geochemistry of all of these plutons supports origin above one or more subduction zones (Huebner and Hatcher, 2017): the mid-Paleozoic granitoid and gabbro plutons are likely related to the central Piedmont suture that marks a subduction zone, and the late Paleozoic gabbros are likely related to the subduction zone that brought Gondwana (Africa) into collision with Laurentia.

Alleghanian Orogen

Alleghanian Synorogenic Clastic Wedges Along the Appalachians

In the Pennsylvania salient, deposition of the Alleghanian synorogenic Mauch Chunk-Pottsville clastic wedge began with progradation of red siliciclastic sediment (Mauch Chunk Formation/Group) over the extensive shallow-marine deposits of the Mississippian Greenbrier Limestone and an eastwardly extensive tongue, the Loyalhanna Limestone (Thomas, 1977; Thomas, in Hatcher et al., 1989). The shallow-marine to deltaic deposits of the Mauch Chunk Group are overlain by Lower Pennsylvanian conglomerates and sandstones, partly on erosion surfaces. Lower-Middle Pennsylvanian coal-bearing siliciclastic strata cap the clastic wedge. The Mauch Chunk-Pottsville clastic wedge, in contrast to the older Taconic and Acadian clastic wedges, begins with shallow-marine deposits rather than a thick deep-water succession of black shales. The shallow-marine facies and relatively thin succession document a long-wavelength:low-amplitude basin, which remained filled to overfilled. The Mauch Chunk-Pottsville clastic wedge has a roughly semicircular outline centered on the Pennsylvania salient (Fig. 8); however, a relatively thick tongue extends southwestward along strike into the Virginia recess. Facies distribution indicates sediment dispersal from the evolving orogenic belt on the east. Detrital-zircon populations document sediment from a diverse orogen, including a dominant contribution from Grenville basement rocks in the external massifs, as well as substantial contributions from Taconic and Acadian synorogenic crystalline rocks; less common contributions are from recycling of zircons from Mesoproterozoic and older Laurentian craton provinces in Iapetan synrift sedimentary rocks (Thomas et al., 2017). Relatively few zircons represent Peri-Gondwanan and Gondwanan accreted terranes. Remarkably, zircon grains from Alleghanian synorogenic igneous rocks are very rare in the Alleghanian synorogenic clastic wedge, even though tonsteins in Pennsylvanian coal beds have both stratigraphic ages and zircon ages that document Alleghanian volcanism (Thomas et al., 2017, and references therein). The initial progradation of Mauch Chunk siliciclastic detritus over the Late Mississippian shallow-marine carbonates indicates an age of ~331 Ma for the initiation of clastic sediment dispersal from the Alleghanian orogen, suggesting the approximate time of beginning of the orogeny in the Pennsylvania salient.

In the Tennessee salient, the Pennington-Lee clastic wedge (Thomas, 1977; Thomas in Hatcher et al., 1989) began with generally fine-grained siliciclastic deposits in shallow-marine environments, and the Mississippian part of the clastic wedge grades upward to maroon and gray muddy deposits that are generally thinner than the Mississippian part of the Mauch Chunk-Pottsville clastic wedge. The finer grained siliciclastic succession grades upward into an array of laterally discontinuous, massive, quartzose sandstones and quartz-pebble conglomerates in the Lower Pennsylvanian (Lee and related sandstones). The stratigraphically higher succession of Middle Pennsylvanian to Lower Permian includes coal-bearing cyclothems, as well as some redbeds. Like the Mauch Chunk-Pottsville clastic wedge, the Pennington-Lee clastic wedge represents a generally filled, long-wavelength:low-amplitude foreland basin. The clastic wedge is centered on the Tennessee salient (Fig. 8), but the Pennsylvanian part of the Pennington-Lee clastic wedge prograded far to the north along strike of the frontal structures of the Pennsylvania salient (Thomas et al., 2017). The Pennington-Lee clastic wedge prograded southwestward over the Mississippian carbonates in the Alabama recess (Thomas, 1977). As in the Mauch Chunk-Pottsville clastic wedge, facies distribution in the Pennington-Lee clastic wedge indicates sediment dispersal from the evolving orogenic belt on the east. Detrital-zircon populations are indistinguishable from those in the Mauch Chunk-Pottsville clastic wedge, dominantly from Grenville basement rocks in the external massifs and substantially from Taconic and Acadian synorogenic crystalline rocks, and less commonly recycled from synrift and passive-margin strata that contain older grains from Laurentian craton provinces and from Gondwanan accreted terranes (Thomas et al., 2017). As in the Mauch Chunk-Pottsville clastic wedge, zircon grains from Alleghanian synorogenic igneous rocks are very rare. The initial progradation and interfingering of Greasy Cove siliciclastic detritus over the Late Mississippian shallow-marine carbonates (Thomas, in Hatcher et al., 1989) indicates an age of ~326 Ma for the initiation of clastic sediment dispersal from the Alleghanian orogen, suggesting the approximate beginning of the orogeny in the Tennessee salient (slightly younger than in the Pennsylvania salient).

Sedimentary Thrust Belt in the Appalachians

The sedimentary thrust belt in the Pennsylvanian salient has a regional décollement below the Cambrian-Ordovician massive carbonate, as well as two prominent upper-level detachments in the Upper Ordovician-Middle Silurian (Taconic) clastic wedge, which includes evaporites, and in the Upper Devonian (Acadian) clastic wedge and more local detachments at other levels within the clastic wedges (Wiltschko and Geiser, in Hatcher et al., 1989). Generally, the detachment ramps upward toward the foreland, leaving the Cambrian-Ordovician carbonates in the footwall in the leading thrust sheets; however, a large-scale brittle duplex accommodated substantial shortening in the massive carbonates in the trailing thrust sheets. The frontal ramps of the upper-level detachments are broadly curved around the salient. The arcuate trace of the thrust front curves around the Pennsylvania salient, where the thrust belt includes numerous frontal ramps. The frontal structures end along strike at lateral ramps, so that the thrust front curves more abruptly than the curvature of strike of the frontal ramps. The overall effect is the along-strike narrowing of the thrust belt from the Pennsylvania salient into the New York recess on the northeast and the Virginia recess on the southwest (Fig. 1B); correspondingly, the salient has a larger number of large-scale frontal thrust ramps than do the recesses. The greater cratonward extent of the thrust belt corresponds to the extent of thicker clastic wedges in the salient, resulting from the availability of more potential stratigraphic levels of detachment (Thomas, 1977).

The Virginia recess has relatively few frontal ramps, which rise from the regional décollement and cut through the stratigraphic succession to the surface. Unlike the broad curves in strike around the Pennsylvania salient, some thrust-belt structures trending south-southwest from the apex of the Pennsylvania salient intersect structures trending east-northeast in the Virginia recess. The recess is formed by an angular bend in strike.

Broadly curved structures outline the Tennessee salient. In general, the Tennessee salient has large-scale frontal ramps that rise from the regional décollement beneath the Cambrian-Ordovician carbonate to the present erosion surface (Wiltschko, in Hatcher et al., 1989). The most frontal structure in the northern arc of the salient, the Pine Mountain thrust sheet and frontal ramp, is detached in Devonian shale in the most distal part of the Acadian clastic wedge, loosely mimicking the rise in detachment level toward the foreland in the Pennsylvania salient. The Pine Mountain thrust sheet ends along strike in both directions, where transverse faults transfer displacement to trailing structures (Wiltschko, in Hatcher et al., 1989). To the southwest along projected strike from the southwest end of the Pine Mountain thrust, the Sequatchie anticline, which is a long narrow fault-tip fold, plunges northeastward and ends, exposing the frontal ramp. The basal décollement ramps upward into the Lower Pennsylvanian coal-bearing clastic wedge as the small-displacement Cumberland Plateau overthrust, which crops out on the west and is traceable southward to the Alabama-Tennessee border (Hardeman, 1966; Harris and Milici, 1977). In a pattern characteristic of other salients, the Tennessee salient includes a larger number of frontal thrust ramps than do either the Virginia recess or Alabama recess, to the northeast and southwest, respectively.

The Alabama recess is a composite bend in regional structure, extending ~400 km along strike from northwestern Georgia, across Alabama, and beneath the cover of the Gulf Coastal Plain into east-central Mississippi (Thomas, 1973; Thomas and Bayona, 2005). In the trailing thrust-belt structures in northwestern Georgia, strike bends gradually around the southern arm of the Tennessee salient; southward from the Tennessee-Georgia state line, strike is north-south. At Cartersville, Georgia, the south-striking structures, including a large duplex of Lower Cambrian clastic and carbonate rocks, intersect west-southwest striking thrust faults that extend westward and curve to southwest strike in Alabama (Fig. 1B) (Thomas and Bayona, 2005). In contrast, the nearly straight frontal structure, the Sequatchie anticline, is tangent to strike in the apex of the Tennessee salient and extends southwest along the thrust front in Alabama. The different structural orientations leave a triangular space between the frontal and trailing structures in Georgia, where sets of interference folds form the roof of a mushwad (a tectonically thickened mass of weak rocks between a floor thrust and roof, defined as Malleable, Unctuous SHale, Weak-layer Accretion in a Ductile duplex; W. A. Thomas, 2001) of Cambrian shale (Cook and Thomas, 2010). Across strike, the thrust belt in the Alabama recess generally contains only five large-scale frontal ramps that rise from the regional décollement below the Cambrian-Ordovician carbonates; however, that thrust belt contains some unusual structures. Four distinct transverse zones, each marked by along-strike changes in each of the large-scale thrust-belt structures, cross the entire thrust belt (Thomas, 1990). The Straight Mountain fault/Murphrees Valley anticline is perhaps the largest scale backthrust in the entire Appalachian thrust belt, but it ends along strike in both directions at lateral ramps along two of the transverse zones. In the central part of the thrust belt, the Coosa deformed belt consists of multiple imbricate thrusts sheets from an upper-level detachment near the top of the Cambrian-Ordovician carbonate, the regional stiff layer. The Cambrian shale-dominated units stratigraphically beneath the carbonate stiff layer vary regionally in facies and thickness as the mud-dominated fill of synsedimentary grabens and the coeval carbonate on horst blocks (Thomas et al., 2000). The thrust sheets that originated over the thick shale deposits in the grabens form the roof of a ductile duplex, a mushwad, in which bulk ductile deformation tectonically thickened the shale and nonsystematically uplifted the roof (W. A. Thomas, 2001). Where décollement-host shale units are thin, the propagation of thrusting is confined, but where the shale units are thick in the synsedimentary grabens, the propagation of thrusting progressively incorporated shale into a detachment fold which expanded nonsystematically. Ultimately, the detachment ramped up over the basement fault that bounds the graben, leading to a frontal ramp at the leading edge of the mushwad. Along the trailing edge of the sedimentary thrust belt, the Talladega thrust sheet contains a low-grade sedimentary succession that includes the thick Cambrian-Ordovician carbonate succession and some other components that are comparable to those in the sedimentary thrust belt; however, the upper part of the Talladega succession is unlike the coeval strata in the thrust belt.

External Basement Massifs in the Southern-Central Appalachians

Scattered along strike of the trailing edge of the sedimentary thrust belt, basement-rooted thrust sheets include the Corbin-Salem Church structures on the Alabama promontory; the Ravens Ford anticline in the Great Smoky Mountains in North Carolina; the Holston-Iron Mountain-Stone Mountain thrust sheet in northeastern Tennessee, western North Carolina, and southwestern Virginia with small chips to extensive sheets of basement rocks; the Blue Ridge (French Broad and Shenandoah massifs) across the Virginia promontory (and south into the Tennessee embayment); the Reading Prong, Honey Brook uplift and Trenton Prong across the corner of the New York promontory (and along the northern edge of the Pennsylvania embayment); the Hudson and Housatonic massifs along the New York promontory; and the Berkshire, Green Mountain, Lincoln Mountain, and Long Range massifs farther north. Unlike the components of the sedimentary thrust belt, the external basement massifs include basement rocks in the hanging walls of the thrust faults; however, the geometry of the faults is like that in the thrust belt, including, for example, frontal ramps and ramp anticlines. In addition to basement rocks, parts of the massifs have sedimentary cover rocks. In the Shenandoah (Blue Ridge) massif (Bartholomew and Lewis, 1984) and the other massifs farther north, the cover strata consist of a basal quartz sandstone and overlying carbonate, indicating passive-margin transgression over an erosion surface on Mesoproterozoic basement rocks. The structurally high position of the top of basement rocks in the rift-to-passive-margin transition indicates an upper-plate setting on a low-angle detachment (Thomas, 1993). In contrast, the French Broad massif (in the Tennessee embayment), as well as the Corbin-Salem Church massif, has a cover of very thick synrift coarse siliciclastic rocks, which are interpreted to be the fill of extensional half grabens on the lower plate of a low-angle detachment fault related to Iapetan rifting. The thick graben-fill accumulations end abruptly northeastward along strike at the Virginia-Tennessee transform of the rifted margin (Thomas, 1991).

