Plate-scale stress fields driving the tectonic evolution of the central Ouachita salient, Oklahoma and Arkansas

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ABSTRACT

Two stages of regional cross-fold jointing reflect the rearrangement of a lithospheric-plate-scale stress field during the Ouachita (i.e., Alleghanian) orogeny. These joints overprint northward-verging thrust-related folds in the Ouachita foreland. Stage-one jointing during the Ouachita orogeny is associated with a stress field recorded by an Atokan and earlier regional joint set, which has a NNE strike. Stage-one jointing is separated into two phases in the central Ouachita salient, where a second-order recess is marked by a prominent bend in the Windingstair fault below the forelandmost sheet of the central thrust belt. The Big Cedar recess developed when the Windingstair sheet overrode the frontal imbricate zone, thereby causing the Big Cedar pinch zone, a structure reflecting fold-parallel shortening proximal to localized dextral transpression in the Choctaw thrust sheet. A later regional joint set, representing the second stage of jointing during the Ouachita orogeny, affects rocks in the Arkoma foreland as well as in the fold belt. Stage-two jointing records a stress field associated with NNW-directed closure during the final stage of plate convergence; this stage persisted into the Desmoinesian.

Keywords: joints, Ouachita fold-and-thrust belt, stress fields, fracture, Arkoma Basin, pinch zone.

INTRODUCTION

The world stress map demonstrates that the upper continental crust within several lithospheric plates is subject to a well-organized if not rectilinear contemporary tectonic stress field (Zoback, 1992). Most of these intraplate stress fields arise from plate-boundary conditions, including shape of the boundary and convergence direction (e.g., Nakamura et al., 1977). Because joints open parallel to the least principal stress more or less instantaneously, a well-organized regional set may record the orientation of a lithospheric-scale maximum horizontal stress, S_H, as is the case for a neotectonic joint set in northwestern Europe (Hancock and Engelder, 1989). Joint sets present in a sufficiently large region of the upper crust reflect past plate-boundary stress fields in several forelands, including the Canadian foothills (Babcock, 1973), the Appalachian plateau (Nickelsen and Hough, 1967; Engelder and Geiser, 1980), the Variscan (Dunne and North, 1990), the Sevier (Laubach and Lorenz, 1992), the Pyrenees (Turner and Hancock, 1990; Arlegui and Simon, 2001), and others. In some instances, the rearrangement of plate-scale stress fields is recorded by crosscutting or abutting regional joint sets (e.g., Younes and Engelder, 1999; Engelder, 2004).

These types of regional joint patterns are found largely in lightly deformed forelands. Moving toward the hinterland of mountain belts, joint patterns become increasingly complex, with joint sets forming in response to local stresses associated with fault-related folding and other processes in the brittle crust (e.g., Delaney et al., 1986; Dyer, 1988; Dunne and North, 1990; Rawnsley et al., 1992; Lemiszki et al., 1994; Cooke et al., 2000; Engelder and Peacock, 2001; Rogers et al., 2004; Fischer and Christensen, 2004). As local structures and cogenetic joint sets increase in complexity, it becomes more difficult to sort out those joints controlled by a foreland-wide stress field arising from tractions at the plate boundary (e.g., Gray and Mitra, 1993; Fischer and Jackson, 1999; Silliphant et al., 2002).

Outcrops in the distal portion of the Ouachita foreland, including the Central Plains and (mostly outer) Arkoma Basin in Oklahoma, also display joints that record a well-organized regional stress field (Fig. 1). There, joints propagate in a fan-like pattern approximately perpendicular (dip system) and parallel (strike system) to overthrust faults of the Ouachita foreland (Melton, 1929). This fan-like pattern of NNW-striking joints in the distal foreland belies the dominant northward vergence of predominately E-W–striking imbricate thrust faults along more than 250 km of the Ouachita salient crossing the Oklahoma-Arkansas border (Fig. 2). Although not consistent with the north-directed kinematics of the central Ouachita salient, the fan-like pattern arguably reflects the plate-scale stress field during assembly of Pangea in the Pennsylvanian.

An objective of this paper is to sort out jointing controlled by a well-organized if not rectilinear salient-wide stress field in the Ouachita foreland from jointing that propagated in response to local structural and stratigraphic boundary conditions. To achieve this end, we couple an outcrop-by-outcrop sampling of joint patterns with detailed geological mapping working outward into the foreland of Arkansas and Oklahoma from the Big Cedar recess in eastern Oklahoma (Fig. 3). Data were collected on the orientation, crosscutting relationships, and the shear reactivation of joints at outcrops covering 10,000 km^2 in a more proximal portion of the Ouachita foreland relative to Melton's (1929) mapping (Fig. 3). Foreland deformation in the Ouachita fold belt consists of three distinct styles pointing to a disparate history of stress-field development across the structural provinces (Arbenz, 1989). This begs the question whether or not there is evidence for a plate-scale stress field preserved in evolving structures of all three foreland provinces of the Ouachita fold-and-thrust belt.

TECTONIC SETTING

The Ouachita fold-and-thrust belt is part of a system of Pennsylvanian-Permian thrust belts formed along the southeastern margin of North

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GSA Bulletin; May/June 2006; v. 118; no. 5/6; p. 710–723; doi: 10.1130/B25780.1; 13 figures; 1 table.

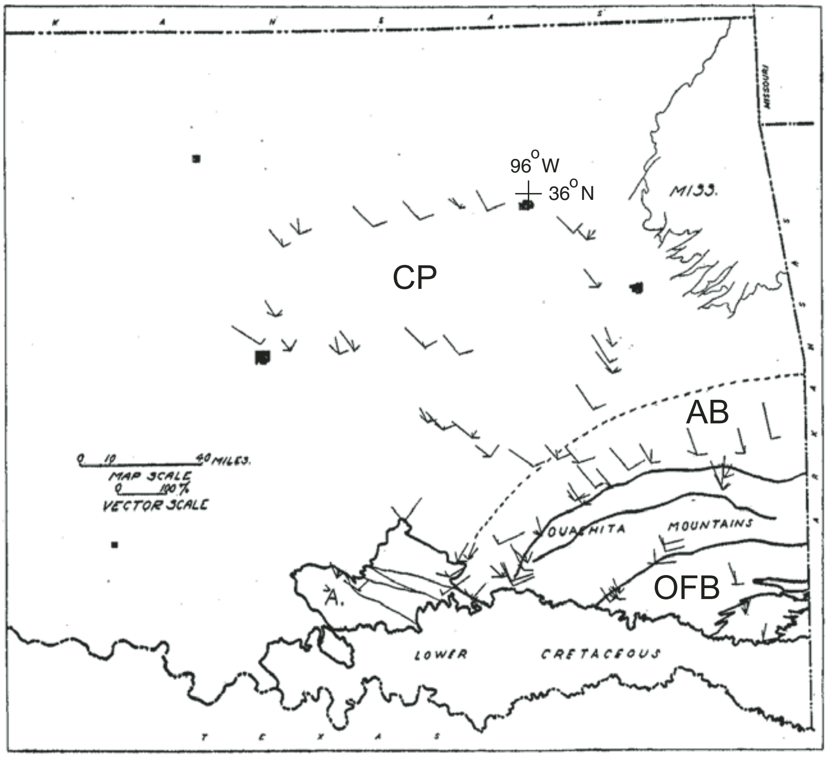

Figure 1. Melton's (1929) map of joint patterns in the Central Plains (CP), Arkoma Basin (AB), and Ouachita fold-and-thrust belt (OFB).

