Foreland signature of indenter tectonics: Insights from calcite twinning analysis in the Tennessee salient of the Southern Appalachians, USA

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ABSTRACT

The Tennessee salient in the Southern Appalachian fold-and-thrust belt is defined by a regional variation in strike of ~55° from southwestern Virginia to northern Georgia. Determination of a primary or secondary origin for the arcuate nature of this part of the belt is the focus of this study. Oriented limestone samples were collected from the thrust belt and the "undeformed" foreland for calcite twinning analysis. Layer-parallel paleostress orientations from 25 sites within the thrust belt reveal a radial pattern that varies systematically along the orogenic front. However, the amount of fanning (~75°) significantly exceeds the belt's frontal curvature, indicating that passive rotation of originally parallel paleostress directions, as proposed elsewhere, is unlikely here. In addition, results from 27 foreland sites display a similarly fanned pattern of paleostress directions, collectively showing that a radial stress regime was imparted on rocks along this part of the Appalachian margin by the onset of thrusting. Differential stress values are comparable to previous results, with decreasing σ_d values from >100 MPa within the thrust belt to ~50 MPa at 40 km from the orogenic front, regardless of orientation.

Instead of the extent of frontal curvature, fanning of paleostress directions in limestones matches the current indenter geometry of the Blue Ridge to the east. We propose, therefore, that radial paleostress directions were imparted in response to the advancing Blue Ridge thrust sheet, with differential thrust displacement creating (primary) curvature instead of secondary rotation during shortening. This resulted in the present-day geometry of the Tennessee salient, which is supported by basic geometric modeling of a sand wedge. It also explains the previously noted increase in displacement and number of major thrusts near the indenter's apex. However, this scenario contrasts with buttress-induced, secondary curvature in the Pennsylvania salient to the north in the Appalachian chain, showing that curvature is not explained by a single mechanism in the Appalachian belt.

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INTRODUCTION

The Appalachians of North America are among the best studied orogens of the past two centuries, but unresolved first-order issues remain regarding the structural development of this belt. One notable issue is the origin of orogenic curvature, manifested in the Appalachians as a series of salients and recesses along the trace of this foreland fold-and-thrust belt (Fig. 1). In the United States, they consist of the Pennsylvania salient, the Roanoke recess, the Tennessee salient, and the Alabama recess, from north to south. The current view of these curved segments is that they evolved from an irregular geometry of the rifted Iapetan margin of Laurentia, which became deformed during the late Paleozoic Alleghanian orogeny (Rankin, 1975; Thomas, 1977, 1991, 2004). However, it remains untested whether the kinematic evolution of the arcuate segments, and in particular the salients, is indeed the same along the belt or whether they reflect distinct histories.

A feature that is common to many fold-and-thrust belts, orogenic curvature can vary from tens of degrees to nearly 180° (e.g., Carey, 1955; Eldredge et al., 1985; Marshak, 1988, 2004; Marshak et al., 1992; Macedo and Marshak, 1999; Weil et al., 2001, 2010). Resolving the nature of curvature in a given orogen is key to understanding its kinematic and mechanical development. Numerous classification schemes have been proposed (e.g., Marshak, 1988; Hindle and Burkhard, 1999; Weil and Sussman, 2004; Yonkee and Weil, 2010), but orogenic curvature can broadly be described as (1) primary, with formation from an initially curved state, (2) secondary, with curvature forming from a straighter geometry that was subsequently rotated, or (3) some combination of the two. The main mechanisms of curvature in fold-and-thrust belts include foreland buttressing, lateral variations in sediment thickness or mechanical strength, indentation, and changes in the regional stress field (Marshak, 2004; Weil and Sussman, 2004). Differentiating between these scenarios requires the amount (if any) of relative rotation along the curved structure to be established. Once the origin is constrained, the nature of curvature, along with regional structural information, allows insight into the belt's structural evolution.

Rock magnetism is one method used to assess orogenic curvature and rotations (Eldredge et al., 1985; McWhinnie at al., 1990; McCaig and McClelland, 1992; Weil et al., 2001, 2010; cf. Hnat et al., 2009). Other studies have recognized that prethrusting features, such as cleavage, fractures, and paleocurrent orientations, can also be used to determine relative rotations within thrust belts (Nickelsen, 1979; Gray and Mitra, 1993; Apotria, 1995; Yonkee and Weil, 2010). Layer-parallel paleostress orientations from the analysis of calcite twins, however, have been particularly useful in determining the nature of orogenic curvature (Ferrill and Groshong, 1993a, 1993b; Hindle and Burkhard, 1999; Kollmeier et al., 2000; Ong et al., 2007), given the relative ubiquity of appropriate rock units within many foreland fold-and-thrust

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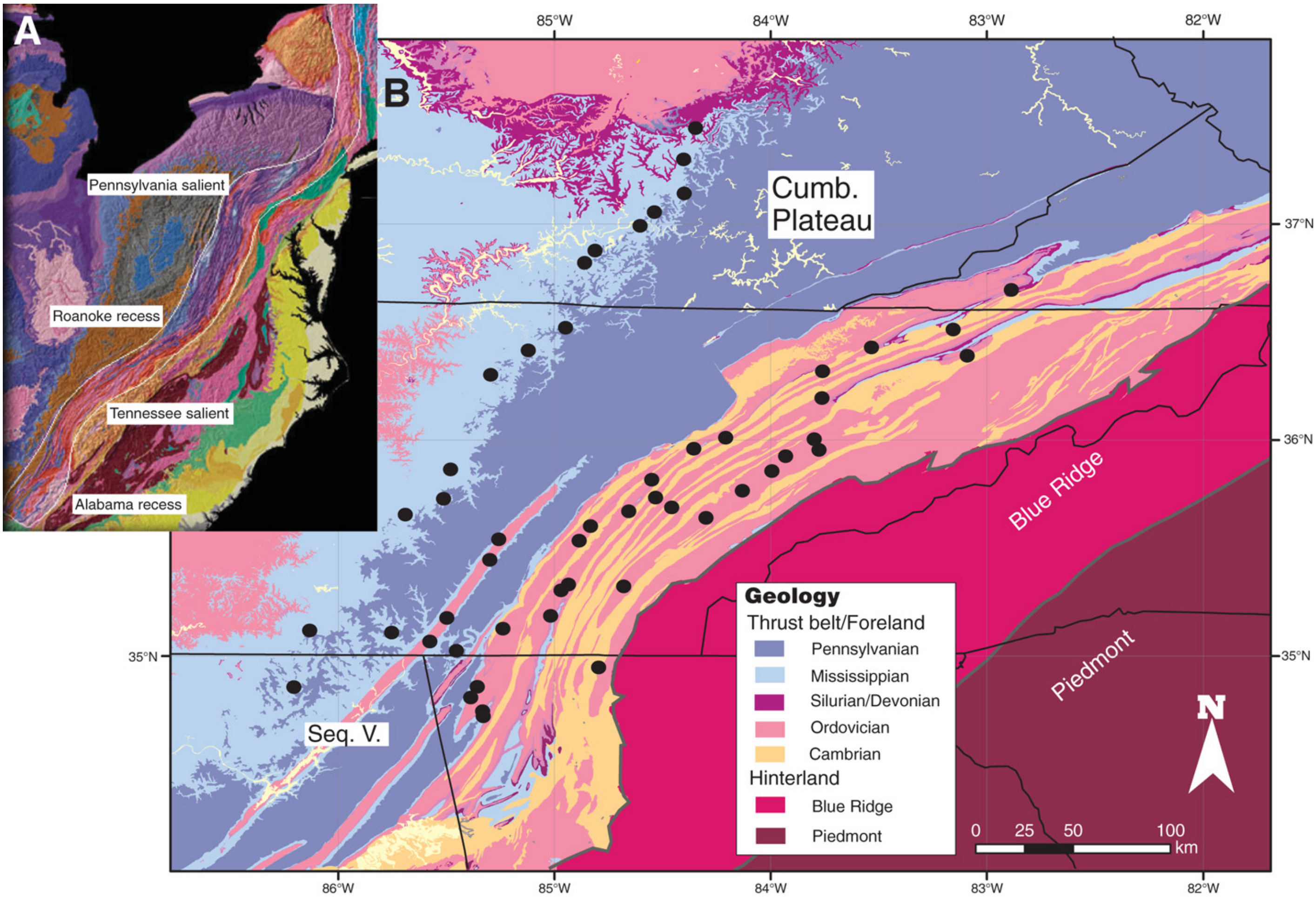