Accreted Laurentian Margin Rocks in the Appalachians

The rifted-margin succession was deposited along the Iapetan margin starting around 750 Ma in an array of proximal rift basins where the Neoproterozoic succession ranges from lacking to a very thin succession on the promontories to as much as 15 km in the Ocoee basin (e.g., King, 1964; Rast and Kohles, 1986), to distal dominantly deep-water clastic facies and mafic volcanic rocks (continental slope and rise) deposited on ocean crust and rifted fragments of continental crust. They consist of the Ashland-Wedowee Group (Alabama), Sandy Springs and Tallulah Falls-Ashe Formation (Georgia through North Carolina), and Lynchburg Group (Virginia). The distal sequences are polydeformed and metamorphosed to medium- to high-grade assemblages (Merschat et al., 2017) and contain highly deformed and dismembered ophiolites (e.g., Hatcher et al., 1984; Swanson et al., 2005) in addition to Ordovician through Mississippian granitoid plutons.

In addition to the proximal and distal rifted margin successions deposited in the Laurentian realm, several small tectonostratigraphic terranes in the western half of the southern and central Appalachians include the Dahlonega gold belt, Cowrock, Cartoogechaye, Cat Square, Milton-Chopawamsic-Potomac, and Westminster terranes (Fig. 1B). Cat Square terrane is a unique assemblage of migmatitic metasedimentary, and felsic and mafic plutonic rocks; it contains zircons from Laurentian sources, as well as from Peri-Gondwanan sources (most likely Carolina). Each of these assemblages contrasts with those of the surrounding terranes, with variations in sedimentary sequences and presence or absence of mafic and ultramafic rocks. All but the Cat Square were accreted during the Taconic orogeny, whereas Cat Square was accreted between Taconian Laurentian terranes and Carolina during the Acadian-Neoacadian orogeny.

Internal Basement Massifs in the Appalachians

The internal basement massifs have basement and cover rocks similar to those in the external basement massifs. Unlike the brittle thrust deformation in the external basement massifs, basement in the internal basement massifs was remobilized, and the cover rocks were infolded with the basement rocks and metamorphosed. The internal basement massifs are scattered along the orogen—Pine Mountain massif on the Alabama promontory; Tallulah Falls and Toxaway domes in the Tennessee embayment; Sauratown

Mountains on the corner of the Virginia promontory; Baltimore domes in the Pennsylvania embayment; Avondale-Woodville structures, Manhattan Prong, and Chester dome along the New York promontory; as well as some other smaller inliers of remobilized basement rocks. The metasedimentary cover on some of the internal basement massifs consists of quartzite and marble, suggesting transgressive passive-margin deposits.

Alleghanian High-Grade and Plutonic Rocks

Coeval with or slightly younger than Alleghanian deposition of sediments in internal basins like the Narragansett basin in Rhode Island, amphibolite-facies metamorphism, polyphase deformation, and plutonism are recorded in an antiformal belt along the Coastal Plain overlap from Virginia to Alabama, variously called the Goochland terrane-Raleigh belt, Kiokee belt, and Pine Mountain terrane. An Alleghanian thermal event is also recorded across much of the Tugaloo and Cat Square terranes in the southern Appalachians (Dennis and Wright, 1997; Merschat et al., 2005).

Southern Appalachian Alleghanian plutons are largely peraluminous, S-type granites with ages ranging from 330 to 300 Ma (Sinha and Zeitz, 1982; Samson et al., 1995; Coler et al., 2000), and a suite of Alleghanian gabbros with ages ranging from 302 to 311 Ma in the Carolina superterrane in the Carolinas (Huebner and Hatcher, 2017). These plutons are also in the Kiokee belt and Goochland terrrane/Raleigh belt metamorphic core, extending from Virginia to South Carolina, and Carolina superterrane, into the Inner Piedmont in the Atlanta region and in the eastern Blue Ridge as the Rabun, Round Mountain, and Looking Glass granites (Mueller et al., 2011; Stahr, 2007).

Kinematics of Alleghanian Deformation

LeFort and Van der Voo (1981) and LeFort (1984) suggested that the Reguibat promontory in West Africa collided with Laurentia in the Pennsylvania embayment before collision of the main African continent in order to explain abupt narrowing of the southern Appalachian internides into the central Appalachians and widening again into New England (Fig. 10). They concluded that collision of the promontory produced an escape tectonics scenario where dextral faults facilitated southward escape of crustal blocks and sinistral faults carried blocks northward out of the collision zone. The movement sense of the array of Alleghanian faults south of the projected collision zone, including the Brevard, parts of the central Piedmont suture, and all of the eastern Piedmont fault system, is clearly dextral; but the movement sense of faults north of the collision zone, including the Clinton-Newbury, Bloody Bluff, and all of those farther north, is also dextral (e.g., Bothner and Hussey, 1999; Goldstein and Hepburn, 1999). On the basis of the ages of stratigraphic sequences and fault kinematics, Hatcher (2002) and Hatcher et al. (2007c) proposed that the collision involved both rotation and transpression, and that collision began at the northeastern end of the Appalachians and closed the Theic Ocean southward like closing a zipper (Figs. 9 and 10). In this scenario, Gondwana would have rotated into head-on collision with southeastern Laurentia in Pennsylvanian to Permian time, producing the Blue Ridge-Piedmont megathrust sheet that pushed foreland deformation in front of it from southern New York to Alabama (Hatcher, 2002). The zipper tectonics scenario fits more of the data related to the tectonostratigraphic and kinematic closing of the Theic ocean and final assembly of Pangea than others.

The Blue Ridge-Piedmont thrust sheet is the product of late Mississippian to Permian collision of Africa with Laurentia (Fig. 11). The thrust sheet moved some 400 km into the interior of Laurentia carrying all of the Laurentian margian and earlier Taconian and Acadian-Neoacadian terranes as a cold basement block that detached from its Paleozoic crust likely along the late Paleozoic brittle-ductile transition (Hatcher et al., 2007b). As the allochthonous sheet moved toward the interior of the continent, it pushed the previously undeformed foreland in front of it like a snowplow, producing a series of rootless thrust faults and folds that verge toward the continental interior and above a detachment dominantly in a basal weak unit, the Rome-Waynesboro Formation that underlies the strong, massive carbonate unit above it (e.g., Rodgers, 1953; Thomas and Bayona, 2005; Hatcher et al., 2007b). Displacement on the Blue Ridge-Piedmont megathrust indenter reaches an estimated maximum of 400 km in the Tennessee embayment producing correspondingly large ($\sim$100 km maximum displacement thrusts totaling $\sim$400 km) incremented displacements in the foreland fold-thrust belt (Fig. 11).

Shortening in the foreland fold-thrust belt is estimated to be 54% in the Tennessee embayment, decreasing to 46% in Alabama to the southwest and 47% to the northeast into Virginia (Thomas and Bayona, 2005). Similar maximum shortening would be reached in the Pennsylvania embayment, and would decrease systematically toward the promontories to the northeast and southwest (Hatcher et al., 1989).

During the early stages of transpressional collision, numerous dextral strike-slip faults formed from the already weak Brevard fault eastward and displaced segments of the Carolina superterrane by varying amounts, perhaps the greatest of which is the emplacement of the Goochland terrane in the southern Appalachians from the northern tip of the central Appalachians (Fig. 1B; Bartholomew and Tollo, 2004). Movement of the Goochland terrane southward also helps account for the narrowing of the Appalachians toward the north end of the central Appalachians.

The Brevard fault in the western Inner Piedmont forms the western limit of the domain of Alleghanian dextral faulting (Fig. 1B). It has an early (pre-Alleghanian, Acadian Neoacadian) history of dextral movement at high temperatures as it formed the western boundary of the proposed tectonically driven orogenic channel that comprises the Inner Piedmont (Merschat et al., 2005; Hatcher and Merschat, 2006). It underwent renewed dextral movement during the Allaghanian orogeny at $\sim$280 Ma (Rb/Sr, Sinha et al., 1988) as part of the movement picture in the eastern Piedmont fault system, and was later reactivated again during the Mid- to Late Permian as a westward vergent out-of-sequence thrust, possibly during movement of the Blue Ridge-Piedmont thrust sheet. The last

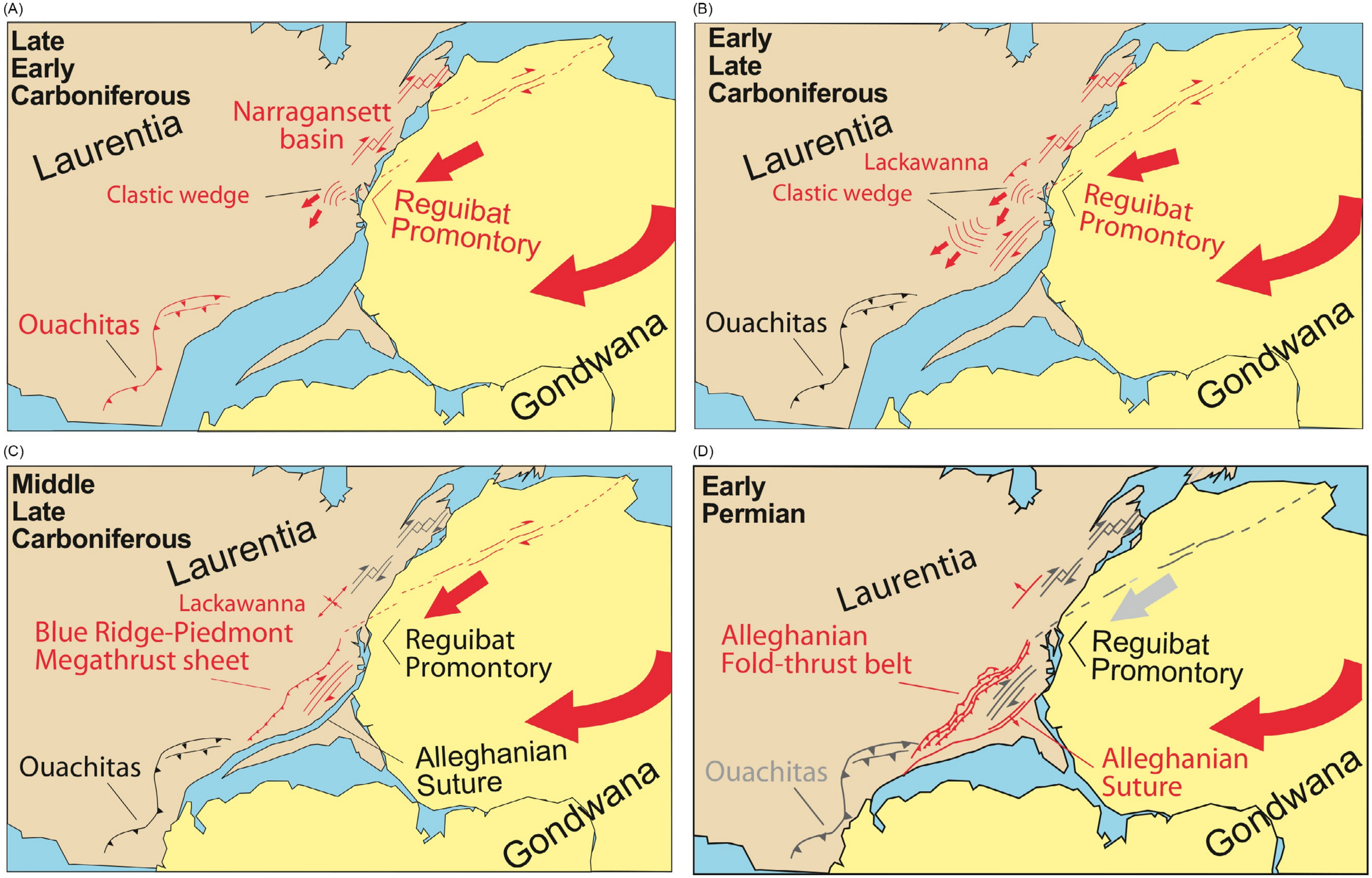


Fig. 10 Zipper closing of Theic ocean to form the Alleghanian orogen (continents are shown on Robinson projection; reconstruction modified from that in Ziegler, 1990). Red lines and symbols indicate feature is active in the time interval shown. (A) Initial contact between Gondwana and Laurentia occurred in late Early Carboniferous (late Mississippian), producing initially sinistral faulting in New England followed immediately by dextral motion and pull-apart basins, then shedding of clastic sediments onto the continent, and Lackawanna-phase deformation. (B) Southward movement and rotation of Gondwana with respect to Laurentia in early Late Carboniferous (early Pennsylvanian) produced dextral motion throughout orogen, waning of Lackawanna phase deformation, and greater dispersal of sediments onto the Laurentian foreland. (C) Continued clockwise rotation of Gondwana with respect to Laurentia during the Late Carboniferous closed the Theic ocean southward, bringing Gondwana into head-on collision with Laurentia, and producing the first movement on the Blue Ridge-Piedmont megathrust sheet. (D) Early Permian head-on collision of Gondwana with Laurentia produced major transport on Blue Ridge-Piedmont megathrust sheet that drove foreland fold-thrust belt deformation (Valley and Ridge and Plateau) ahead of it. From Hatcher RD Jr. (2010) The Appalachian orogen: A brief summary. In: Tollo RP, Bartholomew MJ, Hibbard JP, and Karabinos P (eds.) *From Rodinia to Pangea: The Lithotectonic Record of the Appalachian Region*, pp. 1–19. Boulder, Colorado: Geological Society of America. Memoir 206.