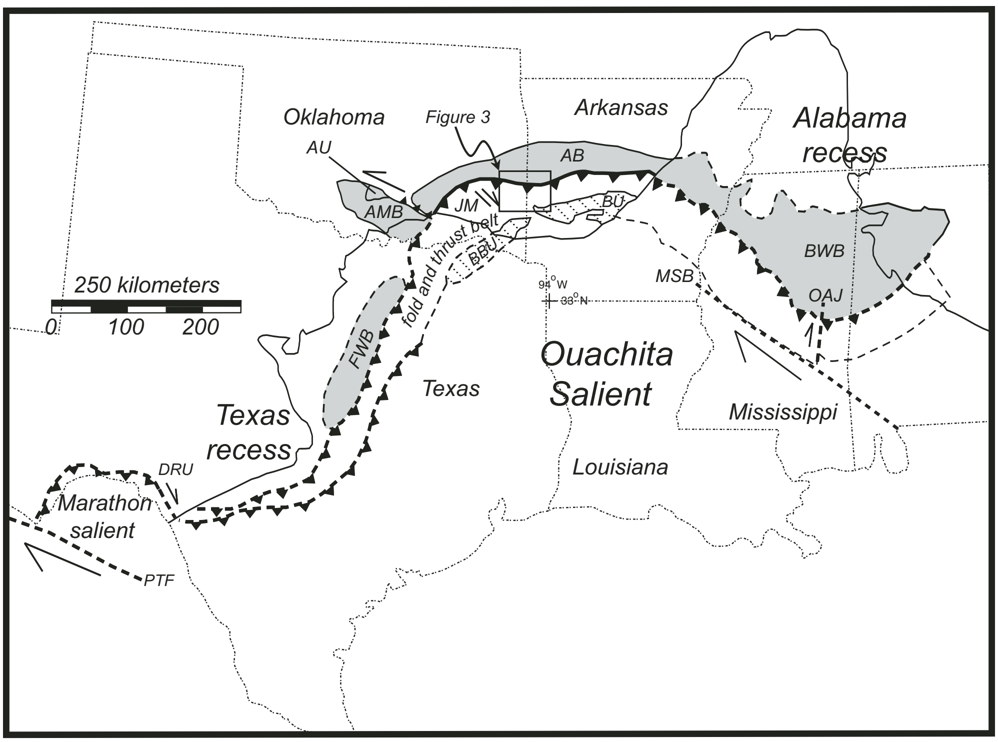

Figure 2. Tectonic map of the Ouachita salient showing zones of strike-slip displacement during the Ouachita orogeny. Background map is after Viele and Thomas (1989). Foreland basins are shaded; Broken Bow and Benton uplifts are stippled. Abbreviations: AB—Arkoma Basin; BWB—Black Warrior Basin; BU—Benton uplift; BBU—Broken Bow uplift; FWB—Fort Worth Basin; AMB—Ardmore/Marietta Basin (sinistral slip from Granath, 1989; Pindell, 1985, indicates the slip is dextral); AU—Arbuckle uplift; JM—Jackfork Mountain (dextral slip from Miser et al., 1954; Arbenz, 1989); MSB—Mississippi slate belt (dextral slip from Pindell, 1985); OAJ—Ouachita-Appalachian juncture (dextral slip from Hale-Erlich and Coleman, 1993); DRU—Devil's River uplift (dextral slip from Pindell, 1985); PTF—Pedregosa Trough fault system (dextral slip from Pindell, 1985).

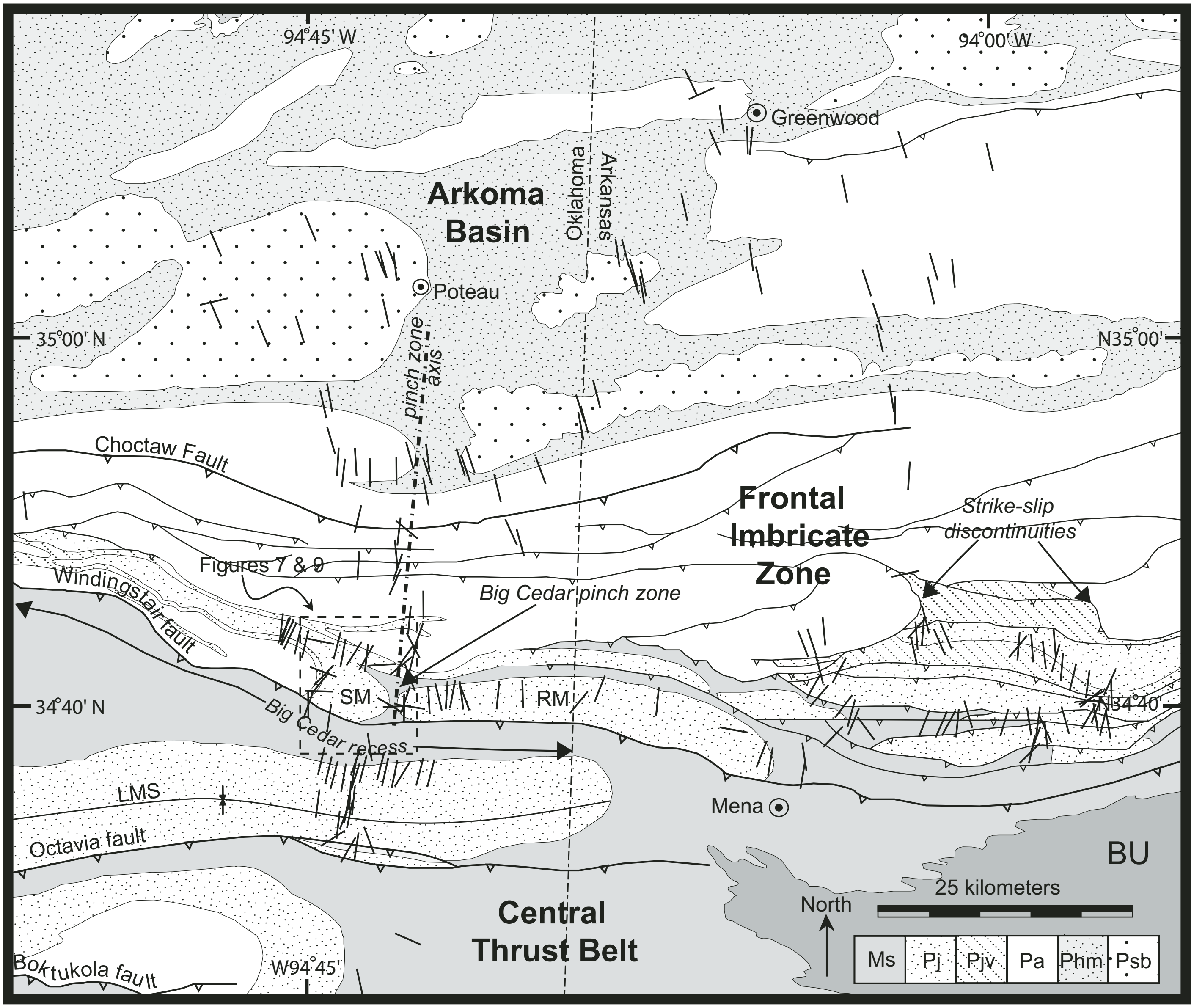

Figure 3. Simplified geological map of the central Ouachita fold-and-thrust belt and Arkoma Basin with mean joint azimuth of the most-frequent joint set plotted for selected outcrops. Major thrust faults (Boktukola, Octavia, Windingstair, Choctaw) are traced with bold lines. Imbrications in the frontal imbricate zone are traced with lighter lines. Formation symbols are: Ms—Mississippian Stanley Group; Pj—Pennsylvanian (Morrowan) Jackfork Group; Pjv—Pennsylvanian (Morrowan) Johns Valley Formation; Pa—Pennsylvanian (Atokan) Atoka Formation; Phm—Pennsylvanian (Desmoinesian) Hartshorne and McAlester Formations; Psb—Pennsylvanian (Desmoinesian) Savanna and Boggy Formations. See Figure 2 for the location of the study area. LMS—Lynn Mountain syncline; SM—Simmons Mountain syncline; RM—Rich Mountain syncline; BU—Benton uplift.

America as Pangea amassed (e.g., Viele and Thomas, 1989). The Ouachita salient is a first-order tectonic feature, the present-day geometry of which was determined first by the embayment developed along the margin of Laurentia during the rifting in the late Proterozoic (e.g., Thomas, 1977) and then by the collision between the southern margin of Laurentia and Gondwanan terranes in the Carboniferous (Fig. 2). Plate reconstructions indicate that the Ouachita salient was occupied by one or more exotic landmasses that encroached from the southeast in the Mississippian and Pennsylvanian periods (Pindell, 1985; Mickus and Keller, 1992).

Paleozoic Ouachita strata consist of deep-water pre-orogenic rocks overlain by a synorogenic sequence that was deposited at extremely high rates (up to 2 km/m.y.) (Viele and Thomas, 1989; Morris, 1989). After convergence commenced in the Mississippian, the Stanley Group (Fig. 4), largely turbidites, accumulated in the Ouachita trough and had an exotic source to the southeast (Johnson et al., 1988). By the early Pennsylvanian deposition of the Jackfork Group, the Ouachita trough had narrowed with continued closing of the ocean basin (Johnson et al., 1988). The Atoka Formation represents the most rapid sedimentation in the Ouachita belt, and the maximum thickness of Atoka is estimated between 6400 (Johnson et al., 1988) and

8500 m (Morris, 1989). Its burial was enhanced by foreland extension induced by tectonic loading to the south (Johnson et al., 1988). By the end of the Atokan, the Ouachita trough had closed fully, and the thrust sheets of the Ouachita fold belt were mostly emplaced (Johnson et al., 1988). The Desmoinesian strata, the youngest deformed in the Ouachita orogeny, are in part an accumulation of sediments from a fluvial system parallel to the Ouachita fold belt (Johnson et al., 1988).

The foreland of the Ouachita orogenic belt of southeastern Oklahoma has three tectonic provinces, each with a unique style of fault-related folding (Arbenz, 1989). These provinces include the central thrust belt between the Boktukula fault in the south and the Windingstair fault in the north, the frontal imbricate zone, extending north from the Windingstair to the Choctaw fault, and the Arkoma Basin north of the Choctaw fault (Fig. 3). Relatively intact, broadly syn-