Figure 1. (A) Map of Appalachian thrust belt, highlighting curvature (Vigil et al., 2000). Cumb.—Cumberland; Seq. V.—Sequatchie Valley. (B) Geologic map of the Tennessee salient displaying calcite twinning sites.

belts and preservation of these fabrics. The bulk orientation of compression derived from an aggregate of twinned calcite grains tracks the orientation of the remote stress field as it forms at low critical resolved shear stress (~10 MPa) in a strain-hardening process (Jamison and Spang, 1976; Teufel, 1980; Wenk et al., 1987). Previous work has shown that the collisional stress field is recorded in limestones far into the "undeformed" foreland (e.g., Craddock et al., 1993; van der Pluijm et al., 1997; Rocher et al., 2005). Early, bedding-parallel compression is preserved within a typical limestone, thereby offering the potential to record subsequent rotation of that unit. Thus, by comparing paleostress orientations from limestones within the thrust belt and those from the foreland, it is possible to constrain the origin and quantify the amount of any rotation that occurred.

Calcite twinning analysis has been successfully applied to a number of curved fold-and-thrust belts, including the Cantabrian-Asturias arc in Spain (Kollmeier et al., 2000), the Subalpine Chain in France (Ferrill and Groshong, 1993a), the Idaho-Wyoming overthrust belt (Craddock et al., 1988), and the Appalachians' Pennsylvania salient (Ong et al., 2007) in the United States. These studies typically showed that curvature formed from an initially straighter geometry (secondary curvature), which was also supported by paleomagnetic data. In the Pennsylvania salient of the Central Appalachians, for example, changes in calcite twinning orientations correlate with changes in strike (~60°) of major fold axes within the fold-and-thrust belt, while foreland data display no such variation (Ong et al., 2007). Likewise, primary paleomagnetic directions record rotation between the limbs of the Pennsylvania salient, whereas remagnetized paleomagnetic directions do not (Kent, 1988; Stamatakos and Hirt, 1994; Cederquist et al., 2006).

Within the Southern Appalachians of the United States, the Tennessee salient is defined by a change in strike of structural trends that is similar to that of the Pennsylvania salient (Fig. 1). Here, we test the hypothesis that curvature in the Tennessee salient reflects the same deformation history as the Pennsylvania salient to the north. To constrain the nature of curvature formation in the Tennessee salient, calcite twinning analysis was performed on limestones from within the fold-and-thrust belt as well as the undeformed foreland. Rock units in this area are particularly suitable, providing a large data set with which to test our hypothesis and evaluate the kinematics of the Southern Appalachian fold-and-thrust belt.

GEOLOGIC SETTING

Curvature of the Tennessee Salient

The Tennessee salient is defined by a change in regional strike within the Valley and Ridge Province, from up to 65° in Virginia and northern Tennessee to roughly 10° in northern Georgia, before returning to a more northeasterly direction (~45°) in Alabama (Fig. 1). However, the curvature is not uniform across the belt. In the hinterland, the structural front of the Blue Ridge megathrust deviates up to 65° from Virginia to northern Georgia. The structural front of the fold-and-thrust belt (not including the thrusts of the Cumberland Plateau) is subparallel to the trend of the Blue Ridge front in the northeast. However, the structural front along the foreland edge of the fold-and-thrust belt only deviates by ~35° to the southwest, diverging from the Blue Ridge front.

Regional Structure

The Southern Appalachian belt is a classic thin-skinned fold-and-thrust belt where many fundamental concepts of thrust belt architecture were first developed (e.g., the ramp-flat model of thrusting; Rich, 1934). Dominated by thick, mechanically strong Cambrian–Ordovician carbonates, the Southern Appalachian foreland fold-and-thrust belt consists of a west-verging stack of thin-skinned thrusts that sole out into a basal detachment within Cambrian shales (Milici, 1975; Woodward and Beets, 1988; Hatcher et al., 1989, 2007). Unlike the fold-dominated belt of the Central Appalachians, the structural style of the exposed Southern Appalachian fold-and-thrust belt is primarily defined by southeast-dipping thrust faults, with overlying stratigraphy following the same general dip (Hardeman, 1966; Harris and Milici, 1977; Hatcher et al., 1989).

The Southern Appalachian fold-and-thrust belt intersects Central Appalachian structures at the Roanoke recess (Fig. 1), where the structural style changes from fault-dominated to fold-dominated. A regional strike change at a sharp intersection, with interfingered Central and Southern Appalachian structures, is typically thought to be an intersection between two phases of deformation, oriented NNW for the Southern Appalachian trend and WNW for the Central Appalachian trend (Rodgers, 1970; Wiltschko *in* Hatcher et al., 1989). However, recent studies have shown shortening directions consistent with progressive migration of deformation around a preexisting promontory (Spraggins and Dunne, 2002). Within the Southern Appalachian trend in Virginia, three major thrust sheets are exposed that gradually increase in displacement to the southwest into Tennessee. The number of major thrust sheets increases to 10 within the Tennessee salient at the latitude of Knoxville, where total displacement and depth of exposure also reach a maximum (Fig. 1; Hardeman, 1966; Rodgers, 1970; Harris and Milici, 1977; Hatcher et al., 1989, 2007). South of this culmination, into northern Georgia, the number of major thrust sheets again decreases, coincident with a decrease in displacement (Woodward, 1985; Hatcher et al., 2007). Here again, the regional strike abruptly changes from 10°–35° in the Tennessee salient to ~50° in the Alabama recess (Hardeman, 1966; Lawton, 1976).