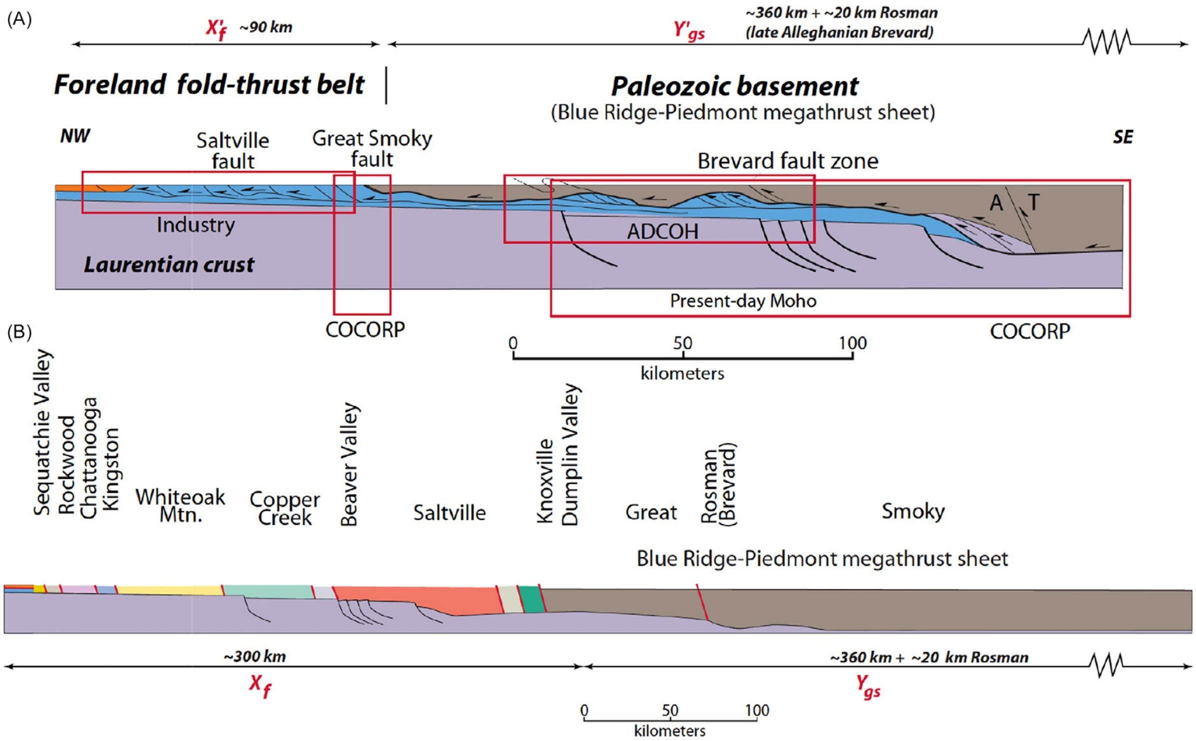


Fig. 11 Restoration of the Blue Ridge-Piedmont section. (A) Unrestored section showing locations of seismic reflection data (red boxes indicate sources of data) employed for construction of the section. X_f' is deformed width of the foreland fold-thrust belt; Y_{gs}' is the deformed width of the Great Smoky (BRP) thrust sheet. Geographic coordinates for the northwest end of this section are: 36.07886°N, −84.809429°W; those for the southeast end of the section are: 32.145092°N, −80.900385°W. (B) Restored sections cartoon constructed by pulling apart the foreland thrusts and placing tectonic units end to end according to estimated displacements, but without respect to geometry, with the BRP thrust sheet shown intact. X_f is undeformed width of the foreland fold-thrust belt; Y_{gs} is the undeformed width of the BRP thrust sheet. From Hatcher RD Jr., Bream BR, and Merschat AJ (2007a) Tectonic map of the southern and Central Appalachians, USA. In: Hatcher RD Jr., Carlson MP, McBride JH, and Martínez Catalán JR (eds.) *The 4-D Framework of Continental Crust*, Memoir 200, pp. 595–632. Boulder, CO: Geological Society of America; Hatcher RD Jr., Bream BR, and Merschat AJ (2007b) Tectonic map of the southern and Central Appalachians, USA, Plate 1. In: Hatcher RD Jr., Carlson MP, McBride JH, and Martínez Catalán JR (eds.) *The 4-D Framework of Continental Crust, Scale 1:2,000,000*, Memoir, 200. Boulder, CO: Geological Society of America; Hatcher RD Jr., Lemiszki PJ, and Whisner JB (2007c) Character of rigid boundaries and internal deformation of the southern Appalachian foreland fold-thrust belt. In: Sears JW, Harms TA, and Evenchick CA (eds.) *Whence the Mountains? Inquiries Into the Evolution of Orogenic Systems: A Volume in Honor of Raymond A*, pp. 243–276. Boulder, CO: Geological Society of America. Price Special Paper 433. their Figure 13.

movement event brought up thrust horses of platform carbonate rocks from the overidden footwall (Hatcher et al., 2017). Horses of Carolina superterrane rocks in the Brevard fault zone suggest that Carolina was emplaced above the Inner Piedmont (and easternmost Blue Ridge) during emplacement of the earlier transpressional horses of crystalline rocks as part of the postulated orogenic channel forming a suprastructure above the Inner Piedmont infrastructure (Hatcher et al., 2017).

A system of dextral faults frames pull-apart fault basins across Maritime Canada, extending from Newfoundland to Rhode Island (Thomas and Schenk, 1988; van de Poll et al., 1995; Williams, 1995). The sedimentary fill varies from basin to basin; the total range of age of sedimentary fill is Devonian to Permian. Some magmas were implaced along the system of faults. Farther south, an array of dextral faults extends from Virginia to Alabama, comprising the Eastern Piedmont fault system in the Carolina superterrane part of the eastern Inner Piedmont in Georgia and Alabama (Hatcher et al., 1977). The dextral fault system extends southward beneath the Coastal Plain and continental shelf into the Brunswick (Charleston) terrane, where it is truncated by the dextral Suwannee-Wiggins suture (Fig. 1B). All of these dextral faults may constitute a continuous system of southward motion of outboard terranes along the margin of Laurentia, and the timing would extend from the Acadian through the Alleghanian orogenies.

The Ouachita-Marathon Orogenic Belt: The Southwestward Extension of the Appalachian Orogen

The Appalachian orogen is expressed as the physiographic Appalachian Mountains across the eastern United States southwestward from the Canadian border in Maine to Alabama, where the Paleozoic orogenic belt passes beneath the Mesozoic-Cenozoic cover of the Gulf Coastal Plain. The onlap edge of the cover strata covers the internal metamorphic belts in eastern Alabama and adjacent Georgia, crosses the foreland sedimentary thrust belt, and extends northward on the eastern side of the Mississippi Embayment of

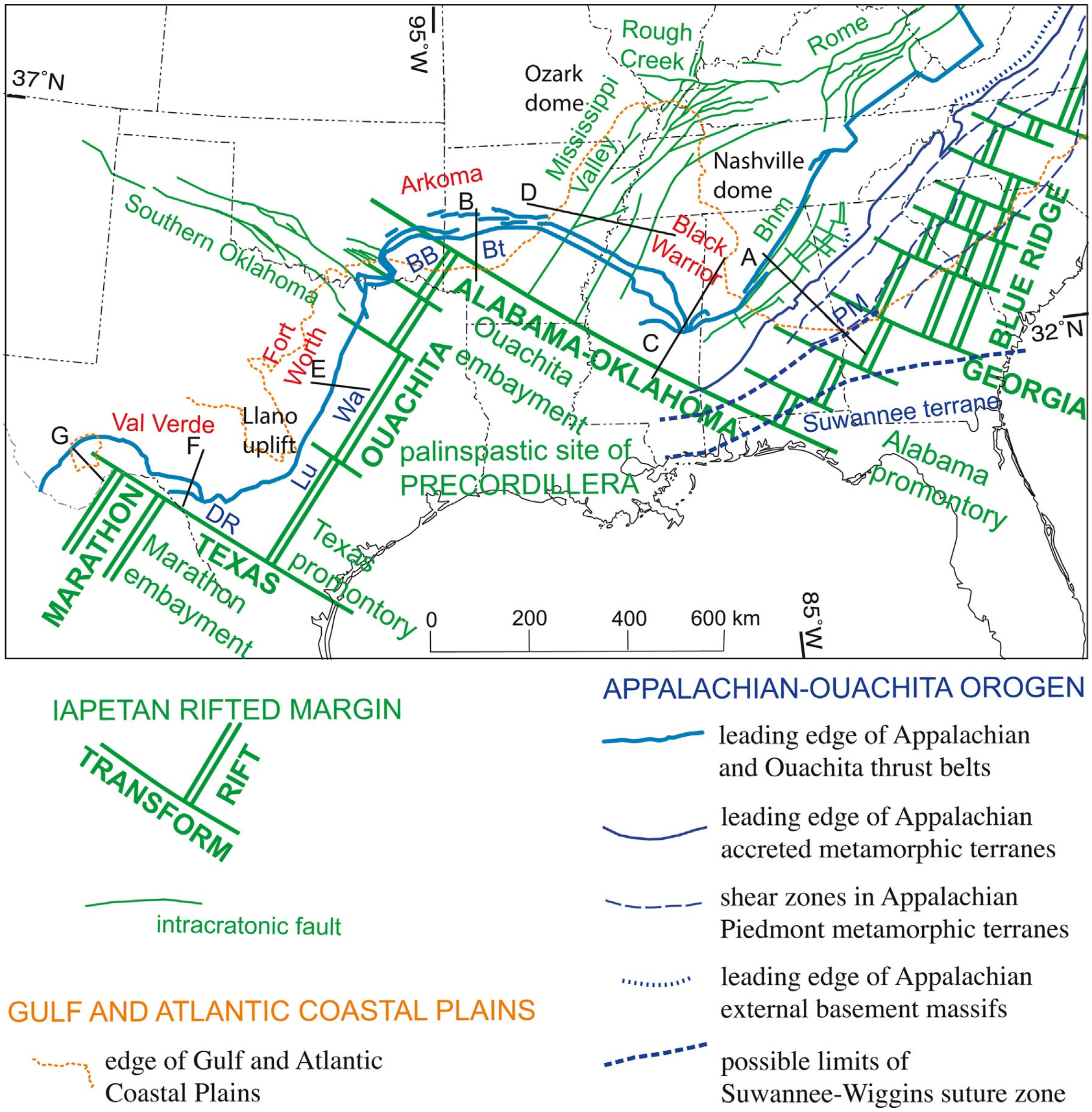


Fig. 12 Outline map of leading edge of Appalachian-Ouachita thrust belt and on-lap limits of the cover sediment of the Gulf and Atlantic Coastal Plains. The Iapetan rifted margin of Laurentia is shown with green lines and labels. The pre-rift palinspastic location of the Argentine Precordillera terrane is shown within the Ouachita embayment of the rifted margin of Laurentia (Thomas and Astini, 1996). Intracratonic basement fault systems are labeled in green letters, abbreviation: Bhm—Birmingham graben. Locations of Ouachita-Appalachian basement uplifts (thrust-ramp anticlines) are shown by abbreviations in blue letters: DR—Devils River uplift, Lu—Luling uplift, Wa—Waco uplift, BB—Broken Bow uplift, Bt—Benton uplift, and PM—Pine Mountain internal basement massif. Locations of Ouachita-Appalachian late Paleozoic synorogenic foreland basins are shown by names in red letters. Locations of intracratonic basement domes are shown by names in black letters. Black line labeled B shows location of cross section in Fig. 13; other cross sections shown by black lines are in Thomas (2011). From Thomas WA (2011) The Iapetan rifted margin of southern Laurentia. *Geosphere* 7: 97–120.

the Gulf Coastal Plain over the undeformed foreland in northwestern Alabama (Fig. 12). From western Alabama, across Mississippi, and into eastern Arkansas, post-orogenic cover conceals the Paleozoic orogenic belt. In central Arkansas, however, the late Paleozoic sedimentary thrust belt emerges in the Ouachita Mountains from beneath the Gulf Coastal Plain (Fig. 12). The exposed thrust belt in the Ouachita Mountains strikes approximately east-west in Arkansas, but bends abruptly to the south in Oklahoma, and passes back beneath the Coastal Plain. Beneath the Gulf Coastal Plain in Texas, a bend around the Texas recess leads westward to relatively small areas of outcrop of the thrust belt in the Marathon salient of western Texas, near the Big Bend of the Rio Grande (Fig. 12).