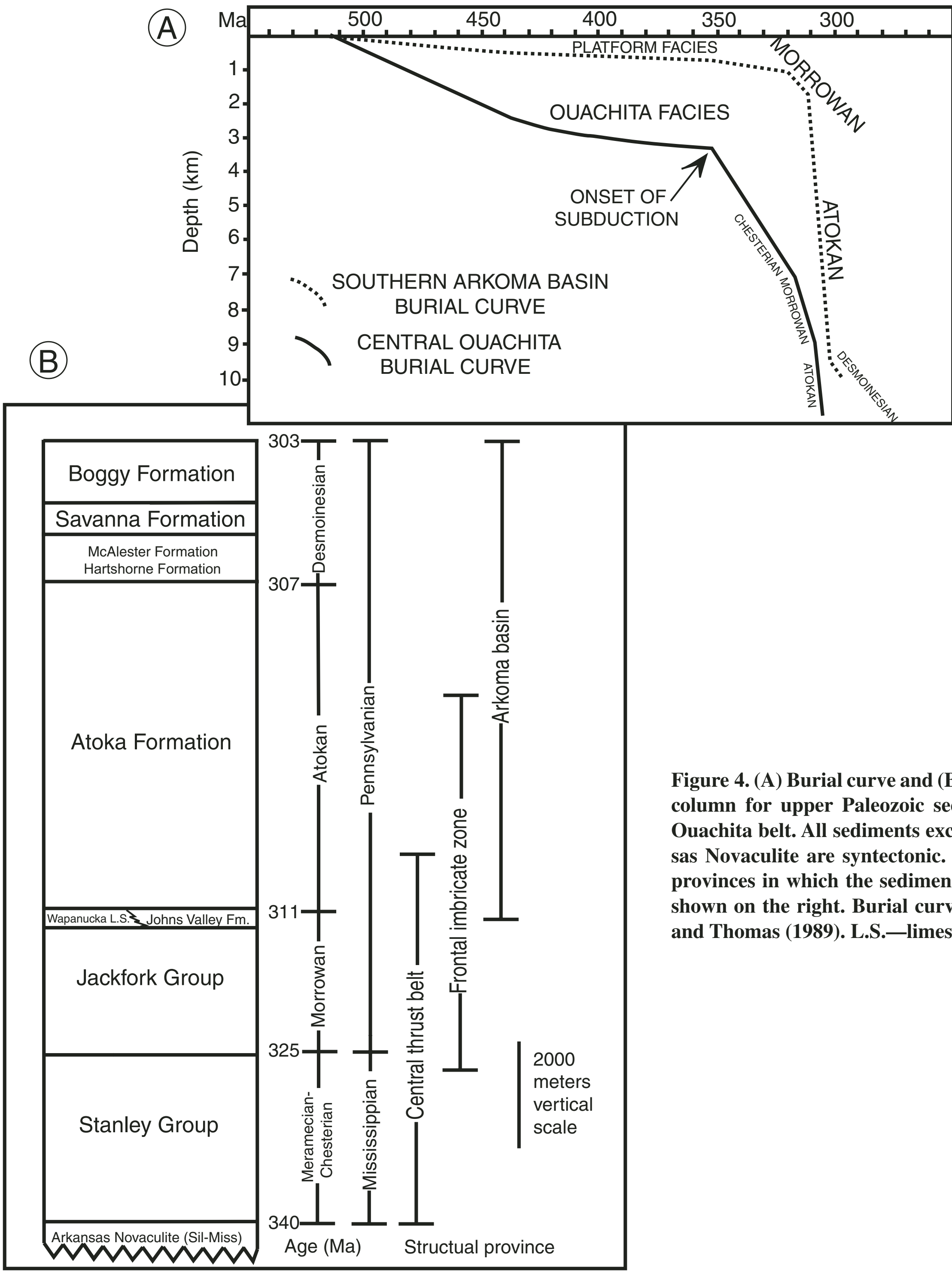

Figure 4. (A) Burial curve and (B) stratigraphic column for upper Paleozoic sediments in the Ouachita belt. All sediments except the Arkansas Novaculite are syntectonic. The structural provinces in which the sediments crop out are shown on the right. Burial curve is after Viele and Thomas (1989). L.S.—limestone.

clinal, thrust sheets separated by overthrust faults spaced 10–15 km apart compose the central thrust belt. In the frontal imbricate zone, thrust sheets are imbricated by smaller faults, which results in more complex fold patterns. The foreland Arkoma Basin consists of gently folded cover rocks disguising a detachment at depth. Thick sediments of the Arkoma Basin lie beneath the relatively thin thrust sheets of the central thrust belt and the frontal imbricate zone (Kruger and Keller, 1986; Mickus and Keller, 1992).

Although the Carboniferous section is as much as 10 km thick, at the onset of folding in the Pennsylvanian, the base of the Jackfork was likely buried to a depth of 3–4 km in the frontal imbricate zone, a situation consistent with the burial curve produced for the central Ouachita belt (Fig. 4) (Viele and Thomas, 1989). Locally, as stacking fault blocks thickened the stratigraphic column, strata at the surface today may have been buried under an additional 1–2 km. In other portions of the Ouachita belt, vitrinite reflectance data indicate that thermal maturity was reached primarily by sedimentary burial (Houseknecht and Matthews, 1985).

DATA

Regional Joint Patterns

In the Ouachita fold belt, most outcrops contain more than one joint set. The pattern of mean joint (i.e., the planes normal to the vector mean pole) orientations of the most frequent set found at outcrops is distinctly different among the structural provinces (Fig. 3). In the central thrust belt, the mean cross-fold joint-set strikes range from 355° to 020°, in the frontal imbricate zone, the range is 340°–025°, and in the Arkoma Basin, 340°–360°. In general, fracture data collected from the three structural provinces indicate that in the nonimbricated Arkoma Basin and central thrust belt, the regional cross-fold joint sets maintain consistent orientation between outcrops (Fig. 3). In contrast, in the frontal imbricate zone, where bedding-dip domains are of limited extent, joints are less organized and occupy a larger range of orientations (Fig. 3).

Fringe cracks are joints that extend from the tip of a preexisting joint subject to mixed mode loading (Pollard et al., 1982; Younes and Engelder, 1999). Fringe cracks at the tips of cross-fold joints identify a clockwise shift of horizontal stress axes in all three structural provinces of the Ouachita belt (Fig. 5). Anticlockwise rotation is also recorded in fringe cracks in the central thrust belt and in the frontal imbricate zone, but not in the Arkoma Basin (Fig. 5).

Trends emerge in the abutting relationships between joints in the three provinces, but not

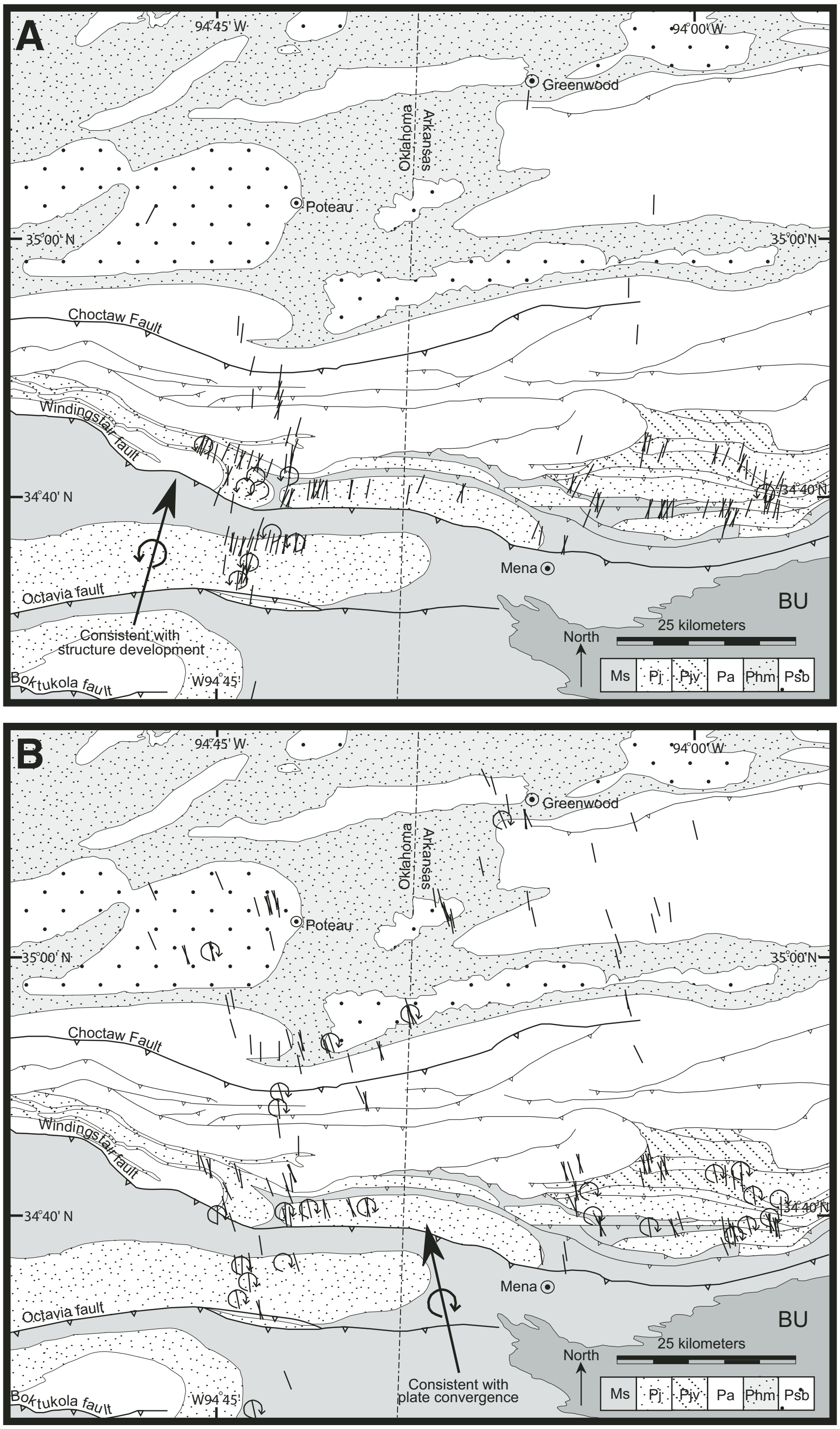

Figure 5. Summary of fringe cracks, cross-fold joints, and tectonic compression directions indicated by joints in the Ouachita Mountains. The display illustrates how the NNE and NNW joint sets can be distinguished by fringe crack development as well as by orientation. The NNE joints formed earlier in Atoka and older rocks. The NNW set formed later and is found in the Desmoinesian Boggy Formation and all older Carboniferous strata. Formations are: Ms—Stanley Group; Pj—Jackfork Group; Pjv—Johns Valley Formation; Pa—Atoka Formation; Phm—Hartshorne and McAlester Formations; Psb—Savanna and Boggy Formations; BU—Benton uplift. A simplified pattern of joints and fringe cracks is shown. (A) Older-stage NNE-striking joints and anticlockwise fringe cracks. (B) Younger-stage NNW-striking joints and clockwise fringe cracks.

