INTRODUCTION

Forty years ago, the eastern margin of North America inspired Tuzo Wilson (1966) to ask, “Did the Atlantic close and then re-open?” The Wilson cycle of closing and opening of ocean basins incorporates the cyclic assembly and breakup of supercontinents. Alternate processes of extension and compression of continental margins suggest an important potential for tectonic inheritance and overprinting.

Now, we recognize a succession of two complete Wilson cycles in eastern North America: closing of an ocean and assembly of the Rodinia supercontinent, breakup of Rodinia and opening of the Iapetus Ocean, closing of Iapetus and assembly of the Pangaea supercontinent, and breakup of Pangaea and opening of the Atlantic Ocean (Fig. 1). Precambrian rocks of cratonic North America indicate less well-defined, earlier cycles. Tectonic inheritance at a range of scales has been recognized in the successive continental margins preserved within the crust of present eastern North America, posing several fundamental questions. Does each episode of supercontinent assembly and breakup adapt to the tectonic framework of a preexisting continental margin and, in turn, leave a mold for the next episode? Is tectonic inheritance through successive Wilson cycles a first-order constraint on the processes through which continental crust is accumulated and continental fabrics evolve? Does tectonic inheritance in the shallow crustal structures reflect a pervasive fabric of the deeper lithosphere?

ASSEMBLY OF RODINIA (THE GRENVILLE OROGEN)

Metamorphic and igneous rocks of the Grenville province, ranging in age from ca. 1350 to 1000 Ma, record closing of an ocean and assembly of the Rodinia supercontinent (e.g., Hoffman, 1991). The long span of ages suggests multiple events during which multiple elements were swept up and sutured successively to cratonic proto-Laurentia (e.g., McLelland et al., 1996; Mosher, 1998). The Grenville front, at the leading edge of the province, is mapped through generally broad curves along the outcrop in Canada and southward with decreasing resolution in the subsurface, using drill and geophysical data, approximately to central Tennessee; subsurface data define a separate segment in Texas (Figs. 1 and 2). No data presently are available to locate the Grenville front precisely beneath a thick sedimentary cover in the Mesozoic-Cenozoic Gulf Coastal Plain; however, the trace must accommodate a substantial dextral bend between the mapped Grenville (Llano) front in Texas and the approximately located trace in the subsurface in central Tennessee (Fig. 2).

The pre-Rodinia (pre-Grenville) continental margin is unknown; however, the dextral bend of the Grenville front beneath the Gulf Coastal Plain suggests possible inheritance from a dextral offset in the older continental margin. Northwest-striking dikes (ca. 1350 Ma) in Oklahoma (Denison, 1982) parallel the trend of the dextral bend of the Grenville front and suggest the possible orientation of the offset of the older rifted continental margin (Fig. 2). Few other hints are available to suggest the trace of the pre-Rodinia rifted margin of cratonic proto-Laurentia. The Grenville front truncates internal tectonic fabrics within, and boundaries between, several older provinces, from the Archean Superior province to the 1500–1300-Ma

Figure 1. Map showing the record of tectonic inheritance through two complete Wilson cycles in eastern North America (compiled from Figs. 2–5). Assembly of Rodinia, opening of the Iapetus Ocean, assembly of Pangaea, and opening of the Atlantic Ocean are color-coded on this map and in Figures 2–5.
Granite-Rhyolite province (Fig. 2), which have distinct ages and tectonic origins. Fabrics from older cycles of tectonic accretion may hold clues to the trace of the pre-Rodinia margin, perhaps extending tectonic inheritance during cyclic assembly and breakup of supercontinents back in time to the Archean cratons.

Sedimentary deposits in the Grenville foreland in Ohio and Kentucky (Fig. 2) are interpreted to record filling of an intracratonic rift system (Drahovzal et al., 1992) or, alternatively, a synorogenic foreland basin (Santos et al., 2002), possibly a broken foreland. Further resolution of the structure of the Grenville foreland may help to constrain the shape of the pre-Rodinia rifted margin by analogy with younger foreland basins that have distinct tectonic inheritance from the preceding rifted margin.