The exposed Appalachian thrust belt in Alabama differs significantly from the exposed Ouachita thrust belt in Arkansas and Oklahoma in both structural style and stratigraphic level of detachment, providing a distinction that can be recognized in drill samples between the outcrops (Thomas, 1972a, 1973, 1989). In the Appalachian thrust belt, the décollement is in Cambrian shale-dominated strata below a massive Cambrian-Ordovician passive-margin shelf-carbonate unit that controls the geometry of long frontal ramps and distinct lateral ramps. In contrast, in the Ouachita thrust belt, the regional detachment is in an off-shelf deep-water mud-dominated passive-margin succession with some chert and an overlying thick succession of muddy and sandy turbidites, which have been thrust over the passive-margin shelf-carbonate facies. In the absence of a dominant stiff layer, small-scale disharmonic folds and thrust faults characterize Ouachita structure. The thick massive carbonates in contrast to the thick mud-dominated succession distinguish the Appalachian and Ouachita thrust sheets, respectively, in drill samples and enable tracing of the two thrust systems in the subsurface (King, 1961; Thomas, 1973, 1985, 1989).

The distinctive drill samples, supplemented by seismic reflection profiles, document the trace of the Ouachita thrust front from easterly strike passing under the Gulf Coastal Plain in Arkansas, through a large-scale curve, into southeasterly strike in the subsurface in eastern Mississippi (Thomas, 1973, 1989; Thomas et al., 1989a). From the other direction, the massive carbonate thrust sheets of the Appalachians can be traced southwestward beneath the Gulf Coastal Plain in western Alabama and into a westerly curve in eastern Mississippi. In eastern Mississippi, the west-southwest-striking Appalachian thrust front truncates the south-southeast-striking Ouachita structures, clearly indicating the sequence of thrusting (Fig. 12).

The Ouachita and Appalachian orogens also differ in overall tectonic history. The Appalachians include distinct events (traditionally the Taconic, Acadian, and Alleghanian orogenies) that span the time from the Middle Ordovician to the Permian. In contrast, a passive margin persisted along the Ouachita-Marathon margin until Mississippian time, when diachronous synorogenic sedimentary deposits first prograded onto the deep-water passive-margin mud and chert succession that characterizes the earlier Paleozoic record (Thomas, 1972a, 1976, 1989; Viele and Thomas, 1989).

The Black Warrior foreland basin is within the nearly orthogonal intersection of the Ouachita and Appalachian thrust belts, and appears to be in the orogenic foreland of both (Fig. 12) (Thomas, 1988; Whiting and Thomas, 1994; Thomas and Whiting, 1995). Both the top of crystalline basement rocks and the overlying Paleozoic strata in the Black Warrior basin dip southwestward beneath the Ouachita thrust front, and the bedding strike is approximately perpendicular to the Appalachian thrust front. Basement normal faults that are dominantly down-to-southwest parallel bedding strike in the basin. Synorogenic sedimentary facies show that the Black Warrior is an Ouachita foreland basin (Thomas, 1972a, 1988, 1995; Thomas, in Hatcher et al., 1989). On the east in Alabama, the Mississippian System includes two successive southwestward deepening and thinning carbonate ramps that are overlapped by northeast-thinning and down-lapping clastic tongues, which pinch out northeastward into the carbonate facies (Thomas, 1988; Mars and Thomas, 1999). Northwest strike of massive ooid grainstones at the top of the upper ramp parallels the structural strike of the basin (Thomas, 1972b). The lower part of the Lower Pennsylvanian has three distinct, laterally related facies (Thomas, 1988, 1995). On the southwest in the deeper part of the basin, seven successive fining-upward delta-front parasequences with abrupt bases have basal sandstones with some quartz pebbles. The delta-front facies pass eastward into a mud-dominated lagoonal facies, which is bordered on the east by massive barrier-island sandstones. The facies transitions along the delta-front and barrier systems trend roughly north-northwest, indicating delta progradation from the southwest and barrier reworking along the delta front. The upper part of the Lower Pennsylvanian is a cyclic succession that includes coal beds, as well as marine fossiliferous shales. The Mississippian-Pennsylvanian strata in the deep trailing synclines in the Appalachian thrust belt display the same facies as those in the Black Warrior basin (Thomas, 1995). Relatively thick Mississippian limestones on the northeast give way to clastic facies southwestward along structural strike of the Appalachian synclines. Pennsylvanian facies are dominated by the massive barrier-island sandstones and the overlying coal-bearing succession. In effect, the exposed up-turned beds along the Appalachian frontal thrust ramps provide cross-sectional views perpendicular to the stratigraphic strike of the Ouachita foreland facies in the Greater Black Warrior basin (defined as the present structural basin in the foreland plus the Ouachita foreland strata in the Appalachian thrust belt). The match of Mississippian-Pennsylvanian facies indicates that the Greater Black Warrior basin in the Ouachita foreland extended across the palinspastic location of the Appalachian thrust sheets, and that Appalachian thrusting imbricated the southeastern part of the Greater Black Warrior basin, further documenting that Ouachita thrusting, tectonic loading, and flexural subsidence of the foreland basin preceded Appalachian thrusting (Thomas, 1989, 1995; Whiting and Thomas, 1994; Thomas and Whiting, 1995; Thomas and Bayona, 2005).

The Ouachita thrust front, along the southwestern trailing side of the Greater Black Warrior basin, is marked by a large-scale frontal thrust ramp, rising northeastward over a system of down-to-southwest basement normal faults that complement down-to-southwest flexural subsidence of the foreland basin (Whiting and Thomas, 1994). The frontal thrust sheets imbricate a thick, Mississippian-Pennsylvanian sandstone-shale succession. Southwest of the frontal thrust belt, drill holes penetrated silty shale that has distinct cleavage and contains vein quartz (Thomas, 1973, 1989). These characteristics are shared with the deformed off-shelf facies exposed in the central Ouachita thrust belt in Arkansas. The distribution of slaty rocks and quartz veins defines a structural boundary that extends from the deep subsurface in Mississippi to the outcrops in Arkansas.

The outcrops in the Ouachita Mountains of Arkansas and Oklahoma provide the largest view of the orogenic belt (Arbenz, 1989, 2008; Viele and Thomas, 1989), and the subsurface south of the outcrops has been explored by seismic velocity and gravity modeling in addition to the many deep exploration drill holes (Keller et al., 1989a; Mickus and Keller, 1992; Thomas, 2011). A comprehensive profile of the orogenic belt includes, in the outcrops north of the Gulf Coastal Plain, the Arkoma foreland basin on the northwest; the frontal thrust belt with thrust sheets of Mississippian-Pennsylvanian synorogenic turbidites; the Maumelle chaotic zone of broken Mississippian-Pennsylvanian sandstone and shale; the central Benton uplift with disharmonic thrust sheets of Cambrian-Mississippian off-shelf passive-margin mudstones, cherts, and less common sandstones; rare slivers of tectonically bounded ultramafic rocks; and a trailing thrust belt with imbricated Mississippian-Pennsylvanian turbidites (Fig. 13) (Viele and Thomas, 1989). To the south, beneath the Gulf Coastal Plain, seismic velocity and gravity models document an abrupt southern margin of Laurentian thick continental crust along the Alabama-Oklahoma transform fault of the Iapetan rifted margin (Keller et al.,

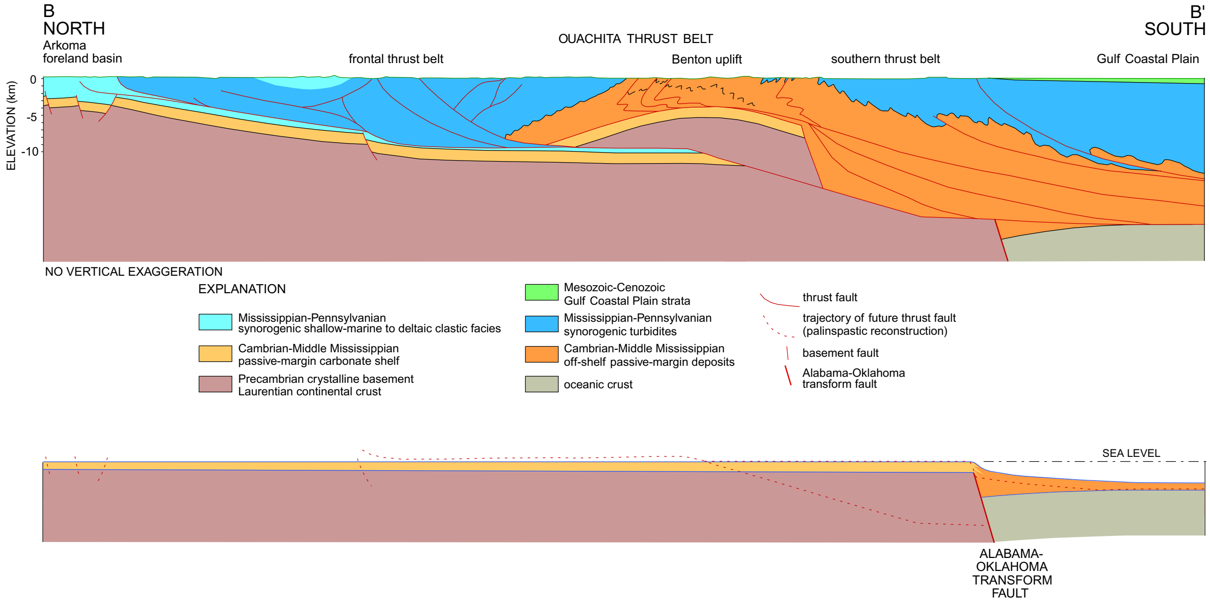


Fig. 13 Structural cross section of Ouachita thrust belt and palinspastic restoration. The location of the cross section is shown by the black line labeled B in Fig. 12. Large-scale northwest-translated thrust faults dominate the structure of the Ouachita thrust belt, but the frontal thrust belt includes a large-scale triangle zone. A late-stage basement-rooted thrust fault inserted a tectonic wedge of basement rocks beneath the sedimentary thrust belt, producing the Benton uplift and southeast-verging folds in the overlying thrust sheets. From Thomas WA (2011) The Iapetan rifted margin of southern Laurentia. *Geosphere* 7: 97–120.

1989a; Mickus and Keller, 1992). South of the transform fault, a thick mass of deformed sedimentary rocks overlies thin transitional or oceanic crust that extends about 100 km south from the transform fault. Farther south, a separate mass of continental crust constitutes the Sabine accreted terrane (Figs. 1A and 14) (Keller et al., 1989a). No drill holes have penetrated the continental basement rocks on the Sabine terrane, so that the precise composition and affinities of the terrane are not confirmed. Drill holes have penetrated volcanic rocks incorporated in the thick mass of deformed Pennsylvanian sedimentary rocks along the northern edge of the Sabine terrane, suggesting a continental-margin arc (Nicholas and Waddell, 1989).

A comprehensive tectonic interpretation of the late Paleozoic Ouachita orogen includes southward subduction of the Laurentian margin and associated pre-orogenic sedimentary rocks beneath a plate that carried the Sabine terrane on the leading edge (Fig. 14) (Houseknecht, 1986; Viele and Thomas, 1989). The Cambrian-Mississippian pre-orogenic passive-margin deposits include a massive carbonate shelf facies on continental crust and a coeval off-shelf succession of siliciclastic mud, carbonate mud, carbonate boulder beds, and sandstone with rare basement boulders, all capped by the extensive chert of the Devonian-Mississippian Arkansas Novaculite (Arbenz, 1989). The relatively thin clastic units and extensive chert indicate low depositional rates off the shelf along the passive margin. Beginning in the Middle Mississippian (middle Meramecian), depositional rates increased abruptly as indicated by the very thick accumulation of the mud-dominated Stanley Shale, indicating initial approach to the subduction zone and synorogenic sedimentation; however, the adjacent Laurentian shelf did not subside and remained shallow marine. The Stanley Shale contains five successive volcanic tuffs with ages of 328–320 Ma (Shaulis et al., 2012), indicating the time of arc magmatism along a continental-margin arc on the leading edge of the Sabine terrane. Very rapid deposition of synorogenic turbidites (Jackfork and Johns Valley) continued thorough the Early Pennsylvanian in a forearc deep-water off-shelf setting, while slow depositional rates persisted on the adjacent shallow-marine shelf. In Middle Pennsylvanian time, abrupt rapid subsidence of the Laurentian margin crust, as recorded in the very thick Atoka turbidites, reflects tectonic loading and flexural subsidence under the tectonic load of the accretionary prism that had advanced onto the continental crust north of the Alabama-Oklahoma transform fault (Houseknecht, 1986; Viele and Thomas, 1989). The turbidite succession grades upward into more deltaic to shallow-marine environments, indicating sedimentary filling of the foreland basin as subsidence rates declined and shallow-marine to deltaic environments prevailed (Sutherland, in Johnson et al., 1988).