without some ambiguity. In the Arkoma Basin, in most cases the cross-fold (i.e., 150°–170°) joints compose the first generation of fractures (Fig. 6). In the frontal imbricate zone, the most-consistent trend shows that strike-parallel joints (i.e., 080°–120°) predate the cross-strike joints (i.e., 160°–030°). Although a few exceptions exist, in the central thrust belt, nearly all strike-parallel (i.e., 080°–120°) joints predate the cross-fold (i.e., 170°–030°) joints (Fig. 6). In the frontal imbricate zone, more joint intersections demonstrate the sequence of cross-fold joints predating fold-parallel joints than in the central thrust belt. It becomes apparent by plotting age relationships that average strikes of Arkoma Basin joints are 20°–30° anticlockwise relative to central thrust belt joints (Fig. 6).

Geology of the Big Cedar Recess

The Big Cedar recess appears as an abrupt change in strike of the Windingstair fault (Figs. 3 and 7). To the west, the Windingstair fault is traced to the northwest at ~290°, and its trace goes due east from Big Cedar (e.g., Miser et al., 1954). This second-order recess in the Ouachita salient is largely developed within the frontal imbricate zone, although it also manifests as a bend in the Windingstair thrust sheet, the forelandmost sheet of the central thrust belt.

Two synclines, the Simmons Mountain syncline and the Rich Mountain syncline, are prominent structural features just north of the Windingstair fault (Figs. 3 and 7). These synclines terminate against each other at the Big Cedar recess in a tight, faulted anticlinal culmination (Fig. 8). Other folds in the Big Cedar recess have hinges that plunge to the east or west, although one notable exception is the anticline with a hinge parallel to, rather than normal to, the transport direction (Fig. 7; Table 1). This structure, herein termed the Big Cedar pinch zone, reflects E-W–directed compression between the Simmons Mountain and Rich Mountain synclines (Fig. 8). A cross section through the Big Cedar pinch zone indicates that the nose of the Simmons Mountain syncline was steepened during eastward transport toward the axis of pinching (Fig. 8).

Occasional outcrop faults are found in the Big Cedar recess. Small thrust faults have strikes uncharacteristic of the regional northward transport of the Ouachita belt (Fig. 9). Strike-slip faults are encountered in clusters and may be associated with tear zones. Oblique-slip faults are the most common outcrop-scale faults, and many reactivate preexisting fractures with a component of dextral slip. The faults were mapped with sense of slip or lineation direction as the exposures permitted (Fig. 9). Where slickenlines were measured, the compression direction responsible for the slip on each fault was arbitrarily assumed to be the horizontal projection of the fault lineation unless the angle to faulting was less than 10°. Then, the compression direction was assumed to be 30° from the strike of the plane; this includes cases where slip was observed without visible lineation (Handin, 1969). Compression directions inferred from oblique faults yield two general trends, one in the direction of transport on thrust faults and the other approximately E-W (Fig. 9).

Jointing throughout the Big Cedar recess is complex as early joints were tilted during fold growth. Poles to joints from steeply and gently dipping beds in the central portion of Simmons Mountain syncline were plotted together, and the distribution of poles indicates that cross-fold joints preferentially dip to the east (Fig. 10). Strike joints align with the WNW trend of the axis of Simmons Mountain syncline.

INTERPRETATION

Timing of Cross-Fold Joint Propagation Relative to Fold Development

Because data on the propagation sequence between the fold-parallel joints and the cross-fold joints are not definitive in each of the three structural provinces of the Ouachita salient

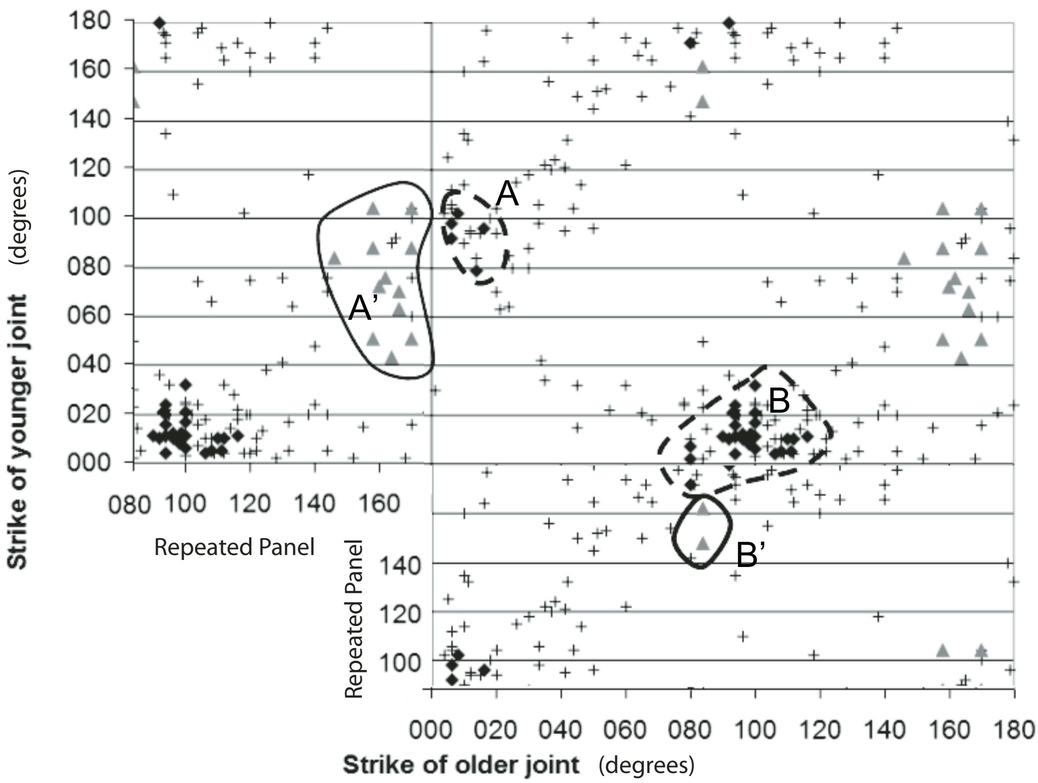

Figure 6. Age relationships among joints in the three provinces. There are two clusters (A–A′ and B–B′) of orthogonal joints. Joints in the Arkoma Basin (A′, B′) are offset in an anticlockwise direction from joints in the central thrust belt (A, B). In the central thrust belt, the E-W joint set is older, whereas it is younger in the Arkoma Basin. These data suggest that the cross-fold joints propagated during anticlockwise stress rotation prior to the onset of folding in the Arkoma Basin. Data from the central thrust belt are plotted as diamonds. Data from the frontal imbricate zone are plotted as crosses. Data from the Arkoma Basin are plotted as triangles. Strikes are normalized to the east component.