The Blue Ridge–Piedmont megathrust sheet is a large-displacement (>300 km), crystalline thrust sheet lying to the east of the foreland fold-and-thrust belt (Hatcher, 2004). This megathrust propagated from the east along the brittle-ductile transition before ramping onto the passive-margin rocks of the foreland, as evidenced by several windows in the thrust sheet, during the Alleghanian orogeny (Boyer and Elliott, 1982; Hatcher et al., 1989, 2007; Goldberg and Dallmeyer, 1997). The Blue Ridge is primarily composed of basement rocks that were metamorphosed during multiple events along the margin of Laurentia, including the Grenville, Taconic, Neoacadian, and earliest Alleghanian orogenies (Goldberg and Dallmeyer, 1997). By the late Paleozoic, internal deformation of the Blue Ridge block was limited to a few minor brittle faults as the block propagated into the foreland (Hatcher et al., 2007).

Stratigraphy

The sedimentary sequence in the Southern Appalachian fold-and-thrust belt is primarily composed of Lower Paleozoic strata that thicken to the east, typical of passive-margin sequences. The Lower to Middle Rome Formation is the oldest exposed unit within the fold-and-thrust belt and represents the mechanically weak unit that forms the basal décollement for much of the belt (Milici, 1973; Harris and Milici, 1977; Woodward and Beets, 1988; Hatcher et al., 1989). A lithologically heterogeneous unit, the Rome Formation is dominated by variegated shales and siltstones, with lesser amounts of reddish-to-buff sandstones, dolomitic beds, and evaporites. Shales and limestones comprise the Cambrian Conasauga Group, grading from more carbonate rich in the east to more clastic in the west (Hardeman, 1966; Milici, 1973). Overlying the Conasauga, there is the Cambrian–Ordovician Knox Group, which primarily consists of a thick (~1000 m) package of massive dolomite beds. The Knox Group is the major mechanically strong unit in the Southern Appalachians. Unconformably overlying the Knox Group, the Middle to Upper Ordovician Chickamauga Group consists of all of the formations that lie between the pervasive Middle Ordovician unconformity above the Knox Group and the Upper Ordovician Juniata Formation (Rodgers, 1953; Milici, 1973). In the western portion of the thrust belt, limestones ranging from fine-grained mudstones to coarsely crystalline reefal grainstones dominate the unit, while toward the east, the Chickamauga's facies grade into clastic sediments (Sevier Shale).

Silurian and younger exposures are typically limited to outcrops in the footwall synclines within the Tennessee salient. Silurian clastics are better preserved to the northeast (Clinch Sandstone) and southwest (Red Mountain Formation) in large synclinoria. The Devonian Chattanooga Shales are primarily relegated to the western edge of the fold-and-thrust belt, but they represent an important detachment level in the Pine Mountain thrust sheet (Milici, 1970; Roeder and Witherspoon, 1978; Mitra, 1988). Mississippian rocks grade from more clastic within the Valley and Ridge Province in the east and north to coarse-grained fragmental and oolitic limestones on the western edge of the Cumberland Plateau and the Valley and Ridge in northern Georgia. Limited outcrops of Mississippian clastic rocks (Grainger Formation) are exposed within the fold-and-thrust belt, being restricted to a few footwall synclines. Pennsylvanian clastic rocks, not presently exposed in most of the Valley and Ridge, dominate exposures in the Cumberland Plateau.

CALCITE TWINNING ANALYSIS

Calcite twinning analysis of limestones has yielded robust results for kinematics and mechanics in experimental (Groshong, 1974; Teufel, 1980; Groshong et al., 1984) and natural studies (e.g., Engelder, 1979; Ferrill and Groshong, 1993a, 1993b; van der Pluijm et al., 1997; Kollmeier et al., 2000). Mechanical twinning occurs in calcite under low differential stresses (<20 MPa) along one of three potential glide planes, where preferential twinning will occur along one plane depending on both the orientation of the remote stress and the ability to overcome the critical resolved shear stress (τ_c) along that plane (Jamison and Spang, 1976; Wenk et al., 1987; Burkhard, 1993; Lacombe and Laurent, 1996; Ferrill, 1998). Orientation of the paleostress is found by determining the *c* axis of the host grain and the pole to the e-twin plane within the host grain (Fig. 2; Turner, 1953). The orientation of these parameters and the fixed angular relationship between the *c* axis and the e-twin plane are used to calculate orientations for the compression and tension axis within a grain (Fig. 2). An average compression direction is subsequently determined for a given sample (or site) from the collective array in an aggregate of twinned grains (Spang, 1972).

Since the formation of calcite twins is a strain-hardening process (Teufel, 1980), twinning patterns commonly preserve bedding-parallel

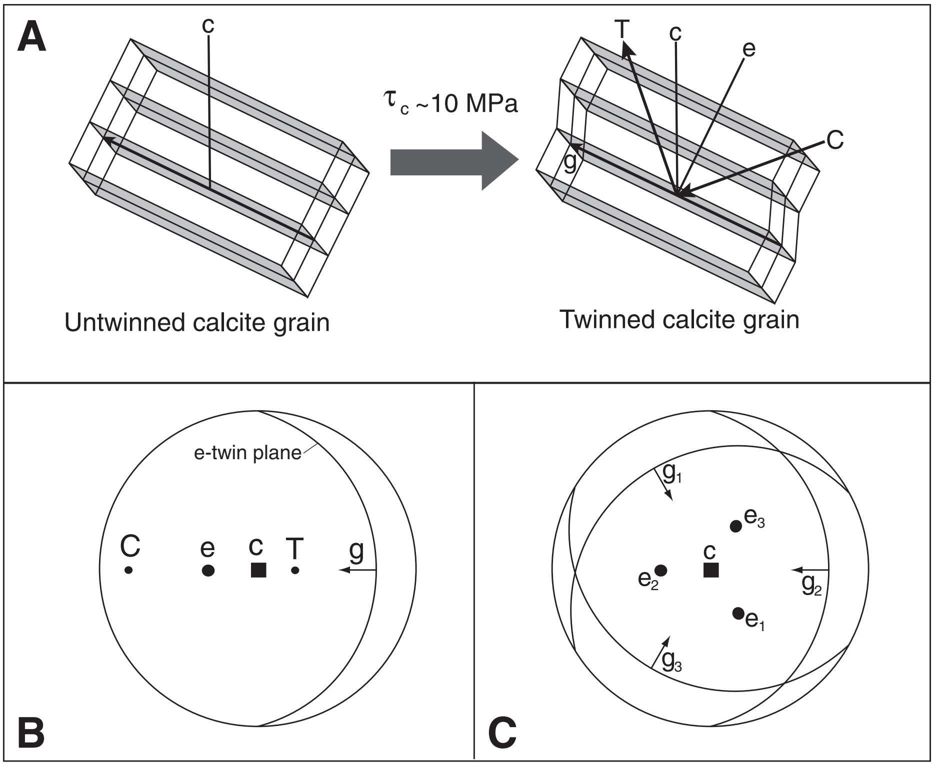

Figure 2. (A) Schematic of angular relationship between a single e-twin plane and the compressive (C) and tensile (T) stress axes (45° from the twin plane). The *c* axis is fixed relative to the twin plane. (B) Equal-area stereo projection showing the angular relationships of the geometry above. (C) All three potential twin planes relative to *c* axis.

shortening during the earliest deformation (e.g., Groshong, 1972, 1974; Engelder, 1979; Spang and Groshong, 1981). This creates the potential to act as a passive marker that records rotation (Craddock et al., 1988, Kollmeier et al., 2000). When present, multiple, discrete deformation events can be identified through superimposed populations of twins when the deformation orientations are at moderate to high angles to one another (Friedman and Stearns, 1971; Teufel, 1980). Separating the deformation events can be achieved by discriminating between twins that have a dominant compression direction ("positive expected values") and those that have a subordinate compression direction ("negative expected values" or "residual values"). This data "cleaning" method was fully described in Groshong (1972) and Evans and Groshong (1994).