With the progress of southward subduction of Laurentian crust, thin-skinned thrusting propagated into the proximal synorogenic basin fill, and ultimately the accretionary complex was thrust onto the pre-orogenic shelf. The Maumelle chaotic zone of broken sandstone and shale is interpreted to be the leading edge of the accretionary prism and is now along the trailing side of the frontal thrust belt (Viele, 1973; Viele and Thomas, 1989). During the later stages of contraction, a basement-rooted thrust inserted the deep subsurface Benton external basement massif beneath the sedimentary thrust belt, raising the older Paleozoic rocks in a large-scale frontal thrust ramp (Lillie et al., 1983; Thomas, 2011). The Benton uplift plunges and flattens westward along strike. The rare tectonic slices of ultramafic rocks in the deformed sedimentary rocks along the crest of the Benton uplift are interpreted to

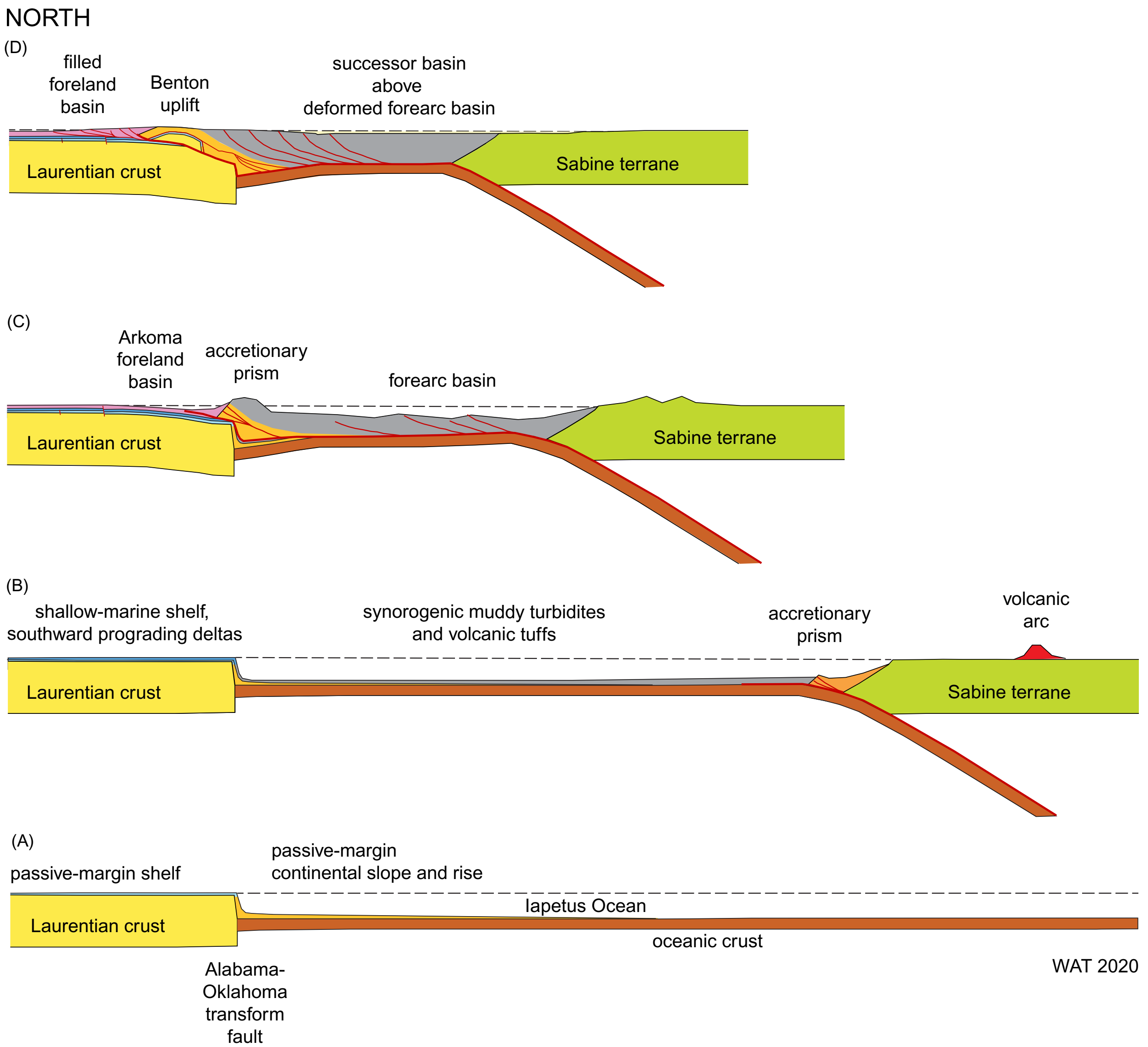


Fig. 14 Sequence of diagrammatic cross sections, illustrating the evolution of the Ouachita segment of the Appalachian-Ouachita orogen. (A) Cambrian to Early Mississippian: Alabama-Oklahoma transform margin of Laurentian crust; sediment deposition on passive-margin carbonate shelf and off-shelf slope and rise. (B) Late Mississippian (Chesterian): subduction beneath continental-margin arc on leading edge of Gondwanan Sabine terrane; deposition of synorogenic muddy turbidites spread across a forearc basin, accretionary prism, trench, and ocean floor; volcanic tuff dispersed widely. (C) early Middle Pennsylvanian (early Atokan): thrusting of accretionary prism onto margin of Laurentian continental crust and rapid flexural subsidence of Arkoma peripheral foreland basin, accompanied by down-to-basin faulting; deposition of very thick sandy turbidites, which thin into deltaic sediment on distal shelf. (D) late Middle Pennsylvanian (Atokan-Desmoinesian): thrusting of tectonic wedge beneath Benton uplift; dispersal of detritus from erosion of Ouachita thrust belt; deposition of shallow-marine to deltaic sediment in distal foreland of Ouachita orogen; deposition of shallow-marine fill of successor basin over trailing Ouachita orogen.

represent the oceanic crust of the Laurentian plate that was picked off from the down-going slab (Viele and Thomas, 1989). In the Ouachita salient, the ocean basin did not completely close, leaving the continental crust of the Sabine terrane about 100 km south of the south edge of Laurentian continental crust along the Alabama-Oklahoma transform fault (Keller et al., 1989a; Mickus and Keller, 1992).

The westerly strike along the Ouachita Mountains in Arkansas bends nearly 90 degrees to the south in eastern Oklahoma (Fig. 12). Farther south, in Oklahoma, the south-trending thrust belt intersects the west-northwest-trending basement faults of the Arbuckle uplift along the regional Southern Oklahoma fault system. Precambrian basement rocks along the Southern Oklahoma fault system belong to the Granite-Rhyolite province (1500–1320 Ma; Fig. 1A) (Thomas et al., 2012). The basement fault system had precursors in a Neoproterozoic-Early Cambrian transform-parallel intracratonic fracture system associated with the late stages of Iapetan rifting and breakup of supercontinent Rodinia. The transform-parallel fracture system hosted an enormous outpouring of synrift magma, which crystallized in plutons and flows with zircon ages of 539–530 Ma (Hogan and Gilbert, 1998; Thomas et al., 2012, 2016; Hanson et al., 2013). Petrology and Hf isotopes indicate juvenile magmas. Locally great thickness of Cambrian-Ordovician passive-margin shelf carbonates documents large-magnitude synrift thermal uplift followed by thermal decay and crustal subsidence (Thomas and Astini, 1999). The Ordovician carbonate succession includes quartzose sandstone units that contain detrital zircons from the Canadian Shield (Superior province), indicating widespread dispersal of quartz sand over the stable carbonate platform from the continental interior (Thomas et al., 2016, and references therein). A stable shelf persisted throughout the middle Paleozoic. In the late Paleozoic, large-magnitude basement faults along the same trend as the Cambrian synrift igneous rocks partitioned the Arbuckle-Wichita-Amarillo basement uplifts from the intracratonic Anadarko basin on the north. Pennsylvanian coarse proximal deposits, called "granite wash," indicate steep fault scarps along the structural boundary between the uplifts and the basin (Johnson et al., 1988). The coarse facies grade northward into finer grained clastic facies. The proximal deposits of latest Pennsylvanian and earliest Permian lap onto the basement uplifts over an unconformity that cuts down though the Paleozoic stratigraphy to the Cambrian synrift igneous rocks and Precambrian (Granite-Rhyolite) basement. Sources of the proximal detritus vary locally from the Cambrian igneous rocks to the Ordovician sandstones that yield Superior-age zircons (Thomas et al., 2016). Permian strata covered the basement uplifts, indicating the end of both the active structural uplifting and the local supply of sediment from the uplifts. The younger Permian deposits had more regional dispersal from distal sources that blanketed the uplifts. The structural style and time of fault movement link the Southern Oklahoma fault system to the late Paleozoic Ancestral Rocky Mountains (Fig. 5) (Kluth and Coney, 1981).

The thrust structures of the Ouachita frontal thrust belt in Oklahoma are, except for strike, somewhat similar to those in Arkansas, but with some broader and deeper trailing synclines; however, some of the frontal thrust faults in Oklahoma are detached in the lower Paleozoic off-shelf stratigraphy, rather than in the upper Paleozoic synorogenic turbidite succession. Trailing the Ouachita frontal thrust belt in Oklahoma, the northeast-trending Broken Bow uplift (Fig. 12) exposes the older off-shelf stratigraphy, similar to that over the Benton uplift in Arkansas. The overall shape of the Broken Bow uplift is a broad northeast-trending and northeast-plunging anticlinorium; however, smaller scale folds within the anticlinorium generally strike east, like the strike of the thrust belt in Arkansas, suggesting structural interference between the two directions (Nielsen et al., 1989). Deep drill holes show that the core of the Broken Bow uplift is a basement rooted thrust sheet like that beneath the Benton uplift. Because of the abrupt bend in strike, the trailing parts of the north-striking thrust belt in Oklahoma blend into the trailing structures of the east-striking thrust belt in Arkansas (Arbenz, 2008).

Where the south-striking structures of the Ouachita frontal thrust belt in Oklahoma impinge on the west-northwest-striking southern Oklahoma fault system, the thrust front is deflected eastward and wraps around the east-plunging end of the Arbuckle uplift (Fig. 12) (Jusczuk, 2002). Structural interference indicates nearly simultaneous basement uplift and thin-skinned thrusting. Similarly, the Arkoma foreland basin bends from easterly strike in Arkansas to southerly strike in Oklahoma. The deep Anadarko basin along the Southern Oklahoma fault system ends up-plunge to the east at a relatively narrow basement arch (southern extension of part of the Nemaha uplift), which separates the intracratonic Anadarko basin from the up-dip distal part of the Arkoma foreland basin, further indicating the near simultaneous history of basement and thin-skinned structures (Johnson et al., 1988).

South of the intersection of the thrust front with the southern Oklahoma fault system, the Paleozoic structures pass beneath the cover of the Mesozoic-Cenozoic Gulf Coastal Plain, where the trace of the Ouachita thrust belt continues southward beneath eastern Texas. Drill holes and seismic reflection profiles reveal that the subsurface thrust belt consists of the same stratigraphic succession as that in the exposures in the Ouachita Mountains. The subsurface thrust belt includes equivalents of the thick synorogenic Mississippian-Pennsylvanian turbidite succession (Stanley, Jackfork, and Atoka) as in the Ouachita outcrops (Mapel et al., 1979); but some of the subsurface frontal thrust sheets also contain the same lower Paleozoic off-shelf passive-margin succession of dark-colored shale and chert as in the Ouachita outcrops (Nicholas and Waddell, 1989; Thomas et al., 1989a). Two basement massifs (Waco and Luling) trail the eastern side of the sedimentary thrust belt, similar to the Benton and Broken Bow uplifts beneath the Ouachita Mountains (Fig. 12) (Rozendal and Erskine, 1971; Culotto et al., 1992). Although all of the Ouachita thrust belt in Texas is covered by Coastal Plain sediments, the upper Paleozoic fill of the Fort Worth basin is exposed in the distal foreland. The Fort Worth basin is an east-dipping homocline that extends southward from the basement uplifts along the Southern Oklahoma fault system, and ends southward up plunge onto the intracratonic Llano uplift (Crosby and Mapel, 1975; Alsalem et al., 2018). As in the Arkoma basin, the Mississippian-Lower Pennsylvanian in the foreland is a relatively thin accumulation of largely shallow-marine sediment, equivalent to much thicker synorogenic turbidites in the proximal foreland basin in the deep subsurface (Crosby and Mapel, 1975; Mapel et al., 1979). The Middle Pennsylvanian Atoka Formation turbidites thin westward in the subsurface. The upper Middle Pennsylvanian through lower Permian beds include cyclic sequences of shallow-marine limestone tongues that thin out eastward and deltaic sandstones that thin out westward (Brown et al., 1973; Galloway and Brown, 1973; Kier et al., 1979). Some of the sandstones contain chert pebbles, indicating a source from the Ordovician-Devonian cherts in the Ouachita thrust belt (Brown et al., 1973). Detrital-zircon populations in the Fort Worth basin are consistent with a source in the Sabine terrane and related arc and forearc systems (Alsalem et al., 2018).