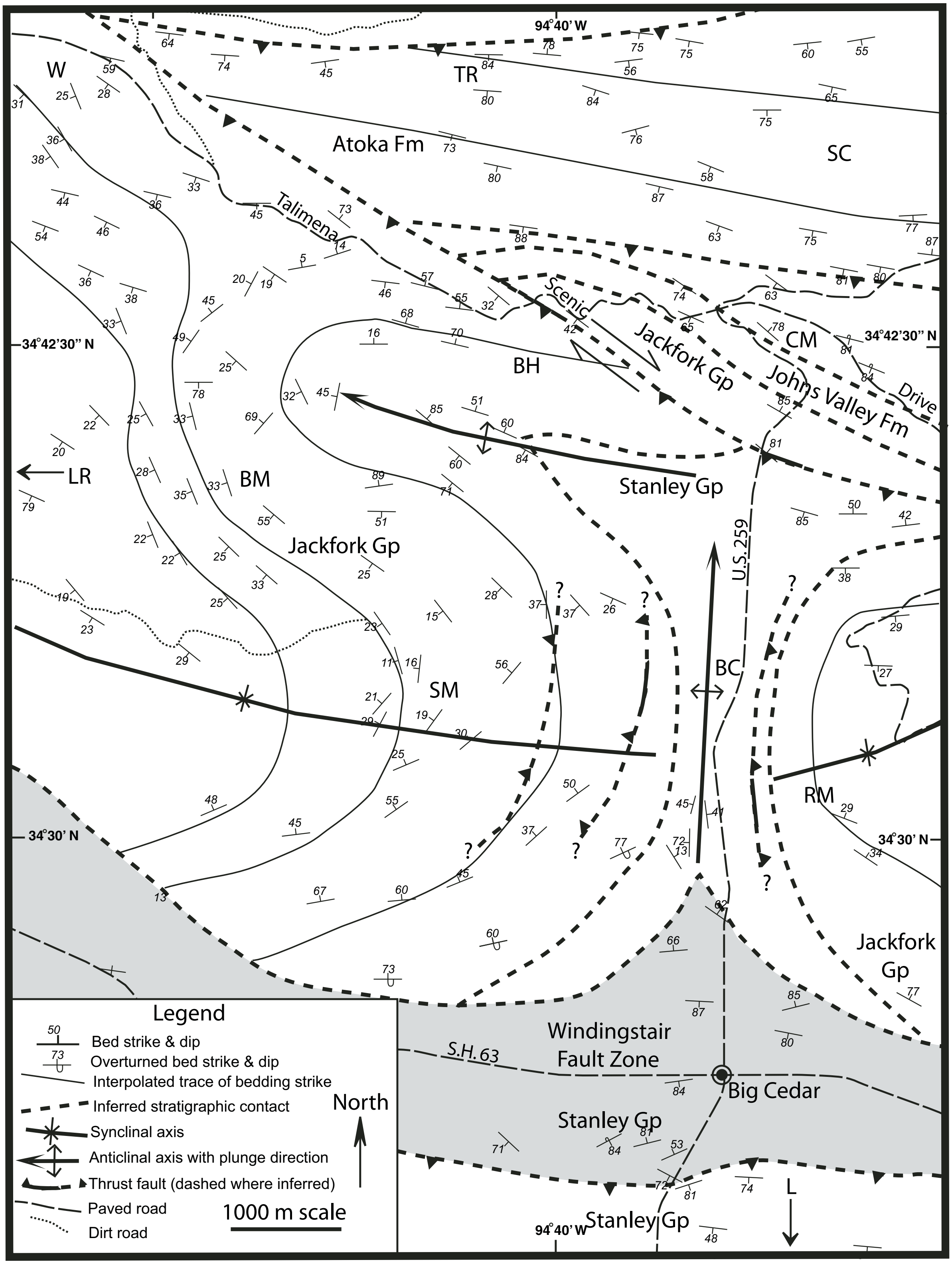

Figure 7. Simplified geological map of the structure of the Big Cedar pinch zone. Bedding attitudes are shown with fine lines interpolating bedding strike between outcrops. Major anticlinal and synclinal hinges are also plotted. Abbreviations: L—Lynn Mountain syncline; RM—Rich Mountain syncline; SM—Simmons Mountain syncline; BC—Big Cedar pinch zone; BM—Bowman Mountain; LR—Lenox Ridge; BH—Billy Hill; CM—Coon Mountain; TR—Tram Ridge; W—Windingstair Mountain; Gp—Group; S.H.—state highway. Approximate stratigraphic contacts are shown as dashed lines. Approximate fault contacts are shown with toothed dashed lines. The highly deformed area around the Windingstair fault is shaded.

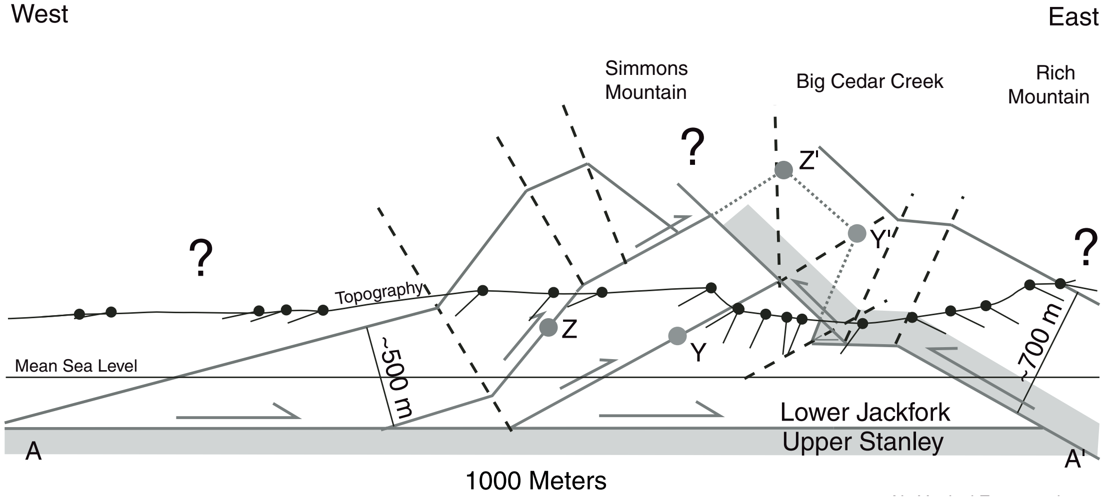

Figure 8. Schematic cross section across the Big Cedar pinch zone. The location of the A–A′ line of section is shown on Figure 9. The shaded area is Stanley Group; all other rocks are Jackfork Group. Tadpoles indicate the apparent dip of bedding to the east or west. The approximate trace of the overturned anticline before it was cut off by the west-verging fault is shown with a fine-dashed line. Fold hinges are coarse-dashed lines. Points Z′ and Y′ would have unfolded to approximately the location of points Z and Y. Question marks indicate that no attempt was made to constrain the roof geometry in those areas.

(Fig. 6), unfolding tests were applied to interpret the timing of cross-fold joints with respect to fold growth. The presence of vertical cross-fold joints in tilted bedding points to postfolding jointing driven by a horizontal least principal stress. Early cross-fold joints are orthogonal to bedding and were later tilted by folding. Timing relative to folding was interpreted by comparing samples of cross-fold joints in their present outcrop coordinates (assuming that the joints postdate the folds) with the same samples rotated to their prefold orientation. Joints were interpreted as prefold if restoring bedding to horizontal caused an increase in dip and as postfold if restoring bedding to horizontal caused a decrease in dip. Joints that changed dip by 1° or 2° were put in an intermediate category generally attributed to prefold jointing (Fig. 11).

Joint Set Correlation: Delineation of Regional Stress Fields

Regional joint sets are proxies for plate-scale stress trajectories (e.g., Engelder and Geiser, 1980). The likelihood that the confidence cones for joint set mean vectors at adjacent outcrops overlap is dependent on the alignment of a plate-scale stress field (Whitaker and Engelder, 2005). If stress trajectories are rectilinear during jointing, the confidence cones for the mean vectors of joint sets from outcrops separated by any distance will overlap. If the stress field controlling joint orientation is disturbed by local structures causing regional inhomogeneity, the radius of curvature of the stress trajectories limits the distance between outcrops that have overlapping joint mean vector confidence cones.

If the 95% confidence cones for joint mean vector overlap at nearby outcrops, the null hypothesis that the joint samples from both stations come from a population with the same mean cannot be excluded at the 95% confidence level (Fig. 12). Another threshold for joint set variability between outcrops, and therefore, stress field inhomogeneity, is that the mean vector confidence cones from nearby samples do not intersect, but the data ranges of the two sets overlap (Fig. 12). Joint sets in this group demonstrate that, statistically, the stress field varied by a small magnitude between outcrops during jointing.

The Arkoma Basin has the highest percentage of joint sets with the same statistical means between outcrops (Fig. 12). Joint set clusters vary little in strike in the Arkoma Basin, so the stress variation recorded between outcrops was generally 5°–10°. About 75% of joint set comparisons between outcrops in the central thrust belt yield the same statistical joint set or overlapping data ranges (Fig. 12). The spacing between outcrops in the central thrust belt averages a few hundred meters, indicating smaller-scale stress variability than in the Arkoma Basin. In addition, since joint confidence cones are smaller in

TABLE 1. BEST-FIT PLUNGE AND PLUNGE DIRECTION OF THE HINGE FOR SOME STRUCTURES IN THE BIG CEDAR QUADRANGLE

Structure name	Plunge (°)†	Plunge direction (°)†	Structure type
Coon Mountain	07	113	Synclinal
Shawnee Creek	18	100	Monoclinal?
Tram Ridge	17	087	Synclinal?
Billy Hill	13	289	Synclinal
Simmons Mountain	18	260	Synclinal
Rich Mountain	15	094	Synclinal
Big Cedar pinch zone	13	003	Anticlinal
Windingstair Mountain	19	273	Synclinal
Bowman Mountain	23	237	Anticlinal
Lynn Mountain	06	267	Synclinal

Note: Lynn Mountain data are taken in part from Briggs (1973). Locations are shown on Figure 7.
†Plunge directions follow the right-hand convention.