Within the Southern Appalachian fold-and-thrust belt, samples were primarily collected from the Middle to Upper Ordovician Chickamauga Group limestones, although some samples were collected from the Mississippian Newman limestones in northern Georgia. During sampling, areas of concentrated deformation (e.g., mesoscopic faults and fold hinges) were avoided to ensure that the results reflect regional patterns, following the recommendations of previous workers (Friedman and Stearns, 1971; Harris and van der Pluijm, 1998). In the minimally deformed foreland (including the Sequatchie Valley), sampling focused on Mississippian limestones, including the Bangor, Monteagle, and Warsaw Formations. Samples were collected either as oriented hand samples or as standard paleomagnetic cores using a portable, gasoline-powered drill, and oriented using a compass. One to two oriented thin sections were cut from each sample and subsequently evaluated for appropriate grains. Thin sections were optically analyzed on a Zeiss universal stage (U-stage) microscope to determine the crystallographic orientation of both twin sets and their host grains for minimally 50 twin sets in most thin sections. To ensure the most accurate results, only straight, continuous twin sets were used. Moreover, to ensure that crystallographic bias was not introduced during measurement, randomness of the crystallographic orientations of the measured host grains was confirmed for each thin section. Compression axes were calculated for each twin set using the method of Turner (1953), and mean paleostress orientations were determined using dynamic analysis of the compression axes (Spang, 1972). Strain tensor determinations using Groshong's (1972, 1974) method were calculated to separate positive and negative expected values in order to clean the data and to identify multiple deformation events (Teufel, 1980; Groshong et al., 1984). Data were rotated into geographic coordinates and compared to bedding to verify layer-parallel paleostress orientations at each site, which occurred for 90% of the samples. All twinning calculations were performed using the GSG/Strain99 program of Evans and Groshong (1994).

Estimates of paleodifferential stress magnitudes can also be obtained for an aggregate of calcite grains. While several methods are available (e.g., Rowe and Rutter, 1990), the relatively simple method of measuring twin set density per grain has been shown to be the most reliable under low-temperature (<200 °C) conditions, with typical magnitude errors of <20% (Jamison and Spang, 1976; Ferrill, 1998). Grains with one, two, or three twin sets indicate progressively higher differential stresses that can be quantified, assuming a critical shear stress threshold for twinning of 10 MPa (Jamison and Spang, 1976; Lacombe and Laurent, 1996; Laurent et al., 2000; Ferrill, 1998). Point counts of at least 200 grains per section were measured on a standard petrographic microscope for a subset of thin sections from both the fold-and-thrust belt as well as the foreland.

RESULTS

Thrust Belt Paleostress Directions

In total, 45 sites were sampled within the fold-and-thrust belt for calcite twinning analysis. Samples with excess matrix and limited coarse fossil and cement grains were omitted from further analysis. Only straight, continuous twins were measured; they are typically thin, indicating deformation at temperatures less than 200 °C (Fig. 3; Ferrill, 1991, 1998; Burkhard, 1993). Thirty-two samples that were identified to have favorable characteristics were measured and analyzed. Of these samples, 25 have a dominant population exhibiting paleostress orientations that are both layer-parallel and at a high angle to strike. Four samples of a subsidiary population are oriented subparallel to strike, while the residual values of four other samples record a population that is roughly perpendicular to bedding. The location of the bedding-normal population can be attributed to loading due to either thrusting or sedimentation, which was also observed elsewhere along the belt (Ong et al., 2007). The four strike-parallel compression directions are too few to be interpreted in a geologically reliable manner.

In the dominant population of paleostress directions, the compression axes are subparallel