Farther east, across strike into the orogen, the Ouachita interior metamorphic belt, consisting of metasedimentary rocks, parallels the trailing part of the sedimentary thrust belt (Viele and Thomas, 1989). The interior metamorphic belt is a distinct band of low-grade metasedimentary rocks along the trailing side of the north-striking thrust belt in Texas (Fig. 1A); to the north, the interior metamorphic belt bends eastward, paralleling the trailing side of the Broken Bow uplift, in Oklahoma. To the east in Arkansas, the distinct metamorphic belt is lost in the thick mass of deformed sedimentary rocks in the forearc basin north of the Sabine terrane. Farther east, in Mississippi, drilling has penetrated slaty shale with vein quartz, similar to rocks in the Ouachita Mountains in Arkansas (Thomas, 1972a, 1973).

Farther south, beneath the Gulf Coastal Plain in the subsurface in southeastern Texas, the trace of the thrust belt, as documented by deep drill holes, bends abruptly from a southerly trend to a westerly trend paralleling the eastern and southern flanks of the intracratonic Llano uplift (King, 1961) (Fig. 12). The curve of the thrust belt, defining the Texas recess, mimics the shape of the Iapetan rifted margin on the Texas promontory, which is framed by the intersection of the north-northeast-trending Ouachita rift and the west-northwest-trending Texas transform (Thomas, 1977, 2006). The Ouachita interior metamorphic belt traces around the bend in strike, paralleling the frontal thrust belt (Fig. 1A). Whether the Sabine terrane collided directly with basement rocks on the Texas promontory is not clearly documented by available data.

West from the bend at the Texas recess, the Devils River basement uplift (Fig. 12) apparently is in direct contact with the frontal thrust belt and is structurally higher than the other basement uplifts along the Ouachita system (Nicholas and Rozendal, 1975). The interior metamorphic belt passes south of the Devils River uplift. In the foreland, the Val Verde basin has a very thin Pennsylvanian succession, indicating a starved basin (Hamlin, 2009). The Permian section is a thicker accumulation presumably with a source in the Devils River uplift.

The thrust belt continues westward and emerges locally from beneath the Coastal Plain cover in the Marathon region of western Texas, where strike bends from westerly to southwesterly defining the Marathon salient of the thrust belt within the Marathon embayment of the Iapetan rifted margin (Fig. 12). The Marathon frontal thrust belt has a lower Paleozoic off-shelf passive-margin succession somewhat like that in the Ouachita salient, but contains more carbonate mud and large carbonate olistoliths from the equivalent shelf facies (King, 1937; McBride, 1989). One olistolith is so large that it was originally mapped as the Monument Spring Limestone Member of the Marathon Limestone. The lower Paleozoic succession contains clasts of volcanic (basaltic to trachytic) rocks with U-Pb zircon ages of 706 Ma, indicating the time of Iapetan rifting (Hanson et al., 2016).

In the off-shelf setting, the muddy deposits of the thick Lower Mississippian-Lower Pennsylvanian Tesnus Formation, overlying the Devonian-Lower Mississippian Caballos Novaculite, indicate an abrupt increase in sedimentation rate as a result of the initial approach of a subduction complex at the leading edge of the Coahuila terrane on the south (Fig. 15) (Ross, 1986; Thomas et al., 2019). The abrupt increase in depositional rates in the Marathon foreland in the Early Mississippian ($\sim$355 Ma) occurred earlier than the comparable event in the Ouachita foreland in the Middle Mississippian ($\sim$335 Ma). The Pennsylvanian Haymond Formation of sandstone-shale turbidites includes boulder and pebble beds with clasts of three types: (1) pebbles from the lower Paleozoic off-shelf units, indicating reworking of Marathon strata (McBride, 1989); (2) boulders of Middle Cambrian shelf-margin carbonates, indicating reworking of an early phase of the passive margin (Palmer et al., 1984); and (3) boulders of igneous and metamorphic rocks, the radiometric ages (rhyolite with U-Pb zircon age of 371 ± 12 Ma with early to middle Proterozoic xenocrysts and granodiroitic gneiss with U-Pb zircon age of 1436 ± 160 and 330 ± 72 Ma metamorphic overprint, Denison et al., 2005) of which indicate a middle Paleozoic orogen that remobilized Mesoproterozoic basement rocks. The stratigraphically higher Pennsylvanian and Lower Permian strata contain some turbidite facies, but are primarily shallower marine deposits, culminating in cyclic sandstone, shale, carbonate sequences, and indicating filling of the foreland basin (Ross, 1986).

Across the thrust belt, broad anticlinoria of disharmonically folded lower Paleozoic off-shelf facies are separated by deep synclines that contain thick successions of the upper Paleozoic turbidites and boulder beds (Muehlberger and Tauvers, 1989). An angular unconformity in the middle Wolfcampian (Lower Permian) records the last stage of contractional deformation in the Marathon thrust belt (Ross, 1986).

The accreted Coahuila terrane is tightly emplaced along the southern side of the sedimentary thrust belt (Fig. 15), separated only by a narrow band of the interior metamorphic belt. The interior metamorphic belt is entirely in the subsurface in Texas, and the only surface exposure is at Sierra del Carmen south of the Rio Grande in Mexico and at the northern edge of the Coahuila terrane. U-Pb zircon ages of igneous rocks in the Coahuila terrane include Mesoproterozoic basement (1232–1214 Ma), Pan-African basement (580 Ma), and Las Delicias arc (331–270 Ma) (Lopez, 1997; Lopez et al., 2001). Detrital zircons from Jurassic-Cetaceous proximal graben-fill deposits on the Coahuila terrane (Thomas et al., 2019) provide a more cosmopolitan sample of the basement rocks, which correspond to basement provinces in Gondwana (Amazonia). Las Delicias arc is the record of a continental-margin arc along the leading edge of Coahuila. Tuff beds in the Tesnus Formation (Imoto and McBride, 1990) further record arc magmatism coeval with part of Las Delicias arc. The ages of detrital zircons from the sedimentary rocks in the Marathon foreland match the ages of all of the components of the Coahuila terrane, indicating that the Coahuila terrane was the source of sediment to the proximal orogenic foreland (Thomas et al., 2019).

Terrane Accretion History

Two large-scale along-strike dip domains mark the bend from the Tennessee salient of the Appalachian thrust belt to the Alabama recess. In northwest Georgia, the interior structures of the sedimentary thrust belt, as well as the frontal structures of the Blue Ridge, strike nearly north-south as far south as Cartersville, Georgia. At Cartersville, however, the strike bends sharply to west-southwest, in part with intersecting faults. In the middle part across strike of the thrust belt in Georgia, the two distinct orientations of thrust faults intersect and interfere in the roof of a mushwad of Cambrian shale (Cook and Thomas, 2010). To the northwest across strike, the frontal structures bridge the sharp bend and simply blend tangentially into the leading bend of the Tennessee salient. Farther southwest along strike, the west-southwest-trending structures truncate the west-northwest-trending frontal structures of the Ouachita thrust belt beneath the Gulf Coastal Plain in eastern Mississippi. The abrupt bend in strike, as well as the prevalent west-southwest strike in western Georgia and Alabama, have a counterpart in the interior of the orogen.

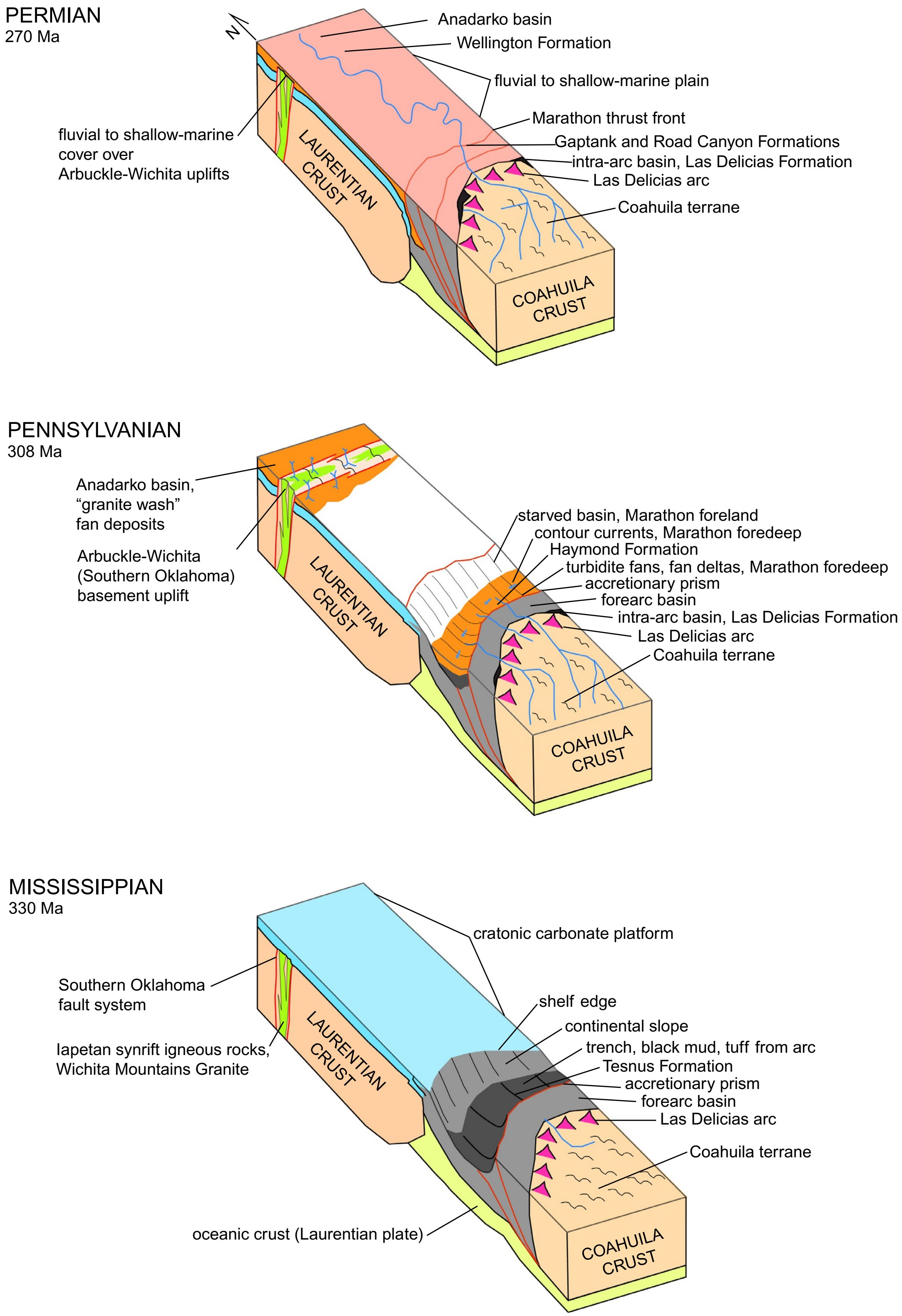


Fig. 15 Sequence of three schematic block diagrams, illustrating the evolution of the Marathon segment of the Appalachian-Ouachita orogen. From Thomas WA, Gehrels GE, Lawton TF, Satterfield JI, Romero MC, and Sundell KE (2019) Detrital zircons and sediment dispersal from the Coahuila terrane of northern Mexico into the Marathon foreland of the southern Midcontinent. *Geosphere*, 15, 1101–1127. https://doi.org/10.1130/GES02033.1.

In the subsurface beneath the Gulf Coastal Plain in northern Florida and adjacent Georgia and Alabama, the Suwannee terrane (Fig. 1) has a Neoproterozoic basement of felsic volcanic and plutonic rocks (Mueller et al., 1994, 2014), and a sedimentary cover of Cambrian(?) or Lower Ordovician to Middle Devonian strata (Chowns and Williams, 1983; Thomas et al., 1989b). The Paleozoic cover includes quartzose sandstone in the lower part, mostly gray shale in the middle part, and interbedded sandstone and shale in the upper (Devonian) part. Detrital zircons from throughout the succession are dominantly of Paleoproterozoic (Eburnian) and Neoproterozoic (Pan-African) ages to the nearly complete exclusion of other ages (such as Grenville or Sunsás) (Mueller et al., 2014). Fossils identified in the sedimentary rocks are chacteristically African (Gondwanan) rather than Laurentian (e.g., Pojeta et al., 1976; Chowns and Williams, 1983). The age of basement rocks, the detrital zircons, and the faunas all indicate that Suwannee is a Gondwanan terrane. The northern border of the terrane is called the Suwannee-Wiggins suture (Fig. 1A and B). Rocks of the suture are exposed across the Georgia-Alabama state line in a narrow area just north of the onlap of Coastal Plain cover. Shear fabrics in multiple wide zones of mylonite show dominant dextral slip of the boundary that strikes east-northeast, and ages of zircon overgrowths indicate emplacement of the fault rocks at 300 Ma (Steltenpohl, 1988; Steltenpohl et al., 2008). A wide zone of seismic reflectors dips southward from the outcrops to the Moho, indicting a crustal-scale structure (Nelson et al., 1985). On the east in Georgia, the Suwannee-Wiggins suture cuts westward across the southern parts of the Brunswick-Charleston terrane and the Carolina superterrane, truncating the Central Piedmont suture, and farther west onto Laurentian basement rocks on the Alabama promontory south of the exposed basement in the Pine Mountain internal massif (Fig. 1A and B) (Thomas, 2011). Dextral-oblique slip (transpression) during accretion of the Suwannee terrane provides a component of north-northwest contraction appropriate to drive the sedimentary thrust sheets with east-northeast strike across the angular intersection at Cartersville. Overall these data indicate a time of Appalachian thrusting at about 300 Ma. The westward extension of the Appalachian thrust front truncates the older Ouachita thrust faults in the subsurface in Mississippi (Thomas, 1973, 1989), consistent with observations that Ouachita thrusting ended approximately 10 m.y. earlier than Appalachian thrusting (Thomas, 2011).