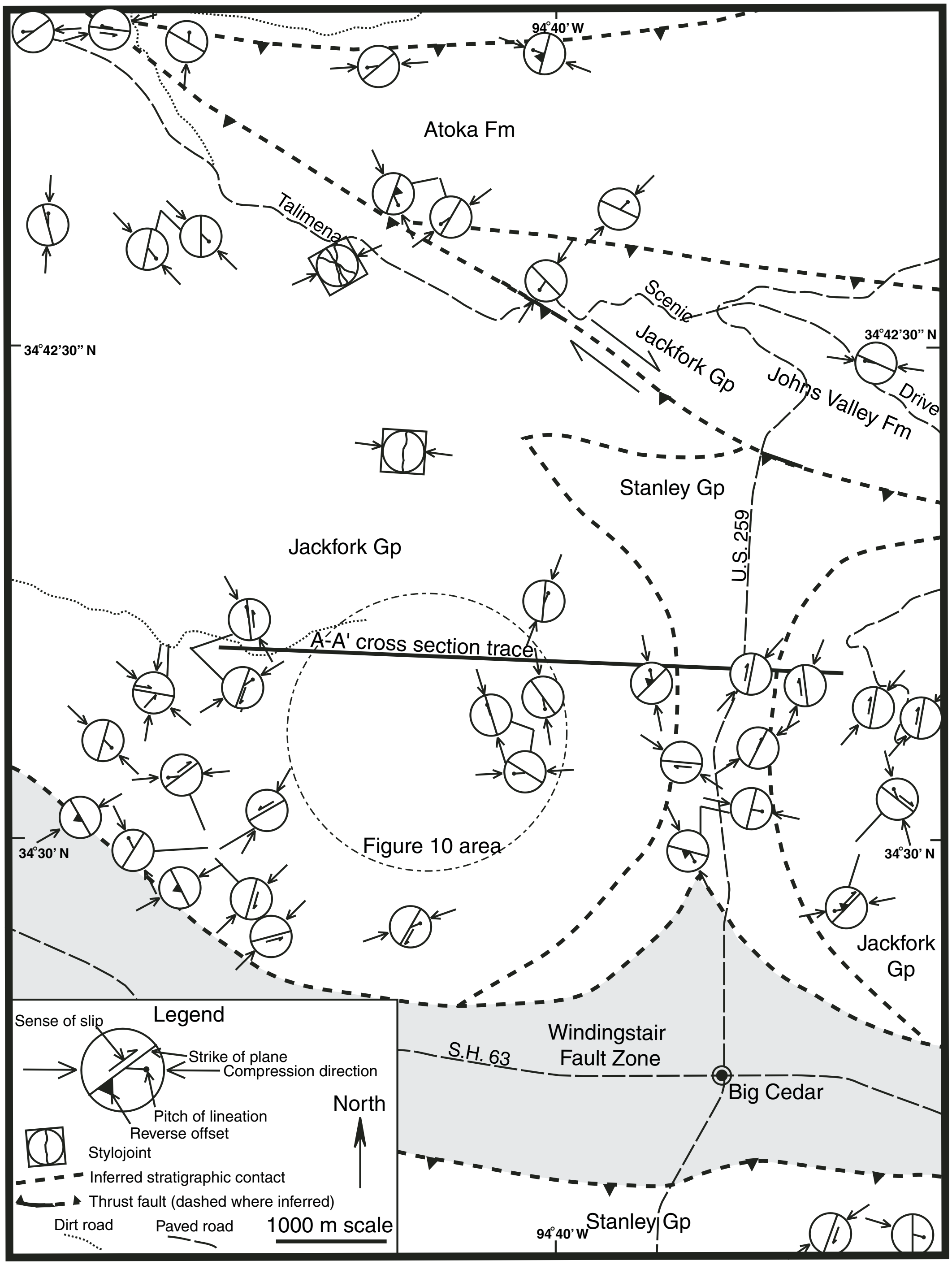

Figure 9. Faults near the Big Cedar pinch zone, the strikes of which are oblique to the primary transport direction. Interpreted compression directions are parallel to the lineation, or, if only a sense of slip was available, they are parallel to the friction angle. A stylojoint is a vertical joint, the surface of which was later stylolitized. The compression direction on the stylojoints is inferred from the stylolitic cleavage. Approximate stratigraphic contacts are shown as dashed lines. Approximate fault contacts are shown with toothed dashed lines. Cross-section A–A′ is shown on Figure 8. The highly deformed area around the Windingstair fault is shaded. The area enclosed by the dashed circle contains the joint data plotted in Figure 10. S.H.—state highway.

the Arkoma Basin, a greater magnitude of stress orientation variability is recorded in the central thrust belt. In the frontal imbricate zone, joint sets sampled at adjacent stations are unlikely to come from populations with the same mean or similar orientations. In the eastern and western frontal imbricate zone, outcrop spacing ranges from a few hundred meters (western) to a kilometer (eastern), which implies considerable stress variability on the scale of hundreds of meters. Differential dispersion during folding and transport along faults cannot account for most of the deviation, so we interpret the dispersion of joints to mean that the plate-scale stress field in the frontal imbricate zone was perturbed by stresses developed about local structures.

The joint mean vectors in the Arkoma Basin vary less than in the central thrust belt and frontal imbricate zone, even with greater distances between outcrops (Fig. 12). Despite comparable outcrop spacing, joint orientations vary more in the frontal imbricate zone than in the central thrust belt. Thus, joint populations may be expected to reflect the character of a plate-scale stress field in the Arkoma Basin, whereas in the frontal imbricate zone, the plate-scale stress may be obscured by local variability.

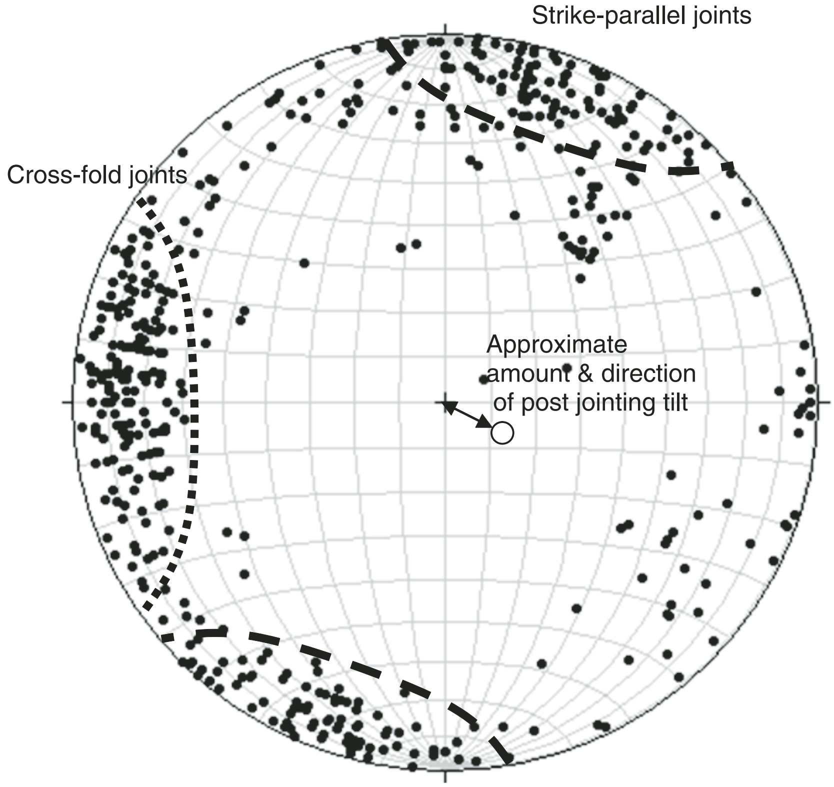

Figure 10. Equal-area stereonet of poles to cross-fold and fold-parallel joints measured in the Simmons Mountain syncline. Figure also shows the ~15° of NW displacement of the two joint sets after their formation. NW displacement occurred with the development of the Big Cedar pinch zone. See Figure 9 for the area in which joints in this plot were measured.

DISCUSSION

Strike-Parallel Pinching in the Big Cedar Recess

The distance between the Windingstair and Choctaw faults is greater to the east of Big Cedar than to the west, perhaps because slip was distributed along frequent, smaller faults in Arkansas (e.g., Haley et al., 1993). Due to greater northward transport of thrust sheets to the west, the Big Cedar recess was the locus for the development of anticlockwise fringe cracks indicating progressive two-phase deformation. Cross-fold jointing during the first phase suggests that folds and thrust faults developed normal to the regional transport direction. Fringe crack formation indicates that a second phase during E-W compression induced by differential displacement along the Windingstair and Choctaw faults caused the Big Cedar pinch zone (Fig. 7). Differential displacement across the pinch zone is manifested by joint rotation during right-lateral drag. Provided that the regional stress field remained fixed, a subsequent generation of joints would contain anticlockwise fringe cracks (e.g., Younes and Engelder, 1999).

Structures consistent with the development of the Big Cedar pinch zone, a right-lateral transpressional feature, include faults reactivated with oblique-slip vectors and a N-S anticline at the culmination between the Simmons Mountain syncline and Rich Mountain syncline (Fig. 8). Evidence for right-lateral displacement is found in the Big Cedar vicinity and is most concentrated in the culmination between the Simmons Mountain syncline and Rich Mountain syncline, suggesting that after the initial formation of these synclines, brittle strain concentrated between them during the second phase of deformation.

The preferential east dip of cross-fold joints at Simmons Mountain syncline (Fig. 10) is also tied to the kinematic evolution of the Big Cedar pinch zone. Prior to the development of the pinch zone, the cross-fold joints appear to have formed with dips clustered around vertical. Vertical rupture is a common phenomenon during early deformation of many forelands (e.g., Savalli and Engelder, 2005). During growth of the anticlinal culmination between the Simmons Mountain syncline and Rich Mountain syncline, westward plunge of the Simmons Mountain syncline increased with movement on east-verging faults, which accounts for the large population of east-dipping joints (Fig. 10).

E-W–striking thrust faults indicate a northward tectonic transport in the central Ouachita belt during the Ouachita orogeny (e.g., Fig. 3). In addition, evidence for large-scale strike-slip displacement is found in several locations along the Ouachita fold belt (Fig. 2). The Mississippi slate belt is thought to have formed during oblique convergence of the Yucatan Peninsula with southern Laurentia (Pindell, 1985). The strike-slip zones at the Ouachita-Appalachian juncture, Anadarko-Ardmore basin, and Devil's River uplift (Fig. 2) have been interpreted as features that accommodate abrupt changes in the trend of the fold belt (Pindell, 1985; Granath, 1989; Hale-Erlich and Coleman, 1993). Strike-slip displacement is also apparent on the smaller scale of the central Ouachita Mountains (Fig. 9). These minor strike-slip zones have a dextral sense and are found in the frontal imbricate zone or are associated with movement on the Windingstair fault.