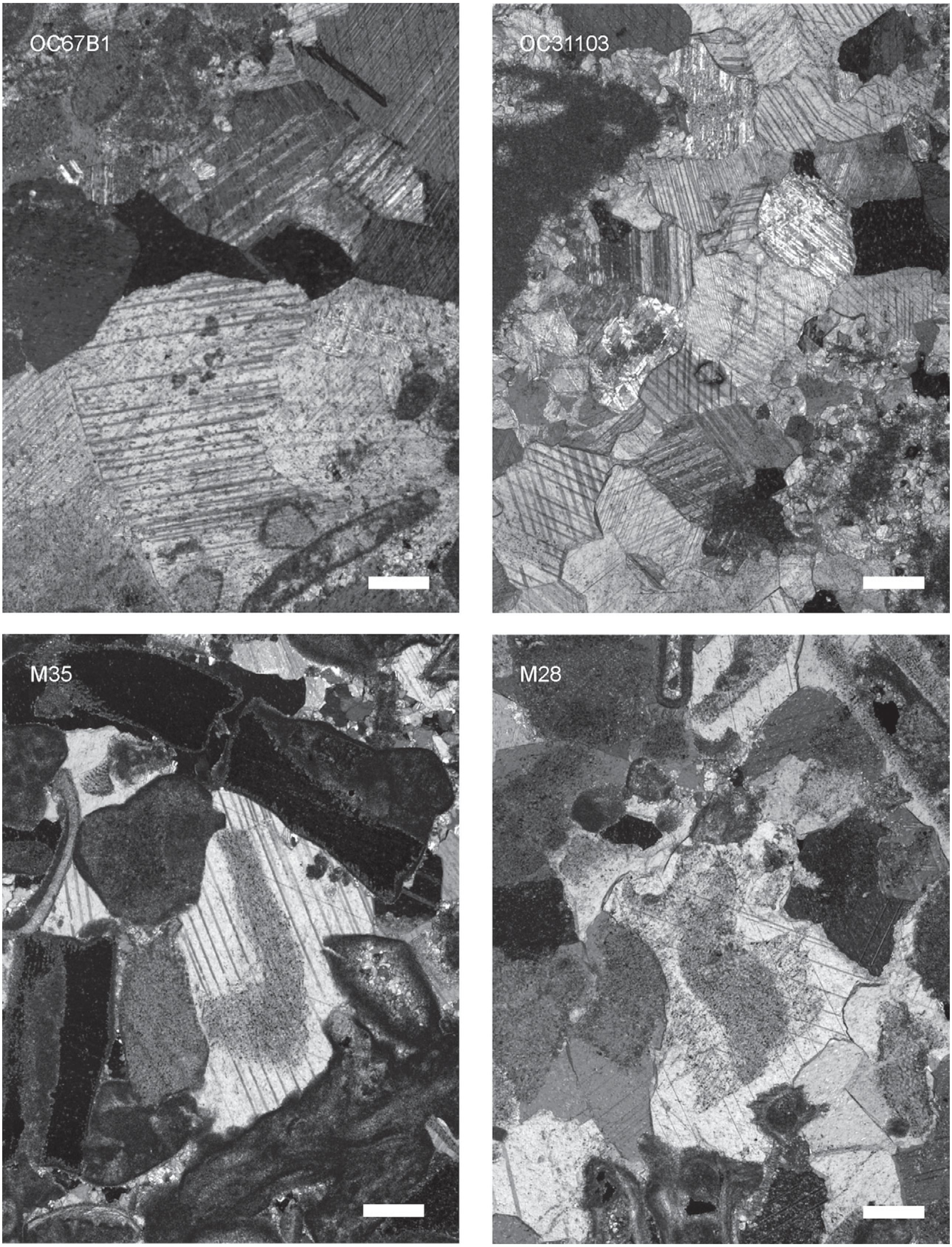

Figure 3. Photomicrographs of representative limestone samples analyzed in this study. Top two panels are samples from within the thrust belt, whereas the bottom two panels show foreland samples. Scale bar is 200 µm.

to the principal shortening axes (e_1); the other principal strain axes (e_2 and e_3) tend to diverge from the principal stress axes (σ_2 and σ_3). Samples generally record less than 3% strain (see GSA Data Repository Table DR1[1]), which is typical for this type of study (e.g., Ong et al., 2007). The dominant population's directions tend to be in or close to the bedding plane (Fig. 4A), reflecting layer-parallel compression, with small deviations attributable to minor grain-scale rotations during progressive folding, as seen in limestones of the Hudson Valley (Harris and van der Pluijm, 1998). Most importantly, the compression directions display a systematic change in orientation along the trace of the Tennessee salient (Figs. 4A and 5).

Foreland Paleostress Directions

Reliable paleostress directions were obtained for 23 samples from foreland limestones, including from the Sequatchie Valley. Twin sets were measured primarily in cement grains, although some fossil grains (mostly crinoids) were also measured; twins are typically thin and straight. Unlike samples from the fold-and-thrust belt, no residual stress directions are present. Paleostress orientations are generally layer parallel. Strains are typically less than 1% for these samples, and the principal shortening axis (e_1) is subparallel to the compression direction (σ_1) (Table DR2). Similar to the main population from the thrust belt, compression directions in the foreland show a systematic change in orientation from NNW in the north to E-W in the south (Figs. 4B and 5).

Paleostress Magnitudes

Paleostress magnitudes were measured for 14 samples within the thrust belt and for 12 samples in the foreland. Within the thrust belt, limestones typically have high percentages of twinned grains, many with two or more twin sets, indicating higher differential stresses. Most samples in the thrust belt thus exceed 100 MPa (Table DR3), with the wide range of values reflecting the diminished precision of the method at higher stresses. Foreland results are variable, with higher values of σ_d near the orogenic front (taken here as the boundary between the Valley and Ridge and the Cumberland Plateau physiographic provinces) and lower values of ~30 MPa beyond 50 km into the foreland (Fig. 6). When compared to the data set of van der Pluijm et al. (1997) from the Appalachian foreland, these results support the previous findings that differential stress values decrease rapidly away from the orogenic front while transmitting low differential stress values farther into the plate interior (Craddock and van der Pluijm, 1989; van der Pluijm, et al., 1997).

[1]GSA Data Repository Item 2011291, tables DR1, DR2, and DR3 containing stress and strain data from calcite twinning analysis, is available at www.geosociety.org/pubs/ft2011.htm, or on request from editing@geosociety.org, Documents Secretary, GSA, P.O. Box 9140, Boulder, CO 80301-9140, USA.

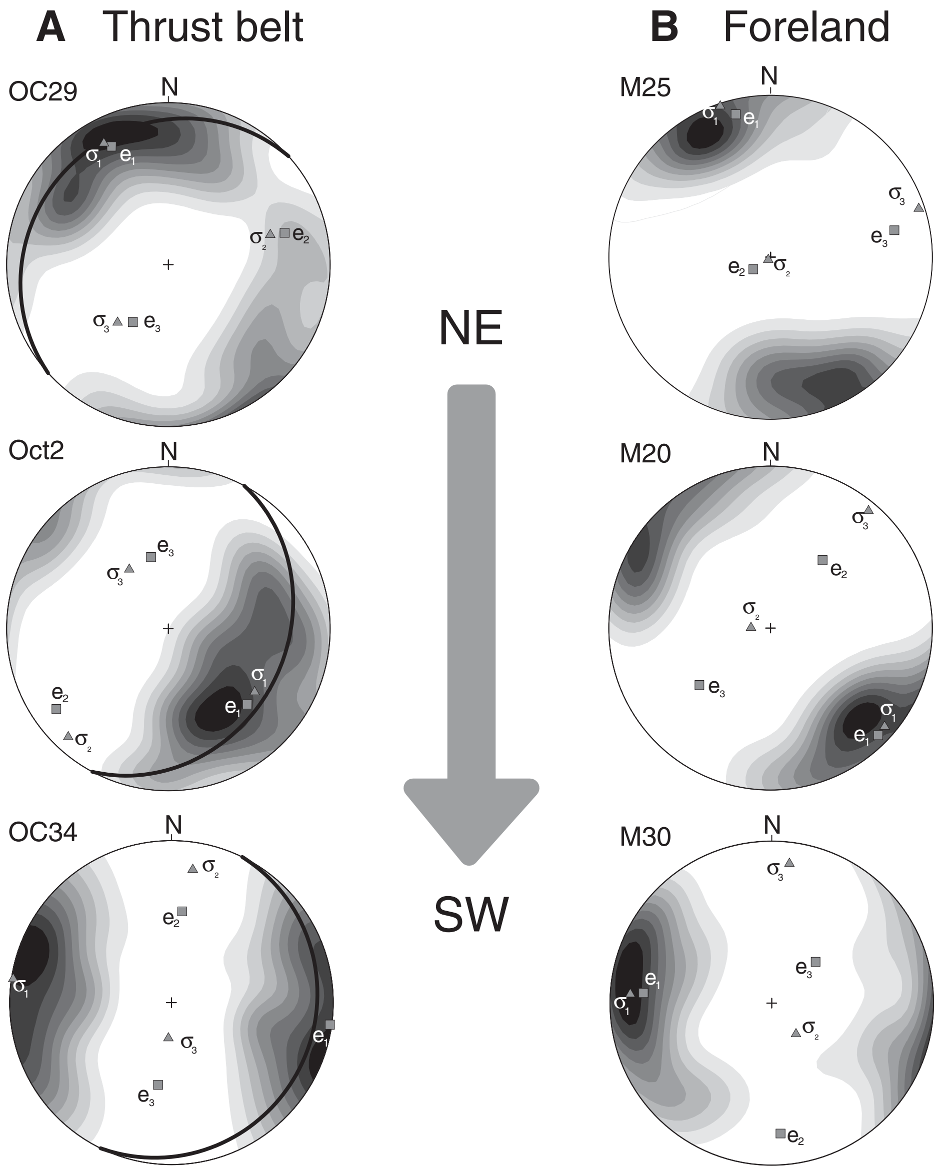

Figure 4. Equal-area stereo projections of results from the thrust belt (A) and the foreland (B), organized from northeast to southwest. Contoured data are Turner compression axes. Great circle represents bedding, triangles represent stress axes (σ_1, σ_2, σ_3) and squares represent strain axes (e_1, e_2, e_3).