The range of ages and compositions of Grenville rocks, variations in Pb isotopic ratios, and tectonic fabrics indicate intra-Grenville sutures, consistent with multiple accreted terranes and conjugate continental margins within the assembly of Rodinia (e.g., McLelland et al., 1996; Hatcher et al., 2004). One possible intra-Grenville suture, the New York–Alabama magnetic lineament (King and Zietz, 1978), has a nearly straight trace that may reflect either accretion along a straight segment of the pre-Grenville rifted margin of proto-Laurentia, accretion at a margin already smoothed by accreted terranes, or orogen-parallel slip cutting across the shape of the margin. A Grenville age and Pb isotopic ratios link the basement rocks of the Argentine Precordillera terrane to Gondwana and transferring the Laurentian Argentine Grenville” rocks of the Blue Ridge province (Thomas, 1993). Any possible relationship offsets of the intracratonic graben systems and older fabrics is obscure.

The palinspastically restored Iapetan rifted margin follows an orthogonally zigzag defined by northeast-striking rift segments offset by northwest-striking transform faults (Figs. 1 and 3). Intersections of rift segments and transform faults frame promontories (convex oceanward) and embayments (concave oceanward) of the rifted continental margin. The trace of the Iapetan Alabama-Oklahoma transform corresponds to the probable location of the large-scale dextral bend in the Grenville front, suggesting tectonic inheritance from the shape of the Grenville orogen, as well as from the possible dextral offset in the pre-Rodinia rifted margin of proto-Laurentia and the northwest-striking 1350-Ma dike fabric (Fig. 3). Excepting the Alabama-Oklahoma transform, no tectonic inheritance from Grenvillian margins, sutures, or other fabrics has been recognized in the Iapetan rift system.

The trace of the Iapetan rifted margin is almost entirely within rocks of the Grenville province, leaving a belt of Grenville rocks along the eastern margin of Laurentia (Fig. 3). Along the Iapetan Alabama-Oklahoma transform, however, granite boulders in Ordovician slope deposits have ages (Bowering, 1984) that correspond to the Granite-Rhyolite province, suggesting that the rift and transform in the corners of the Ouachita embayment cut across the Grenville front (Fig. 2). The Iapetan rift evidently cut across intra-Grenville sutures, for example, leaving some isotopically distinct, possibly “non-Laurentian Grenville” rocks of the Blue Ridge attached to “Laurentian Grenville” rocks (Loewy et al., 2002; Hatcher et al., 2004) and transferring the Laurentian Argentine Precordillera terrane to Gondwana (Thomas and Astini, 1996). Further resolution of traces of intra-Grenville sutures and terranes will define additional piercing points for reconstruction of conjugate margins within the assembly of Rodinia.

Contrasts in crustal structure and tectonic history distinguish transform, upper-plate-rift, and lower-plate-rift segments along the Iapetan rifted margin of Laurentia, consistent with a low-angle-detachment simple-shear mechanism (Thomas, 1993, Figure 2 therein). Narrow (~25 km) zones of transitional crust characterize transform faults, which function as vertical fracture zones to offset the rift and to bound domains of opposite dip of the detachment (e.g., Lister et al., 1986). A wide zone (>200 km) of extended transitional crust with rotated basement graben blocks and thick (>10 km) synrift sediment on a lower-plate rifted margin contrasts with a more narrow zone of transitional crust, general lack of preserved synrift sediment, and a post-rift residual thermal uplift on an upper-plate margin (e.g., Thomas, 1993; Thomas and Astini, 1999). Despite the important contrasts in crustal structure, no clear association with fabrics of Grenville and older rocks indicates tectonic inheritance of the internal style of the Iapetan rift; however, these structures did set the stage for pervasive inheritance during the assembly of Pangaea.

Rift-parallel graben systems (Mississippi Valley, Birmingham, and Rome; Fig. 3) indicate Early to early Late Cambrian, late synrift extension inboard from the rifted margin (Thomas, 1991). A dextral offset from the Mississippi Valley graben to the Rome trough, including the transverse Rough Creek graben, suggests a transform offset of the intracratonic graben systems (Thomas, 1993). Any possible relationship between the intracratonic rift-parallel graben systems and older fabrics is obscure and presently unrecognized; however, like the structures of the rifted margin, these faults provide a mold for tectonic inheritance by later structures. The Southern Oklahoma fault system parallels the Alabama-Oklahoma transform and extends into the Laurentian craton from the Ouachita embayment in the rifted margin (Fig. 3). Bimodal igneous rocks (539–530 Ma) along the Southern Oklahoma fault system (Gilbert and Denison in Van Schmus et al., 1993) suggest a leaky transform, which, like

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1Originally termed “reentrant” (Thomas, 1977) but changed to “embayment” (Thomas, 1983) to avoid confusion with the term “recess,” which denotes a cratonward concave bend in a thrust belt.
the Alabama-Oklahoma transform, parallels the dextral bend in the Grenville front, the strike of the 1350-Ma dikes, and the possible dextral offset in the pre-Rodinia continental margin, clearly indicating tectonic inheritance.