Right-lateral strike-slip faulting in the western Ouachita belt is attributed to extension around the Ouachita salient (Arbenz, 1989), but central Ouachita strike-slip zones apparently arose due to differential displacement on thrust faults. As one segment of the thrust sheet moved toward the foreland, a transfer zone developed between it and the segment left behind. If the displacement vector of the moving section of the thrust sheet was nearly parallel to the retarded thrust sheet, a tear zone appeared. This is approximately the behavior of strike-slip discontinuities north of the Benton uplift (Fig. 3). Westward in Oklahoma, the displacement vectors of adjacent thrust sheets were not parallel, and this set up pinching of each sheet in the emerging recesses (e.g., Fig. 8). The Big Cedar pinch zone, a bend in the Ouachita fold belt 50 km northward from Big Cedar, formed as a result of east-west pinching toward the axis of the right-lateral zone (Fig. 3).

Plate-Scale Stress Fields During Tectonic Evolution of the Ouachita Salient

The distribution of joint orientations in the Ouachita belt demonstrates that the three structural provinces can be distinguished on the basis of joint domains as well as by deformation style (Fig. 3). In the central thrust belt, the mean strike of cross-fold joint sets ranges 25° from 355° to 020°. Faulting and fold growth in the two-phase development of the frontal imbricate zone (i.e., northward transport, then strike-slip pinch zones) promoted the propagation of spatially discontinuous fracture sets, which had a mean strike ranging 45°, from 340 to 025°. In the Arkoma Basin, cross-fold joint sets had mean strikes approximately between 340° and 360°, which most closely resemble Melton's (1929) joint set (Fig. 1).

A comparison of joint orientations with fold tilt removed relative to their present coordinates shows that cross-fold jointing occurred sporadically spatially throughout folding in each structural province (Fig. 11). As a result, each province has outcrops where most cross-fold joints are of the prefolding type and outcrops where most joints are of the postfolding type (Fig. 11). On average, at each outcrop in the central thrust belt and frontal imbricate zone, about half of joints are prefolding (Fig. 11A). In the Arkoma Basin, only a fifth of cross-fold joints (Fig. 11C) formed before folding, but they are found in rocks as young as the Boggy Formation (Fig. 4), and thus can be used to date the onset of macroscale folding in the Arkoma Basin as late as post-Desmoinesian.

In all three structural provinces, the joint data in present and prefold coordinates imply that some cross-fold joints propagated prior to folding, probably propagated during folding, and some formed after folding. At individual outcrops in each of the provinces, the strikes of the prefolding cross-fold joints overlap the strikes of postfolding joints, which demonstrates the orientation stability of a large-scale stress field throughout folding. The strike ranges of prefold and postfold joints overlap in the Arkoma Basin, indicating temporal persistence of a large-scale, rectilinear stress field past the Desmoinesian.

Jointing in the three tectonic provinces of the Ouachita foreland reflects two large-scale, nearly rectilinear stress fields (Fig. 5). In the central thrust belt and west of the Big Cedar recess in the frontal imbricate zone, the most common cross-fold joint set strikes east of north (Fig. 5A). In the Arkoma Basin, the most common cross-fold joints strike west of north (Fig. 5B). NNE-striking joints are rarely seen in Arkoma Basin outcrops, only in the Atoka Formation (Fig. 5A). In contrast, the NNW-striking joints occur throughout the foreland (Fig. 5B).

We argue that the scales of both nearly rectilinear stress fields in the Ouachita salient are large enough to reflect lithospheric plate-boundary tractions during assembly of Pangea. Furthermore, the orientation of these rectilinear stress fields reflects the convergence direction, much like the dikes of the Aleutian Islands reflect current tractions developed by the subduction of the Pacific plate below the North American plate (e.g., Nakamura et al., 1977). Thus, the plate-scale stress field under

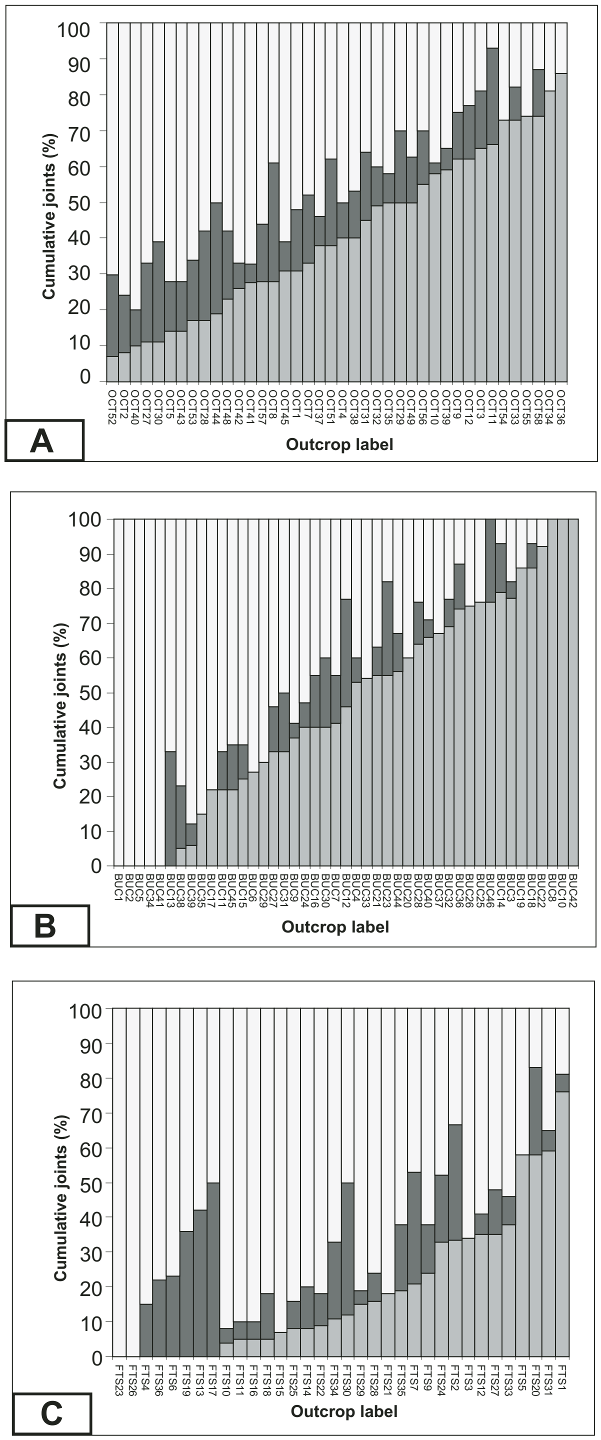

Figure 11. Graphs of the results of transforming cross-fold joints to prefold coordinates by station in Ouachita belt. In the central thrust belt and frontal imbricate zone, about half of joints formed before folding, whereas Arkoma Basin joints primarily formed after folding. The gray bars indicate joints that are steepened by the transformation of joints to prefold coordinates. The dark gray bars represent joints that are marginally steepened (<2°) by the transformation of joints to prefold coordinates. Together, black and gray compose prefolding joints as discussed in the text. The white bars represent joints made shallower by the transformation of joints to prefold coordinates and are referred to as postfolding joints in the text. (A) Outcrops from the central thrust belt. (B) Outcrops from the frontal imbricate zone. (C) Outcrops from the Arkoma Basin.

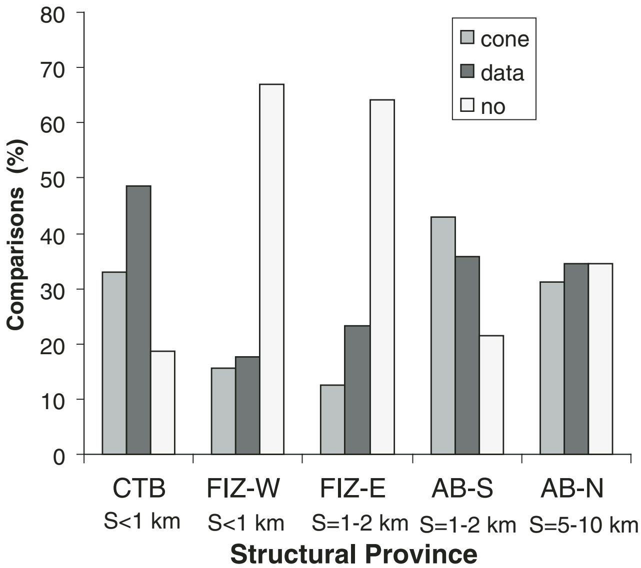

Figure 12. Station to station continuity of joint sets in three structural provinces of the Ouachita belt. Plot illustrates that even with greater spacing between outcrops in the Arkoma Basin (AB), joint orientations remain consistent. Also, frontal imbricate zone (FIZ) joints rarely have continuous orientations, even at closely spaced outcrops. "Cone" indicates that the 95% confidence cones for joint sets at two adjacent stations overlap; "data" indicates that the data range for joint sets at two adjacent stations overlap; and "no" indicates that there is no data range overlap for joint sets at two adjacent stations. Abbreviations: CTB—central thrust belt; FIZ-W—western frontal imbricate zone (Oklahoma); FIZ-E—eastern frontal imbricate zone (Arkansas); AB-S—southern Arkoma Basin; AB-N—northern Arkoma Basin; S—(average) spacing between outcrops.

which the NNE joints propagated and their driving mechanism were in place by the Atokan because this set is absent in the post-Atokan rocks (Fig. 5A). Sometime during the Atokan, plate-boundary conditions changed, leading to a regional stress field with S_H trending to the NNW (Fig. 5B) and affecting rocks throughout the fold belt and into the Arkoma Basin at least through the Desmoinesian.