DISCUSSION

Nature of Curvature in the Tennessee Salient

Paleostress directions in limestones of the Southern Appalachians from both within the fold-and-thrust belt and from the "undeformed" foreland show a systematically fanning distribution of compression orientations along the Tennessee salient. Such fanning compression patterns derived from calcite twinning analysis in previous studies of curved fold-and-thrust belts have typically been used as an indication of secondary curvature (Craddock et al., 1988; Kollmeier et al., 2000; Ong et al., 2007). Secondary rotation of these belts has been supported by both paleomagnetic data and, in particular, an absence of similar fanning in foreland directions. In the Tennessee salient, on the other hand, a correlation between strike

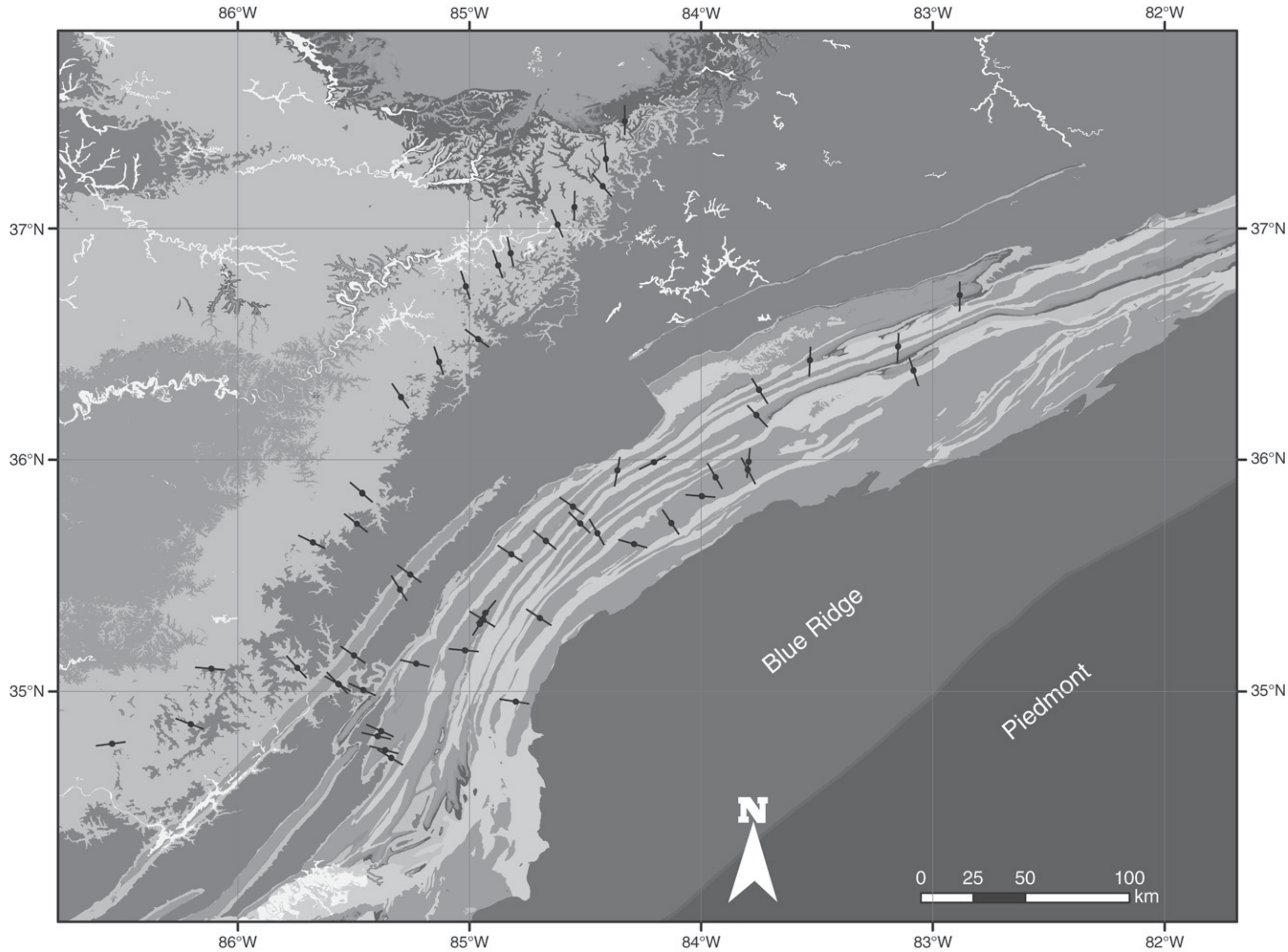

Figure 5. Geologic map of Tennessee salient with the geographic distribution and orientation of compression directions.

and compression directions exists both in thrust belt and in the foreland, showing that the fan pattern is primary and that secondary rotation of the salient's limbs did not occur. Curvature in the Tennessee salient is therefore interpreted as a primary feature, which is also supported by syndeformational paleomagnetic data from the thrust belt (Hnat et al., 2009). This is in contrast to the secondary origin of curvature in the Pennsylvania salient to the north, which has been interpreted as primarily controlled by the paleomargin geometry (Rankin, 1975; Thomas, 1977; Wise, 2004; Ong et al., 2007).

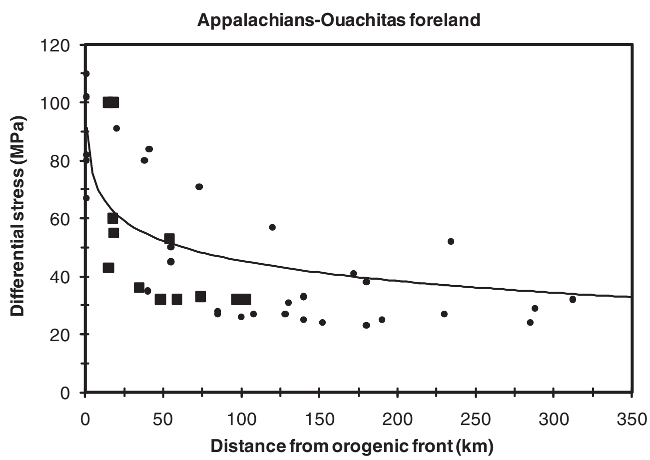

Figure 6. Plot of paleodifferential stress estimates versus distance from the orogenic front. Data from this study and those of van der Pluijm et al. (1997) are represented by squares and circles, respectively.