**ASSEMBLY OF PANGAEA (THE APPALACHIAN-OUACHITA OROGEN)**

The Appalachian-Ouachita orogenic belt records the successive, diachronous Taconic (Ordovician-Silurian), Acadian (Devonian-Mississippian), and Alleghanian (Mississippian-Permian) orogenies (Drake et al., 1989; Osberg et al., 1989; Hatcher et al., 1989), culminating in closure of Iapetus and assembly of the Pangaea supercontinent in Permian time. The well-mapped trace of the orogen from Newfoundland to Alabama exhibits sweeping curves of salients (convex cratonward in the direction of tectonic transport) and more angular recesses (concave cratonward) (Fig. 4). Westward from Alabama in the subsurface beneath the Gulf Coastal Plain, deep drill and seismic reflection data, as well as outcrops in the Ouachita Mountains and in the Marathon region of west Texas, document curves of similar magnitude (Thomas et al., 1989).

Appalachian-Ouachita salients are located at embayments of the Iapetan margin, and recesses are on promontories (Rankin, 1976; Thomas, 1976, 1977). The leading part of the thrust belt wrapped around the shape of promontories and embayments of the older rifted margin (Fig. 4), indicating a grand scale of tectonic inheritance. Other specific manifestations of tectonic inheritance are expressed at a range of scales.

Each of the three comprehensive orogenic episodes encompasses substantial along-strike diachronieity, which reflects a systematic relationship to the shape of the Iapetan rifted margin. From the St. Lawrence promontory to the Alabama promontory, a stratigraphically upward transition from shelf carbonates to black shale records Taconic tectonic loading, foreland subsidence, and synorogenic sedimentation (Drake et al., 1989). The times of initial Taconic tectonic loading and foreland subsidence vary systematically in relation to the shape of the Iapetan rifted margin: first, on the St. Lawrence promontory in Newfoundland; next, on the Alabama promontory followed by migration...
Figure 4. Assembly of Pangaea as recorded in the Appalachian-Ouachita orogen (compiled from references cited in text). Patterns for synorogenic clastic wedges show areas where thickness is $>50\%$ of the maximum (in present allochthonous position not palinspastically restored); dashed line shows deeper part of the intracratonic Anadarko basin. BWb—Black Warrior basin.

Figure 5. Breakup of Pangaea and opening of the Atlantic Ocean (compiled from Klitgord and Schouten, 1986; and references cited in text). SGBfz—Southern Grand Banks fracture zone (transform); SGb—South Georgia basin.
into the Tennessee embayment; then, on
the New York promontory followed by
migration into the Pennsylvania embay-
ment; and finally, in the Quebec embay-
ment (Bradley, 1989, Figures 1 and 7
therein). Taconic terrane accretion must
have modified the shape of the margin;
however, initial Acadian foreland subsi-
sidence migrated progressively south-
ward from the St. Lawrence promontory
to the Virginia promontory (Ettensohn,
1985, Figures 1 and 2 therein). Along the
Appalachian orogen, late Paleozoic
Alleghanian foreland subsidence over-
printed the Taconic and Acadian fore-
lands; however, along the Ouachita mar-
gin westward from the corner of the Ala-
bama promontory, a passive margin per-
sisted until Mississippian time (Thomas,
1989). Ouachita tectonic loading of the
Laurentian margin began in middle Miss-
sissippian time in the Black Warrior fore-
land basin along the southeastern part
of the Alabama-Oklahoma transform on
the Alabama promontory and migrated
northwestward along the transform to the
Arkoma foreland basin in the Ouachita
embayment in Early Pennsylvanian time
(Fig. 4) (Houseknecht, 1986; Thomas,
1989), continuing the pattern of adapta-
tion of the shape of the orogen to that of
the Iapetan rifted margin.

Regardless of the diachronicity of fore-
land subsidence and synorogenic sedi-
mentation along the orogen, maximum
subidence, as indicated by maximum
thickness of synorogenic sediment along
the Taconic, Acadian, and Alleghanian
forelands, is centered consistently in
embayments of the Iapetan rifted mar-
gin (Fig. 4) (Thomas, 1977, Figures 5–10
therein). Although the differences in the
magnitude of subsidence could reflect
along-strike variations in the magnitude
of the tectonic loads, the systematic rela-
tionship of differentially greater foreland
subidence in the embayments than on
the promontories suggests a systematic
spatial variation in the strength of the
lithosphere in relation to the shape of the
older rifted margin. Brittle structures in
the shallow crust define the shape of the
rifted continental margin; however, the
distribution of magnitudes of foreland
subsidence suggests tectonic inheritance
at a lithospheric scale.