The first stage of the Ouachita orogeny reflects the accretion of terranes represented by the Sabine and Monroe uplift (e.g., Pindell, 1985) to Laurentia (Fig. 13A). The motion of these terranes toward the NNE relative to Laurentia is not consistent with the later docking of the Yucatan landmass (Fig. 13). The orientation of S_H during this stage is continuous in the frontal imbricate zone from west of the Big Cedar recess to north of the Benton uplift in Arkansas (Fig. 5A). These outcrops are in close proximity to the area of NNE transport on the Windingstair fault that was responsible for the development of the Big Cedar pinch zone (Fig. 8). Thus, the early NNE-striking joint set is the manifestation of a remote stress field that drove the stacking of the central thrust belt over the frontal imbricate zone (Fig. 13A). Such stacking with lateral ramps leads to a regional extension that favors cross-fold joint propagation (Srivastava and Engelder, 1990). The later NNW stress field (Fig. 13B), manifested in joints throughout the central Ouachita belt, is consistent with the inferred closure direction of the ocean basin (Pindell, 1985). This second stage may reflect closure of the Yucatan landmass behind the docked Sabine/Monroe terrane and the development of the Mississippi slate belt (Pindell, 1985).

Cross-fold joints postdate fold-parallel joints in the majority of outcrops of the central thrust belt and frontal imbricate zone, whereas in the Arkoma Basin, cross-fold joints are earliest (Fig. 6). This is consistent with Central Appalachian foreland fracture architecture, where fold-parallel joints are the primary vertical set in some of the units of the Valley and Ridge (i.e., Srivastava and Engelder, 1990) but are secondary to cross-fold joints in the Appalachian Plateau (i.e., Engelder and Geiser, 1980). Fold growth driven by the docking of the Sabine/Monroe terrane (i.e., the stage one plate-scale stress field) was under way before the initiation of cross-fold joints in the Windingstair thrust sheet, and largely so in the Choctaw thrust sheet. The development of the Big Cedar pinch zone is late Atokan in age, as indicated by joints found in Atokan and older rocks in the orientation of the NNE transport on the Windingstair fault (Fig. 5A). In late Atokan and post-Atokan time, the Ouachita trough closed as the Yucatan landmass moved to the NNW (e.g., Pindell, 1985) to set up the stage two plate-scale stress state in the central Ouachita belt (Fig. 13B).

Fringe cracks recording a clockwise rotation of the regional stress field have been observed throughout the central Ouachita belt and thus appear to reflect a final rearrangement of the plate-scale stress field in the salient (Fig. 5B). The clockwise development of fringe cracks along cross-strike joints is found on a large scale in the central Ouachita belt, even in the Desmoinesian rocks (Fig. 5B). Thus, the counterclockwise rotation of S_H reflects the final locking of the Gondwanan terranes with a margin-normal shove in the Ouachita salient. This follows a progressive westerly development of foreland basins along the southern margin of Laurentia (Meckel et al., 1992). The plate-scale stress field responsible for the Ouachita clockwise fringe cracks developed soon after the post-Desmoinesian emplacement of Arkoma Basin folds.

SUMMARY

Joints formed in the central Ouachita fold belt under a two-stage progressive deformation reflecting the rearrangement of plate-scale stress fields. In the first stage, regional northward transport direction was established by the southward subduction of the oceanic lithosphere and the obduction of sediments onto Laurentia. During this stage, local transport directions, such as movement on the overthrusts and the Windingstair fault, were consistent with a NNE plate-scale stress field, which is indicated by NNE early cross-fold joint propagation in the central Ouachita belt (Fig. 5A). Where displacement between the overthrust sheets was not equal, a phase of deformation associated with strike-slip discontinuities developed. If the displacement vectors of adjacent sheets were neither equal nor parallel, pinching, such as that in the Big Cedar pinch zone, occurred in the strike-slip zones. In the frontal imbricate zone of the Big Cedar recess, the development of the strike-slip pinch zone largely postdates initial folding due to northward transport. Joints with NNW strikes reflect a later stage of Ouachita deformation under the influence of a second plate-scale stress field set up by closure of the Yucatan landmass. This NNW stress field affected both the fold belt and the Arkoma Basin where rocks are of post-Atokan age (Fig. 5B).

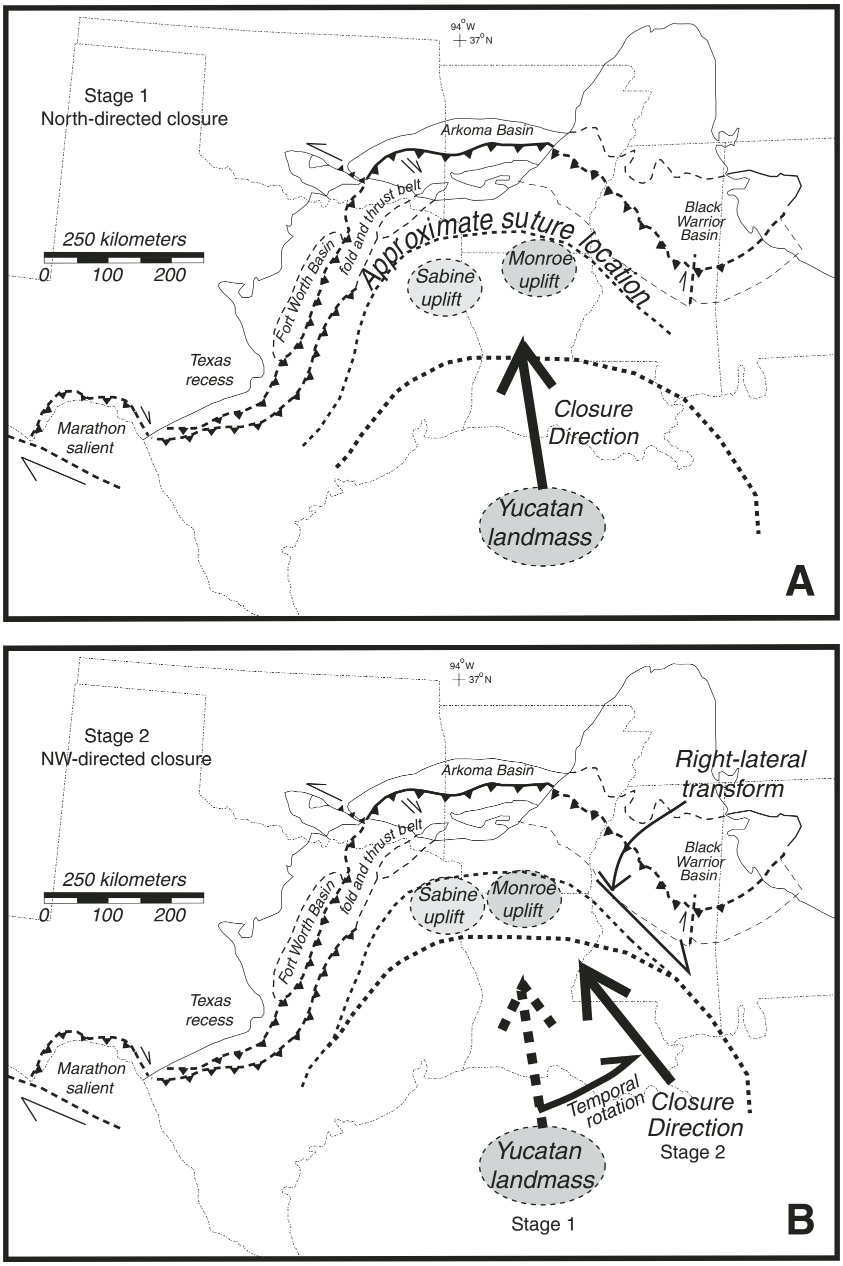

Figure 13. Two-stage tectonic evolution of the Ouachita salient. Map is after Pindell (1985) and Viele and Thomas (1989). (A) First stage of the Ouachita orogeny characterized by northward S_H during closure of the Sabine/Monroe terrane. (B) After the docking of the Sabine/Monroe terrane, continued closure of the Yucatan landmass forms the Mississippi slate belt (right-lateral transform) and NW-directed S_H.

ACKNOWLEDGMENTS

The funding of this project came from a U.S. Geological Survey EDMAP grant, the Penn State Seal Evaluation Consortium (SEC), an American Association of Petroleum Geologists (AAPG) Grant-in Aid, and the Krynine Memorial Fund, Penn State Geosciences. Field assistance from Karen Whitaker, Jen Bobich, and Hilary Gittings is appreciated. Helpful conversations with Don Fisher prompted the development of the pinch-zone model for the Big Cedar quadrangle. We are grateful for the valuable time and effort expended by Don Wise, Jim Hibbard, and an anonymous reviewer during the review process.

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Manuscript Received by the Society 17 December 2004
Revised Manuscript Received 22 September 2005
Manuscript Accepted 25 November 2005

Printed in the USA