Mechanism of Curvature

Comparisons of the compression directions with regional strike and orogenic features give new insight into the nature and origin of curvature development. Plots of normalized, projected compression directions against strike, analogous to declination versus strike plots used in paleomagnetic studies (e.g., Schwartz and Van der Voo, 1983), are shown for both the thrust front (Fig. 7A; defined as the boundary between the Valley and Ridge and the Cumberland Plateau) and the more easterly Blue Ridge front (Fig. 7B). Raw data projected to the orogenic front (Fig. 7A) show a reasonable correlation (r^2 = 0.61), while a moving average window (n = 3) of the data, which reduces the effect of single outliers, improves this correlation to r^2 = 0.80 (see also Ong et

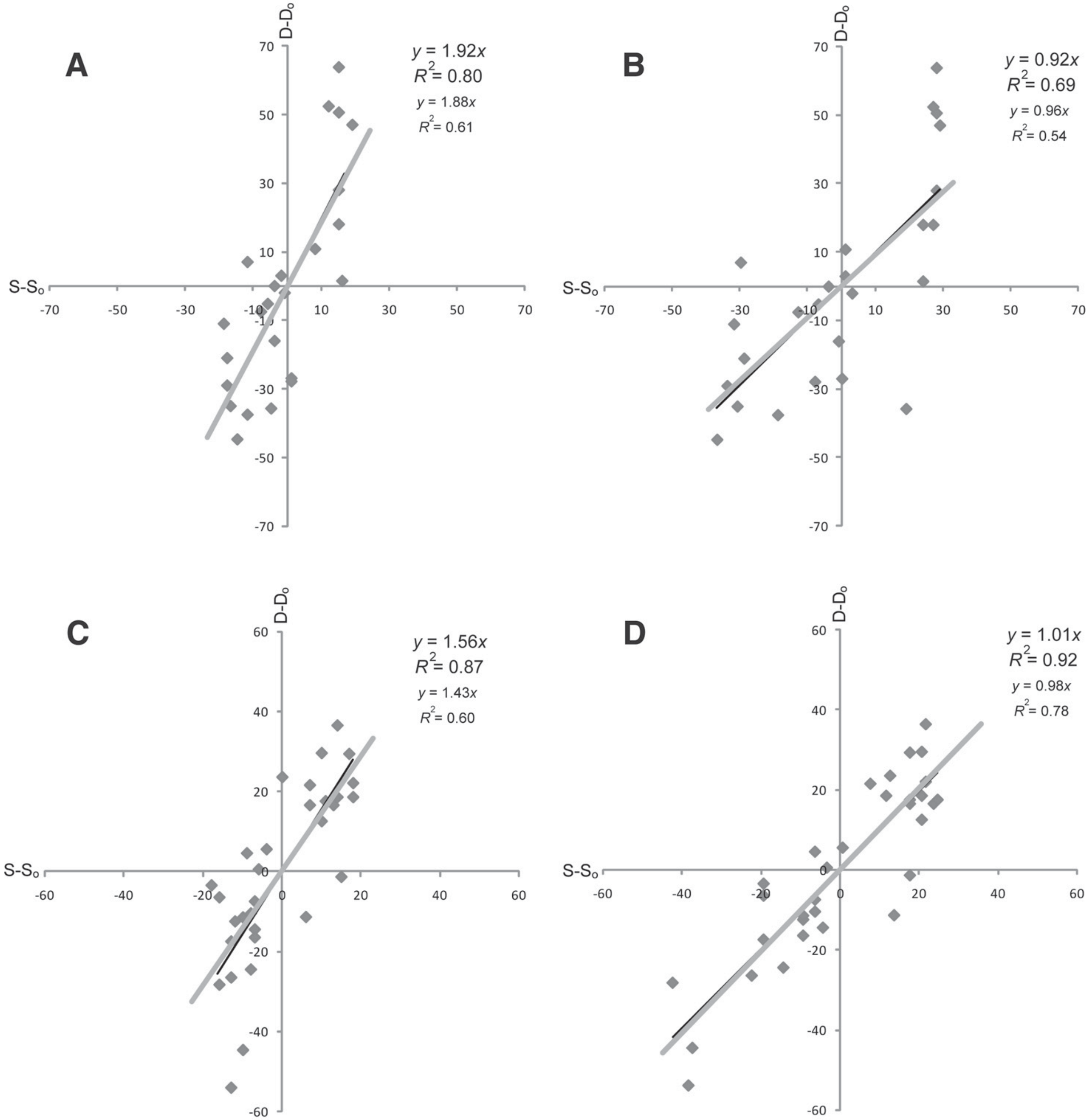

Figure 7. Plots of compression direction (D) versus regional strike (S), normalized to their respective means (D_o and S_o). Linear regression lines of both raw data and moving window analysis are shown, with darker lines representing the latter. Slope of line and correlation coefficient for the moving window analysis are shown in large text, whereas the smaller text shows these parameters for the raw data. (A) Thrust belt samples against orogenic front. (B) Thrust belt samples against Blue Ridge front. (C) Foreland samples against orogenic front. (D) Foreland samples against Blue Ridge front.

al., 2007). Regardless, the slope of the best-fit line is ~1.9, indicating that these data record significant excess fanning, given the amount of curvature of the front. Despite a lower correlation coefficient due to the presence of some data outliers, the data projected to the hinterland Blue Ridge front (Fig. 7B) show a slope much closer to one (slope = 0.96; r^2 = 0.54), which further improves with a moving window analysis (slope = 0.92; r^2 = 0.69), suggesting a relationship between the shape of the Blue Ridge front and the distribution of paleostresses within the fold-and-thrust belt. For foreland rocks, nine sites from previous work of Wiltschko (*in* Hatcher et al., 1989) are included with the 23 new sites of this study. Compression directions from the foreland, as with the thrust belt data, are projected to both boundaries of the fold-and-thrust belt (Figs. 7C and 7D). As with limestones from within the thrust belt, the data projected to the orogenic front display excess fanning of compression directions (Fig. 7C), but when projected onto the Blue Ridge front, they display a near perfect 1:1 correlation (slope = 0.98; r^2 = 0.78), which further improves with a moving window analysis (slope = 1.01; r^2 = 0.92).

The similar radiating patterns of compression directions recorded in limestones from both the foreland and from within the thrust belt match the geometry of the hinterland Blue Ridge block, which we interpret as a causal relationship between its emplacement and the regional paleostress field. We propose that indentation of the fold-and-thrust belt by the advancing Blue Ridge block imparted a radial stress field on foreland rocks, some of which were subsequently included in the thrust belt, while others remained as "undeformed" foreland. A scenario of indentation is therefore proposed as the origin for the fanned compression directions preserved in these rocks.

Kinematic Considerations

While basement morphology and sediment thickness variation may have had some influence, the primary mechanism driving curvature in the Tennessee salient is considered to be the Blue Ridge indenter. Thrusting in the Southern Appalachians developed via differential displacement along strike ahead of the Blue Ridge thrust. Maximum displacement and the number of thrusts in the fold-and-thrust belt at the apex of curvature of the Blue Ridge front (Fig. 5; as noted by Hatcher et al., 2007) further support this indenter scenario for the Southern Appalachians.