In addition to thrust-belt curvature
convex toward the craton, where thrust-
belt salients bend around embayments
of the rifted margin, the thrust belt prop-
agated to a greater width and farther cra-
tonward in salients than in recesses (Fig.
4). The geometry of the salients adapted
to the greater thickness of sedimentary
cover and to greater depth to crystalline
basement rocks beneath foreland basins
in the embayments. Along the Appala-
chian orogen, the thin-skinned décolle-
ment in salients is within the Paleozoic
sedimentary cover succession above
Precambrian crystalline basement rocks.

On some promontories along the arms
of thrust-belt recesses, the Appalachian
allochthon incorporates crystalline base-
ment rocks in external basement massifs
(Fig. 4), indicating that the décollement
cuts down from the thick sedimentary
cover in embayments along strike into
basement rocks beneath a thinner sedi-
mentary cover on promontories. Uncon-
formable overstep of Silurian conglomer-
ate onto basement rocks on the southern
part of the New York promontory (Drake
et al., 1989) indicates that the Taconic
foreland, like the later Alleghanian fore-
land, incorporated an external basement
massif on the promontory.

Synorogenic brittle reactivation of
Iapetan synrift intracratonic faults
inboard from the rifted margin is evident
from the proximal to the distal foreland,
indicating compressive stress from Appa-
lachian-Ouachita orogenesis (e.g., Kolata
and Nelson, 1991). The thin-skinned
thrust belt includes both frontal and
lateral ramps that rise above basement
extensional faults and transverse faults,
respectively (e.g., Thomas and Bayona,
2005). Reactivated faults and a south-
plunging arch overprinted the Iapetan
Mississippi Valley graben (Thomas, 1991).

Reactivation of the Southern Oklahoma
fault system generated the Arbuckle-
Wichita-Amarillo basement uplifts
(Perry, 1989); the associated Anadarko
basin along the fault system is among the
deepest known cratonic basins.

In the Appalachian metamorphic
interides, which include accreted ter-
ranes and internal basement massifs,
orogen-parallel strike-slip faults (Gates et
al., 1988) show no systematic adaptation
to the shape of the older Iapetan rifted
margin (Fig. 4), suggesting oblique colli-
sion, transpression, and orogen-parallel
tectonic transport. The effects of tectonic
inheritance evidently diminish outboard
from the older rifted margin, probably
because accretion of successive terranes
modified the shape of the margin.

The latest episodes of Alleghanian
foreland thrusting appear nonsystem-
atically diachronous along the orogen.
Although not precisely dated, the last of a
succession of Alleghanian events around
the Alabama promontory was continen-
tal-continent collision with African con-
tinental crust, now marked by a suture
beneath the Gulf Coastal Plain (Fig. 4).
The suture is oblique to the Iapetan
rifted margin, diverging eastward from
the corner of the Alabama promontory.
Continental-continent collision drove pre-
viously accreted terranes onto the contin-
ental shelf of the Alabama promontory,
accounting for a diachronous succession
of Ouachita and Appalachian thrusting
(Thomas, 2004). The shape of the
Iapetan margin, and not the shape of the
collider, evidently controlled the orien-
tation of Appalachian-Ouachita foreland
structures.

Appalachian-Ouachita structures, from
the scale of salients and recesses to fore-
land basins to individual thrust ramps
and basement faults, have a clear pattern
of tectonic inheritance from the trace
and structures of the Iapetan rifted margin
of eastern Laurentia. Most of the inher-
ited structures are in the brittle, shallow
crust; however, localization of maximum
synorogenic flexural subsidence of the
foreland in embayments of the Iapetan
margin along transform faults (at ocean-
ward concave intersections of transfor-
mult faults with rift segments) suggests
tectonic inheritance at a lithospheric
scale. The assembly of Pangaea also set
the mold for subsequent structures that
formed during supercontinent breakup.