To the southwest, the trace of the Suwannee-Wiggins suture may pass through the Wiggins terrane, deep in the subsurface in southernmost Alabama (Figs. 1B and 12). That trace places the Suwannee-Wiggins suture far to the south of the intersection of the Ouachita and Appalachian thrust belts.

The Sabine terrane, inside the curve of the Ouachita salient, evidently is a Gondwanan terrane with full-thickness continental crust (Fig. 1A) (Keller et al., 1989a; Mickus and Keller, 1992). The time of initial terrane accretion, as indicated by an abrupt great increase in rate of deposition of clastic sediment, is late Middle Mississippian (Viele and Thomas, 1989). Sediment progradation into the Greater Black Warrior foreland basin began in early Late Mississippian (Thomas, 1988) at about 331 Ma. Tuffs in the Stanley Shale date arc volcanism at 328–320 Ma (Shaulis et al., 2012). The end of Ouachita thrusting as indicated by an angular unconformity near the leading edge of the Sabine terrane is at the Atokan-Desmoinesian boundary at about 310 Ma (Nicholas and Waddell, 1989), and as indicated by the youngest folded beds in the Ouachita distal foreland is early Desmoinesian at about 309 Ma (Denison, 1989). The Ouachita thrust belt is truncated by the Appalachian thrust front beneath the Gulf Coastal Plain in eastern Mississippi (Thomas et al., 1989a), and the Ouachita synorogenic facies in the Greater Black Warrior foreland basin are imbricated in the Appalachian thrust belt in Alabama (Thomas, 1995). These observations together place the completion of Sabine accretion at about 309 Ma, consistent with the later age of 300 Ma for accretion of the Suwannee terrane and Appalachian thrusting.

The Coahuila terrane inside the curve of the Marathon salient of the thrust belt is documented by detrital-zircon populations and ages of igneous rocks to be a Gondwanan terrane with full-thickness continental crust (Keller et al., 1989b; Thomas et al., 2019). Initiation of accretion is signaled by the abrupt increase in clastic sedimentation in the Early Mississippian, which is somewhat earlier than the comparable event in the Ouachita salient at the front of the Sabine terrane, as well as earlier than the initial deposits in the Pennington-Lee clastic wedge and in the Mauch Chunk-Pottsville clastic wedge in the Alleghanian foreland of the Appalachians. Whether Coahuila and Sabine are parts of a single terrane, perhaps parts of the much larger Oaxaquia terrane, accreted together or in pieces is not established. Arc magmatism is approximately Late Mississippian (325 Ma) on the basis of stratigraphic position of tuff beds in the Tesnus Formation (no radiometric ages are available; Imoto and McBride, 1990); the stratigraphic age of the tuff beds is coeval with part of Las Delicias arc (331–270 Ma) on the Coahuila terrane. Final thrusting in the Marathon system is dated as middle Early Permian by an angular unconformity at $\sim$295 Ma, somewhat younger than in the Ouachita system and the southern Appalachian Suwannee-Wiggins suture. The available data show a non-systematic diachronous succession of events distributed along the orogen, including the Ouachitas, the southern Appalachians, and the Marathons.

Tectonic Inheritance

The diachronous rifting events during the breakup of supercontinent Rodinia left an orthogonally zigzag rifted margin of Laurentia by early Paleozoic time (about 530 Ma) as the pre-existing continental margin that ultimately became the framework for the Paleozoic Appalachian-Ouachita orogenic belt (Thomas, 1977, 2006, 2019a). Synrift basement faults, inboard from the rifted margin, including both rift-parallel extensional structures and transform-parallel strike-slip systems controlled some thrust-belt structures (Thomas, 2019a).

The rift-stage crustal structures influenced or controlled the subsequent contractional structures of the leading part of the Appalachian-Ouachita orogen. The most obvious and largest scale manifestation of this tectonic inheritance is in the sinuous trace of the foreland thrust belt and the trailing external basement massifs, where the trace of the contractional structures bent to accommodate the pre-existing shape of the rifted continental margin during accretionary events (Fig. 16). The resulting salients

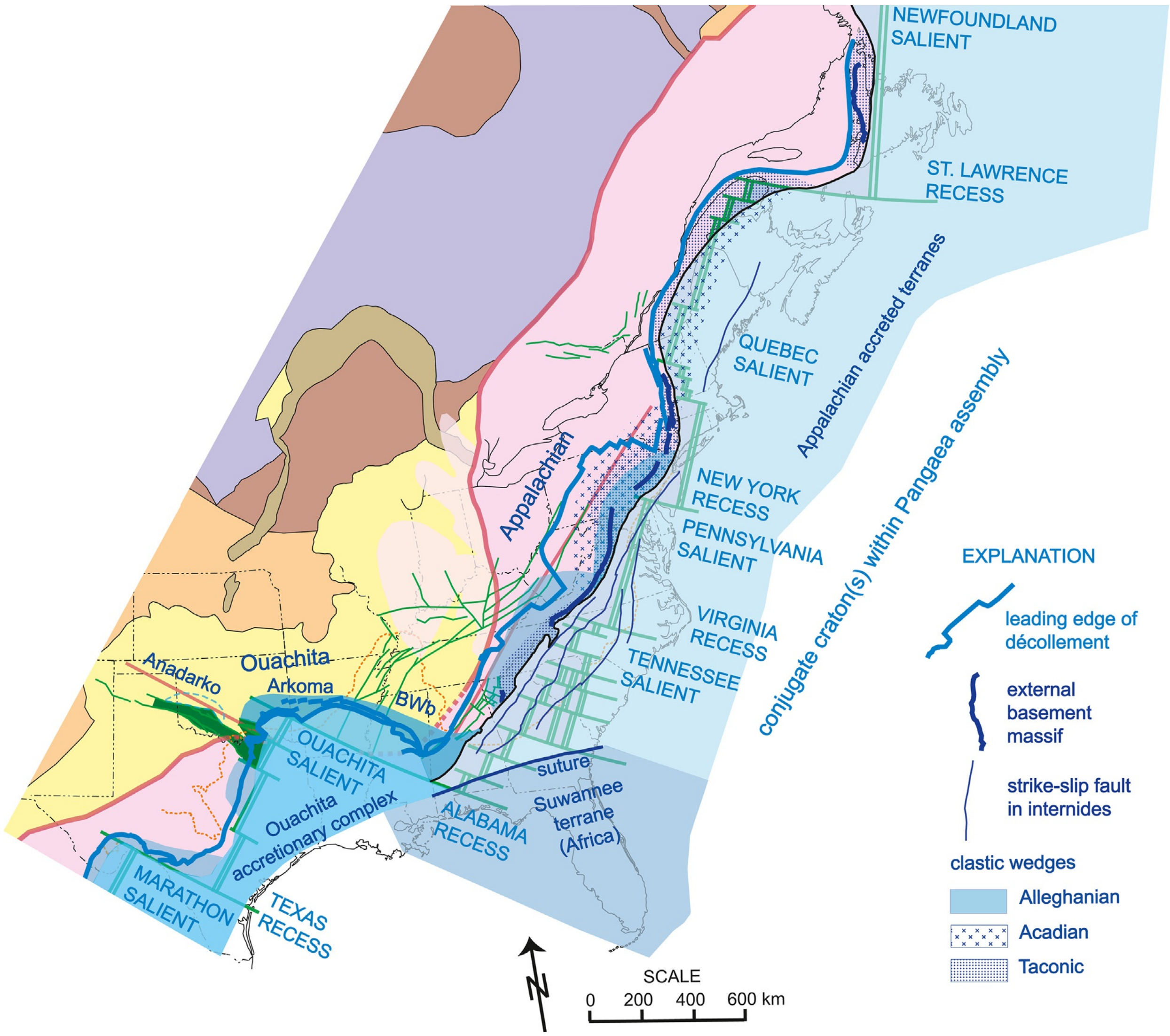


Fig. 16 Late Paleozoic configuration of the Appalachian-Ouachita orogen and assembly of Pangaea. From Thomas WA (2006). Tectonic inheritance at a continental margin. *GSA Today* 16: 4–11.

(convex toward the craton) of the thrust belt curve around the embayments of the continental margin, and the resulting recesses (concave toward the craton) of the thrust belt are more angular bends, commonly including interference between thrust systems from two non-parallel trajectories. These contractional structures may be viewed as ocean waves being refracted around a headland (a continental promontory) and advancing in sweeping curves into the adjacent bays (continental embayments), as John Rodgers (1975) so elegantly suggested. The large-scale bends in strike form sinuous curves of salients and recesses along the Appalachian-Ouachita orogen from Newfoundland to Texas, specifically the Newfoundland, Québec, Pennsylvania, Tennessee, Ouachita, and Marathon salients and the intervening St. Lawrence, New York, Virginia, Alabama, and Texas recesses (Fig. 16) (Thomas, 1977, 2006). Smaller scale examples of tectonic inheritance from rift-stage structures range from abrupt offsets in frontal contractional structures at intracratonic basement faults to localization of frontal thrust ramps over synrift basement normal faults. Where synrift intracratonic grabens localized an exceptionally thick accumulation of muddy sediment at the stratigraphic level of the regional Appalachian décollement, the thick shale was ductilely deformed and tectonically thickened into mushwads (W. A. Thomas, 2001, 2019b; Cook and Thomas, 2010).

Tectonic inheritance from structures of the rifted margin are, of course, limited by the preserved extent of the continental crust, and the effects of the shape of the rifted margin are diminished in the trailing components of the orogen. The orogen-scale system of dextral strike-slip faults effects a boundary that smears across the promontories and embayments of the rifted margin, leaving a system of roughly straight structures that somewhat anastomose around the accreted terranes. The large-scale strike-slip faults are almost entirely outboard from the preserved continental crust of Laurentia; however, locally, strike-slip faults cut across the Iapetan rifted margin. The best-documented example is on the corner of the Alabama promontory, where the Suwannee suture cuts Laurentian crust (Thomas, 2011). Very distinctly, the frontal structures of the orogen adapted to the pre-existing shape of the pre-orogenic continental margin; however, the trailing components, especially the accreted terranes, are constrained by a system of dextral slip (Fig. 16).

Post-Paleozoic History of the Appalachians

The rocks and structures of the Appalachian-Ouachita-Marathon orogen represent the final assembly of supercontinent Pangaea during the Permian, completing the Wilson cycle of continental breakup (opening of Iapetus in the Neoproterozoic to Early Cambrian) followed by closing of the ocean basin during the Paleozoic (e.g., Thomas, 2019a). Very soon, however, continental rifting and breakup of Pangaea began the opening of the modern Atlantic Ocean during the Late Triassic and Early Jurassic, with emplacement of the extensive Central Atlantic magmatic province (CAMP) diabase dikes and basalt flows at ~199 Ma (Hames et al., 2000). The Triassic-Jurassic rifted margin included promontories and embayments similar to those along the Iapetan rifted margin of Laurentia in the previous Wilson cycle (Fig. 17) (Thomas, 2006, 2019a). The Atlantic rift segments generally are within