Indenter tectonics can also explain the deviation in strike of the southern limb of the salient. Strikes of thrust sheets closest to the front of the Blue Ridge are more parallel, whereas those more distal tend to deviate and become closer to the trend of the northern limb. Basic analogue models of thrust belt geometries have shown that this deviation can be a kinematic response to an advancing indenter (Marshak et al., 1992; Lickorish et al., 2002). We similarly applied a simple sandbox experiment, based on Marshak et al. (1992), which shows that the Tennessee salient geometry can be readily achieved by indenting a rigid block with the shape of the Blue Ridge into undeformed sand (Fig. 8). The experiment was done multiple times with commercial sand (sifted to <1.0 mm), spread 2–3 cm throughout a wooden box. The indenter was created with modeling clay attached to a Plexiglas sheet that was pushed from behind to mimic the advancing Blue Ridge thrust sheet. In this example, thrusts forming toward the foreland tend to curve less than those closest to the indenter, which was seen in all runs of the

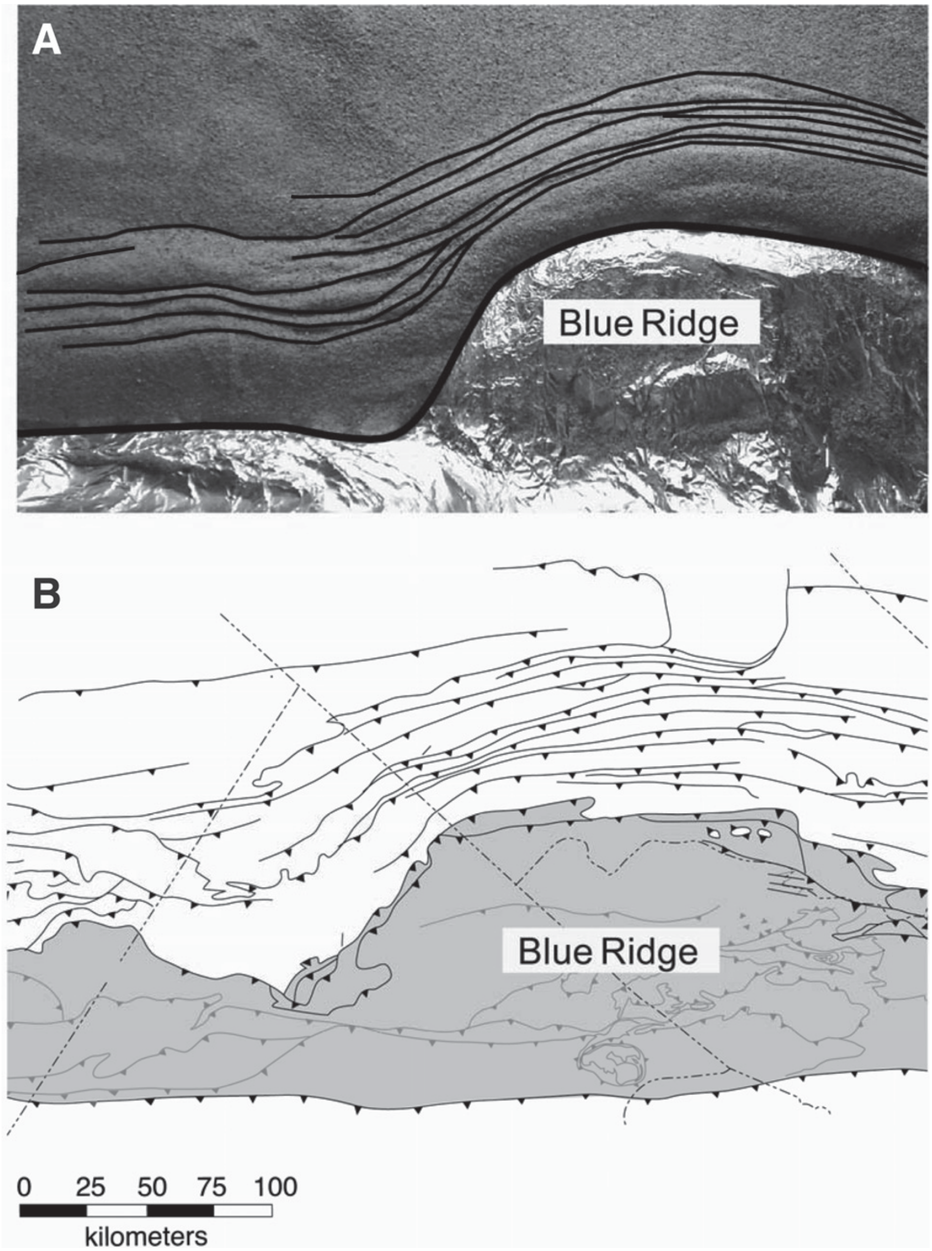

Figure 8. (A) Sandbox model showing deformation ahead of an indenter shaped after the Blue Ridge front. Lines trace the position of the faults in the sand. (B) Thrust distribution in the Tennessee salient (modified from Hatcher, 2004). Note the excellent similarity between this basic geometric model and the natural thrust belt.

experiment. Whereas the model is not mechanically scaled to natural conditions, this simple geometric model, along with the radiating pattern of foreland compression directions, additionally supports the hypothesis that the rigid Blue Ridge block is the primary driver of curvature in the Tennessee salient.

A radial pattern of compression directions has been documented in curved belts elsewhere, and these were similarly related to an indenter. The Jura fold-and-thrust belt shows no paleomagnetic evidence for secondary curvature (Gehring et al., 1991) but preserves a fanned distribution of paleostress orientations from calcite twinning analysis that extends into the foreland (Hindle and Burkhard, 1999; Rocher et al., 2005). A hinterland indenter has been identified as the primary driver of deformation in the Jura (Hindle and Burkhard, 1999; Homberg et al., 1999), collectively suggesting that a radial pattern of foreland compression directions may be a key indicator of indenter tectonics in arcuate fold-and-thrust belts.

CONCLUSIONS

Calcite twinning analysis of limestones in the Tennessee salient of the Southern Appalachians reveals a systematically fanned distribution of compression directions in both the fold-and-thrust belt and its foreland. Within the Tennessee salient, paleostress orientations projected onto the frontal fold-and-thrust belt show a range nearly twice that of the regional strike. When projected onto the more hinterland Blue Ridge block, however, the compression directions correlate well with the frontal shape of this block. The foreland limestones display a similarly matching pattern, leading to the conclusion that the rigid Blue Ridge block imparted a radial stress pattern on rocks in this part of the Appalachian margin of the Laurentia. Differential displacement during thrusting, instead of secondary rotation, produced the present-day geometry of the salient, which also explains the increase in displacement and number of thrusts near the indenter's apex.

The observed pattern implies that curvature of the Tennessee salient is a primary feature, having initially formed in its present geometry. Since the Pennsylvania salient of the Central Appalachian fold-and-thrust belt to the north reflects secondary curvature, we reject our working hypothesis and conclude that the origin of curvature along the Appalachian front is different between these salients. We also conclude that the paleostress signature of indenter tectonics as observed in the Tennessee salient might be applied to other curved belts with (rigid) crystalline units in the hinterland.

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