BREAKUP OF PANGAEA
AND OPENING OF THE ATLANTIC
OCEAN

Triassic grabens adjacent to the Atlan-
tic Coastal Plain document inboard ex-
tension associated with the breakup of
Pangaea, the opening of the modern
Atlantic Ocean, and the isolation of the
North American continent. Unlike the
records of earlier Wilson cycles, this
latest event is recorded in the modern
continental shelf and ocean floor, includ-
ing transform faults that extend from
the Mid-Atlantic Ridge to offsets in the
shelf margin (Fig. 5). In addition to the
exposed Triassic faults, subsurface data
The Southern Grand Banks fracture zone (transform) along the southern margin of the Grand Banks of Newfoundland (Keen and Haworth, 1985) is aligned with the trace of the Iapetan transform at the southern margin of the St. Lawrence promontory (Fig. 5). The trace of the Atlantic rifted margin east of the Grand Banks promontory roughly parallels the trace of the Iapetan rifted margin, but it is far outboard of the Iapetan rift, leaving accreted terranes attached to the North American margin, a pattern that persists southward to the Florida promontory.

Tectonic inheritance on a large scale is reflected in the coincidence in location of large transform offsets of the rifted continental margins. The extraordinary subsidence and sediment accumulation in the Mississippi River delta within the Gulf embayment is comparable to other examples of differentially greater subsidence along transforms. Inboard from the Bahamas transform margin, subsidence of the Mississippi Embayment, a south-plunging syncline in the Gulf Coastal Plain, overprints the Pangaeo (late Paleozoic) south-plunging arch and the Iapetan intracratonic Mississippi Valley graben, documenting successive inheritance at a pervasive zone of weak crust. The same zone of weak crust hosts the modern New Madrid seismic zone. On a smaller scale, Atlantic-opening extensional faults reactivated accretionary compressional fabrics of the Pangaeo assembly (e.g., Boyarchick and Glover, 1979).

**CONCLUSIONS**

Transform faults and aligned compresional structures show repeated tectonic inheritance through successive Wilson cycles of supercontinent assembly and breakup (Fig. 1). In contrast, rift segments of continental margins accumulate accreted terranes, because subsequent rifts break across terrane boundaries, fragmenting the supercontinent assembly. Brittle extensional structures and upper-crustal orogenic structures reflect processes in the shallow crust, as do the many examples of smaller scale tectonic inheritance and reactivation of individual faults. Two relationships, however, suggest inheritance at a lithospheric scale: successive reoccupation of traces of transform faults at the continental margin and differential crustal subsidence along transform faults at rift offsets in continental embayments. A pervasive fabric may vertically partition the lithosphere, both controlling the locations of transforms during successive events of supercontinent breakup and reducing the elastic strength of the lithosphere along transforms, thereby accounting for locations of greatest differential subsidence.

Kinematics of plate boundaries require that transform faults are small circles around the pole of rotation, are parallel to the direction of plate motion, and are essentially vertical, consistent with extent down through the lithosphere. In contrast, rift segments are brittle upper-crustal structures above low-angle detachments that flatten downward within the crust, consistent with inheritance at the scale of individual faults in shallow (brittle) crust.

Recognition of tectonic inheritance has implications for a range of applications beyond the fundamental questions of crustal structure and evolution of continental crust and lithosphere. Differential subsidence at zones of lithospheric weakness, primarily along transform systems, localizes the potential for petroleum provinces in exceptionally thick sedimentary accumulations. Mineralizing brines may be selectively driven from the thicker sedimentary thrust loads in thrust-belt salients at rift-margin embayments, including into the distal foreland. On a smaller scale, frontal thrust ramps over older basement faults, thin-skinned transverse zones over basement transverse faults, and reactivation of basement faults in the foreland provide predictable controls on fracture sets that affect fluid flow in both petroleum and groundwater systems. Repeated inheritance of zones of crustal weakness suggests a focus for modern seismicity.

Studies of tectonic inheritance generally rely on data from the shallow crust, limiting evaluations to a crustal scale. The pervasiveness of zones of crustal weakness associated with transform faults, however, requires a lithospheric scale of investigation. Recent studies of seismic anisotropy define lithosphere-penetrating zones of distributed shear along transform systems (e.g., Baldock and Stern, 2005). The probable significance of transform inheritance and lithospheric properties suggests a fruitful line
of investigation, because transform faults appear to be the dominant controls on tectonic inheritance at large scales along continental margins during supercontinent breakup and assembly, as well as on locations of differential subsidence and exceptionally thick sediment accumulations. Resolution of the lithospheric structure of transform faults in the context of tectonic inheritance offers an exciting new perspective and understanding of the evolution of continental crust and lithosphere.

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REFERENCES CITED


Wilson, J.T., 1966, Did the Atlantic close and then reopen?: Nature, v. 211, p. 676–681.

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