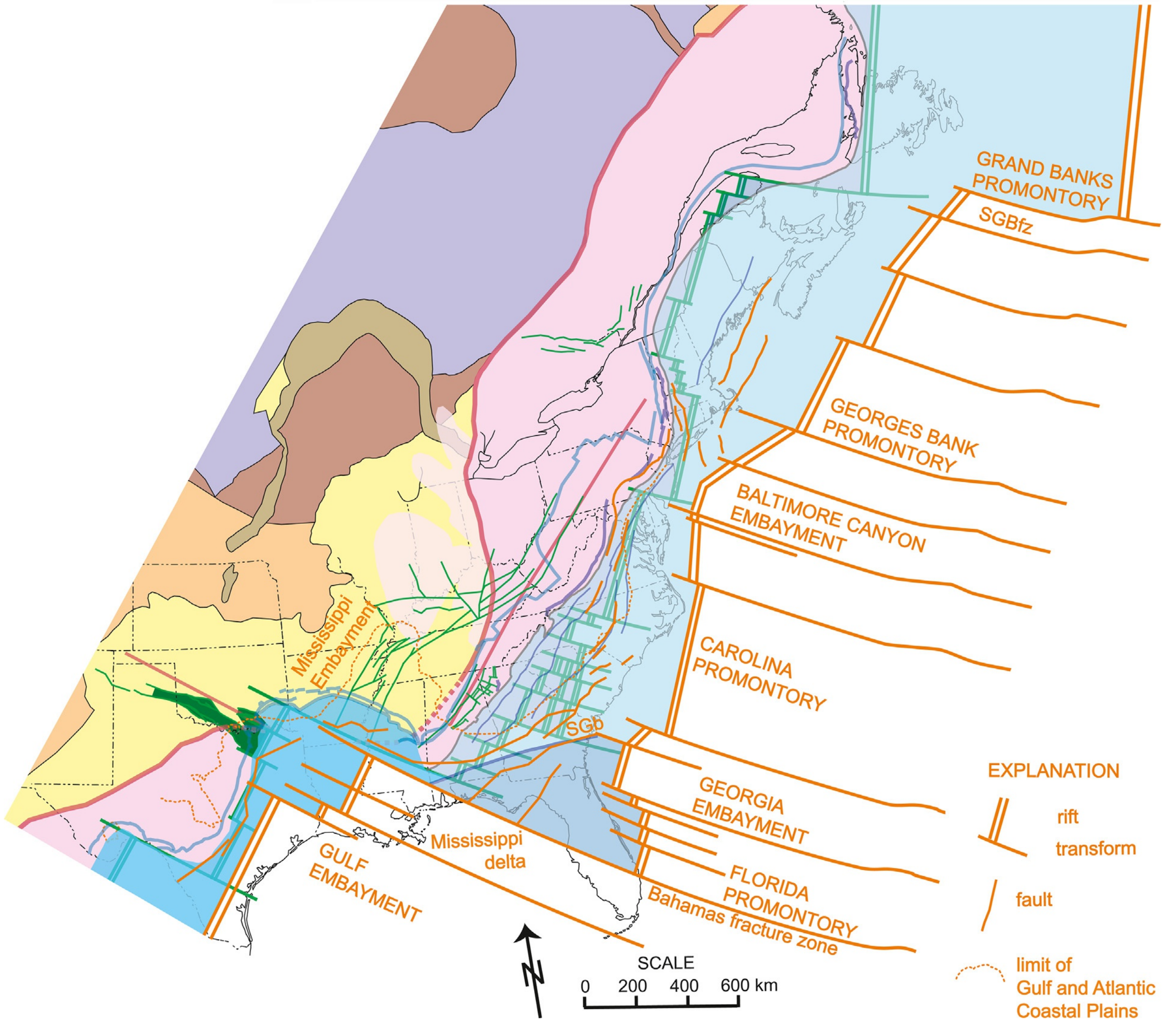


Fig. 17 Map of Mesozoic rifted margin of eastern North America and opening of the Atlantic Ocean. From Thomas WA (2006) Tectonic inheritance at a continental margin. *GSA Today* 16: 4–11.

the Appalachian-Ouachita-Marathon accreted terranes outboard from, but roughly parallel with, the Iapetan continental rift margin. In contrast, however, transform faults of the Atlantic rifted margin generally inherited the locations and traces of the transform faults along the Iapetan rifted margin. Inboard from the Atlantic rift margin, graben blocks filled with siliciclastic sediment generally parallel the rift margin, much like the intracratonic rift-parallel faults of the Iapetan rift margin. In addition to the tectonic inheritance of the locations of transform faults, some of the intracratonic Triassic faults are localized along pre-existing Paleozoic Appalachian contractional structures. For example, beneath the cover of the Gulf Coastal Plain, the Mesozoic South Georgia basin (Fig. 17) is overprinted over the late Paleozoic Suwannee suture (Thomas, 2019a). Father west, Mesozoic rifting and opening of the Gulf of Mexico dismembered the Oaxaquia terrane and its components, translating the Maya terrane from inside the Ouachita embayment to the present location in Yucatan (Pindell and Kennan, 2009). Around the Gulf of Mexico, the Triassic fault system can traced in the subsurface beneath the Gulf Coastal Plain northwestward from southern Alabama to southern Arkansas, and around an abrupt bend southward across Texas. The graben-fill stratigraphy generally begins with coarse redbeds (Eagle Mills Formation), and the latest stage of rift filling is the very thick Louann Salt.

Following deposition of the rift-fill sediment, the transition to a passive margin and marine transgression is expressed in extensive Jurassic carbonates in the Smackover Limestone. The Upper Jurassic Cotton Valley Group includes an array of deltaic facies, a barrier-island complex, and shallow-marine carbonates extending from Alabama to Texas (Thomas and Mann, 1966). The deltaic deposits represent the earliest indication of the Ancestral Mississippi River in the Late Jurassic, and vestiges of the Ancestral Mississippi River can be recognized throughout the stratigraphic record to the present (Mann and Thomas, 1968). The post-Jurassic stratigraphy represents mostly deltaic, coastal, and shallow-marine deposits that extend around the Gulf Coast from north Florida to Texas. The succession is mostly shale and sandstone but includes various carbonates and evaporites. In particular, persistent and thick Upper Cretaceous chalk extends from Alabama to Texas, partitioning a succession that is generally dominated by siliciclastic sediment both above and below the chalk. Southward in Florida, the entire succession from Jurassic up to the present sea floor grades laterally into carbonate with some minor evaporites (but not one quartz grain or clay flake, based on the first author's personal experience of sitting a well that drilled it in early 1960).

In large scale, the structure of the Gulf Coastal Plain is a simple homocline dipping toward the Gulf, and bending from southward dip in Florida, Alabama, and Louisiana to eastward dip in western Texas. Some synrift faults of the Mesozoic Gulf-opening system were reactivated at various times, and some cut through to the present surface. A large system of down-to-the-coast synsedimentary faults with classic roll-over anticlines parallels the coast, and continues into the offshore. Parts of the area include salt domes that rise from the Louann Salt. The apparently simple homocline is deformed by broad, coastward-plunging folds. The Mississippi Embayment is an enormous coastward-plunging syncline, along which the present Mississippi River flows. The San Marcos arch plunges coastward in Texas along the Gulf Coastal Plain.

We were taught in junior high that the Appalachians are an "old worn-down" chain, whereas the Rockies are a "young rugged" range: some still believe that. Atlantic-Gulf Coastal Plain stratigraphy, however, reveals several cycles of post-Paleozoic uplift and erosion interrupted by carbonate deposition during the Mesozoic and Cenozoic as the Atlantic Ocean and Gulf of Mexico opened (Poag and Sevon, 1989; Galloway et al., 2011). The post-Paleozoic history of the Appalachian region is marked by long periods of erosion during the early Mesozoic following the Alleghanian orogeny and development of a carbonate platform during opening of the Atlantic Ocean (Fig. 2). Uplift of southeastern North America occurred again in the Late Cretaceous spilling large quantities of sediment onto the Atlantic and Gulf continental margins from the Late Cretaceous well into the Eocene. Carbonate deposition resumed during the mid-Cenozoic, but uplift of the Appalachian region resumed beginning in the late Miocene-early Pliocene producing the modern topography of the exposed southern Appalachians and supplying sediment to the Atlantic-Gulf Coastal Plain (e.g., Hack, 1979; Prowell and Christopher, 2006). Present-day topography and major drainages in the non-glaciated Appalachians reveal anomalous patterns that alone indicate Paleozoic-early Mesozoic tectonics and rock types play a minor role in modern topography: major drainages that drain the western Appalachians head in the eastern Blue Ridge and Piedmont. The 1500–2000 m maximum Appalachian elevation shifts from the southern Appalachian Blue Ridge to the central Appalachian foreland (Fig. 18) into contrasting lithologies from those in the Blue Ridge.

Appalachian crust today remains >50 km thick in some regions beneath the Valley and Ridge, Blue Ridge, and western Piedmont, but thins abruptly at the location of the Iapetan rift margin to <35 km thick from the central Piedmont suture eastward beneath the Coastal Plain from Virginia into Georgia. Late Jurassic to Early Cretaceous reversal of Triassic-Early Jurassic extension to ridge-push-related compression could account for the Cretaceous uplift, but does not account for late Miocene-early Pliocene uplift.

Either deep or shallow mantle flow, or erosional processes and sediment deposition disturbing isostatic equilibrium, undoubtedly controlled the late Mesozoic-early Tertiary and Miocene-Pliocene uplift events. Tomographic data in southeastern North America reveal a high-velocity, southeast-dipping mantle slab (high density?) west of the Appalachians and a low-velocity mantle (low-density?) to the east. This has been interpreted as a dynamic system of downward flow of the high-velocity slab and upward flow beneath the high southern Appalachians, but smaller high-velocity zones underlie the high topography, and low-velocity zones underlie the Piedmont (Biryol et al., 2016). Others have suggested that modern Appalachian topography may be the product of interaction of the descending Farallon plate in the deep mantle with upper mantle and crustal elements (Conrad et al., 2004), even though the plate may have fragmented beneath the western U.S. (Liu and Stegman, 2011). Despite great strides in tomographic resolution of mantle structure, the mismatch between modern topography and tomographic data reconfirm our imperfect understanding of mantle structure (Hatcher et al., 2013).

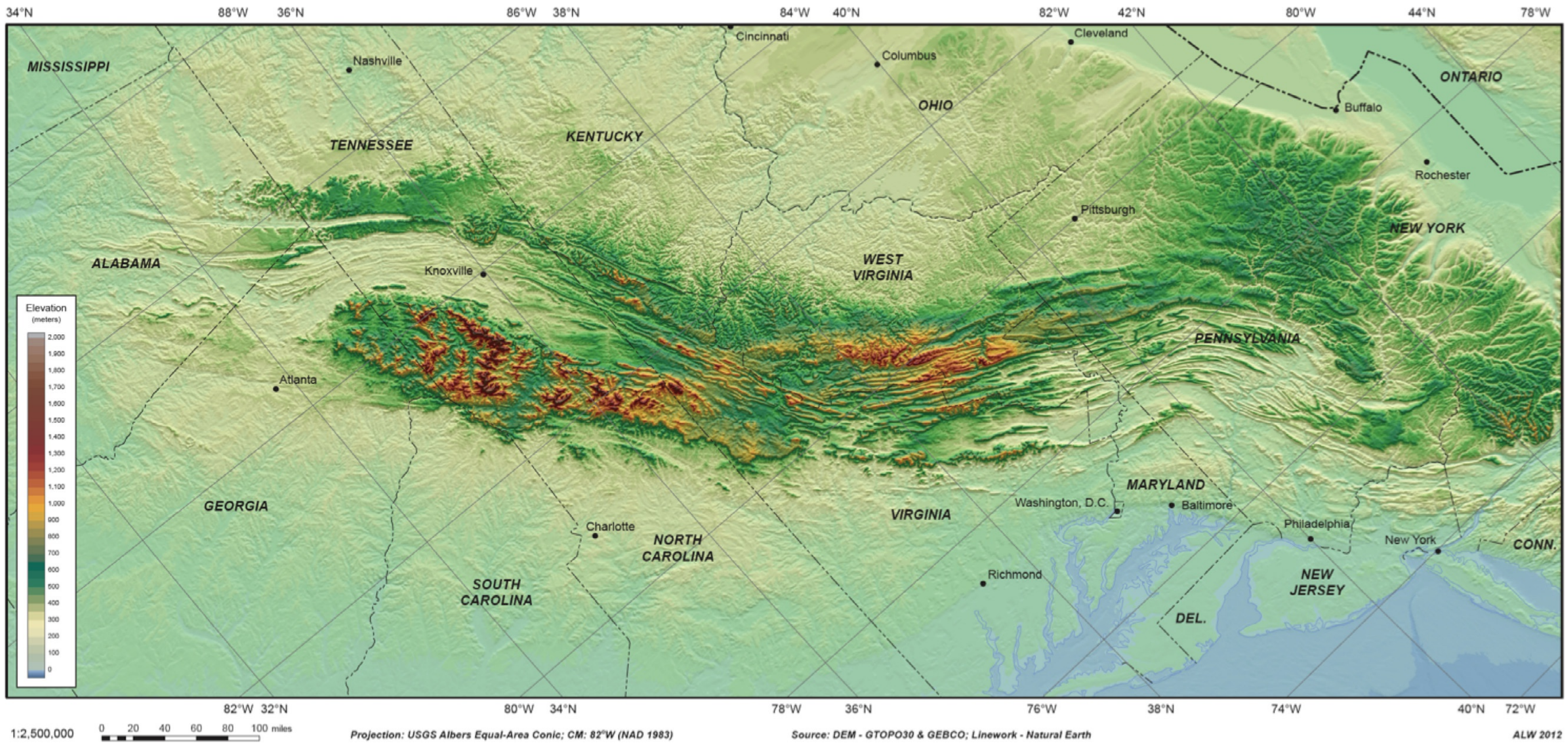


Fig. 18 Digital elevation model of the southern and central Appalachians showing major drainages and the change of highest topography from the crystalline rocks of the Blue Ridge fron North Carolina southward to the foreland sedimentary rocks in Virginia and West Virginia.

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