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REGIONAL SHORTENING FABRICS IN EASTERN NORTH AMERICA: FAR-FIELD STRESS TRANSMISSION FROM THE APPALACHIAN-OUACHITA OROGENIC BELT

John P. Craddock
Geology Department, Macalester College, St. Paul, Minnesota

Mike Jackson
Department of Geology and Geophysics, University of Minnesota, Minneapolis

Ben A. van der Pluijm
Department of Geological Sciences, University of Michigan , Ann Arbor

Robert T. Versical
Department of Geology, Western Michigan University, Kalamazoo

Abstract. Paleozoic carbonates of cratonic eastern North America comprise the footwall of the Appalachian-Ouachita fold-and-thrust belt and contain a layer-parallel shortening (lps) fabric that is preserved by mechanically twinned calcite. Shortening directions are generally parallel to the Appalachian-Ouachita thrust-transport direction in carbonates of the thrust belt proper (restored width ~400 km) and within carbonates up to 1700 km into the foreland, giving a pre-thrusting sedimentary prism ~2100 km wide through which compressive orogenic stresses were transmitted. The shortening strain magnitudes (<6%) and the inferred calcite twinning differential stress magnitudes (<90 MPa) decrease exponentially away from the orogenic front. Calcite twinning strain patterns in other adjacent tectonic provinces, such as the Grenville, Laramide, Keweenawan Rift, and Newark Basin, are distinct from the twinning strains preserved in the cratonic Paleozoic carbonates. (Appalachian orogen, far-field stresses, calcite microstructures.)

INTRODUCTION

Lateral migration of orogenically expelled fluids from an evolving fold-and-thrust belt into the physically continuous footwall sediments has received considerable attention following Oliver's [1986] contribution which attempts to explain the presence of numerous geologic phenomena of Permian age within the Paleozoic cratonic sediments of eastern North America. The common, Permian-aged geologic phenomena hosted by these Paleozoic carbonates include several Mississippi Valley type (MVT) lead-zinc deposits, chemical remagnetizations, authigenic feldspar overgrowths, dolomitization of host carbonates, and a regionally gradational distribution of hydrocarbon deposits (coal, oil, and gas [e.g., Bethke and Marshak, 1990]. Additionally, micro-structural and magnetic studies of these same carbonates have revealed the widespread presence of mechanically twinned calcite and a magnetic anisotropy fabric [Craddock and van der Pluijm, 1989; Jackson et al., 1989]. The shortening strains from both of these fabrics are generally subhorizontal and parallel to the inferred direction of Appalachian-Ouachita thrust transport, which is also subparallel to the inferred direction of orogenic brine migration from the thrust belt into the adjacent foreland [e.g., Sverjensky, 1986; Miller and Kent, 1988; Halliday et al., 1991].

Deformation within the foreland of a fold-and-thrust belt has been excluded from efforts to model the mechanical development of thrust belts, where the sedimentary wedge is thought to be everywhere critically stressed [e.g., Chapple, 1978; Davis et al., 1983]. Field observations in the foreland beyond the limits of surface thrusting, however, record observable and measurable deformations: folds and detachments [Rodgers, 1963; Gwinn, 1964; Anderson, 1988], joint and cleavage fabrics [Nickelson, 1966; Geiser and Engelder, 1983], deformed fossils [Engelder and Engelder, 1977; Engelder and Geiser, 1980], recurrent faulting [Onasch and Kahle, 1991], calcite twinning strains [Engelder, 1979a, b; Gasteiger, 1980; Craddock and van der Pluijm, 1989] and magnetic remanence strain anisotropy [Jackson et al., 1989]. The extent of thrusting deformation in the Appalachian plateau, which is underlain by a Silurian salt detachment, has been charaterized by Wiltschko and Chapple [1977] and Davis and Engelder [1985].

In this paper we extend previous data based on 23 samples [Craddock and van der Pluijm, 1989] with 25 new cratonic samples that were analyzed for stress and strain orientations using Groshong's strain gauge technique for mechanical twins in calcite [Groshong 1972; Groshong et al., 1984)] In this study we also include twin fabrics from adjacent tectonic provinces. These data are obtained from direct measurements on rocks and should therefore provide valuable input for future modeling efforts. The collective data are used to discuss the orientation and magnitude of compressive Appalachian-Ouachita stresses, the resultant strain fields preserved by the twinned calcite, and the extent of lateral transmission of these stresses and strains into the cratonic foreland and within the deforming wedge.

RESULTS

Calcite Twinning Fabrics

Twinning in calcite requires a resolved shear stress of 10 MPa and can occur along three glide planes. At low metamorphic grades this crystal plastic mechanism is temperature and normal stress independent [Wenk et al., 1983]. Strain analysis of naturally and experimentally deformed carbonates have documented the accuracy of the maximum principal shortening axis (e1) to ~6 when the number of grains oriented unfavorably for twinning (negative expected values:NEV) is low [Groshong et al., 1984]. Calcite strain hardens once it is mechanically twinned, and the development of a second twin lamellae set requires a higher, noncoaxial stress state with respect to the orientation of the stress that initially twinned the calcite. Analysis of the twinned calcite, using the Groshong technique, computes the orientation of the Turner [1953] compression axis for each sample which reflects the paleostress orientation responsible

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for the twinning strain, as well as the orientation and magnitude of the strain ellipsoid. Calcite twin analysis is a powerful three -dimensional strain-measuring technique because of the sensitivity of calcite twinning to low stresses; however, the universal stage limits one to using only a low-power objective on the microscope (some micritic limestones do have twins, but they cannot be measured), and regional studies such as this need also consider the facies and grain size variability of carbonates.

Appalachian-Ouachita Thrust Belt and Foreland

Paleozoic limestones and dolomites were collected throughout the foreland of the Appalachian-Ouachita fold-and-thrust belt (73 sample sites, 90 strain analyses) at distances up to 1700 km from the orogenic front, as well as from within the thrust belt. Samples were also collected from five adjacent tectonic provinces to demonstrate the distinctiveness of the twinning strains preserved in the Appalachian-Ouachita foreland (Figure 1 and Table 1).

Our regional analysis is now based on a total of 90 widely separated strain analyses and includes previously published calcite strain data from the Appalachian plateau in New York (15 strain results [Engelder, 1979a, b]), Oklahoma (nine strain results [Gasteiger, 1980]) and the Pine Mountain thrust block of the southern Appalachians (25 strain results [Wiltschko et al., 1985; Kilsdonk and Wiltschko, 1988]) and 23 samples from previous work [Craddock and van der Pluijm, 1989]. We have compiled 18 new cratonic strain analyses, of which 17 preserve a thrust transport-parallel and

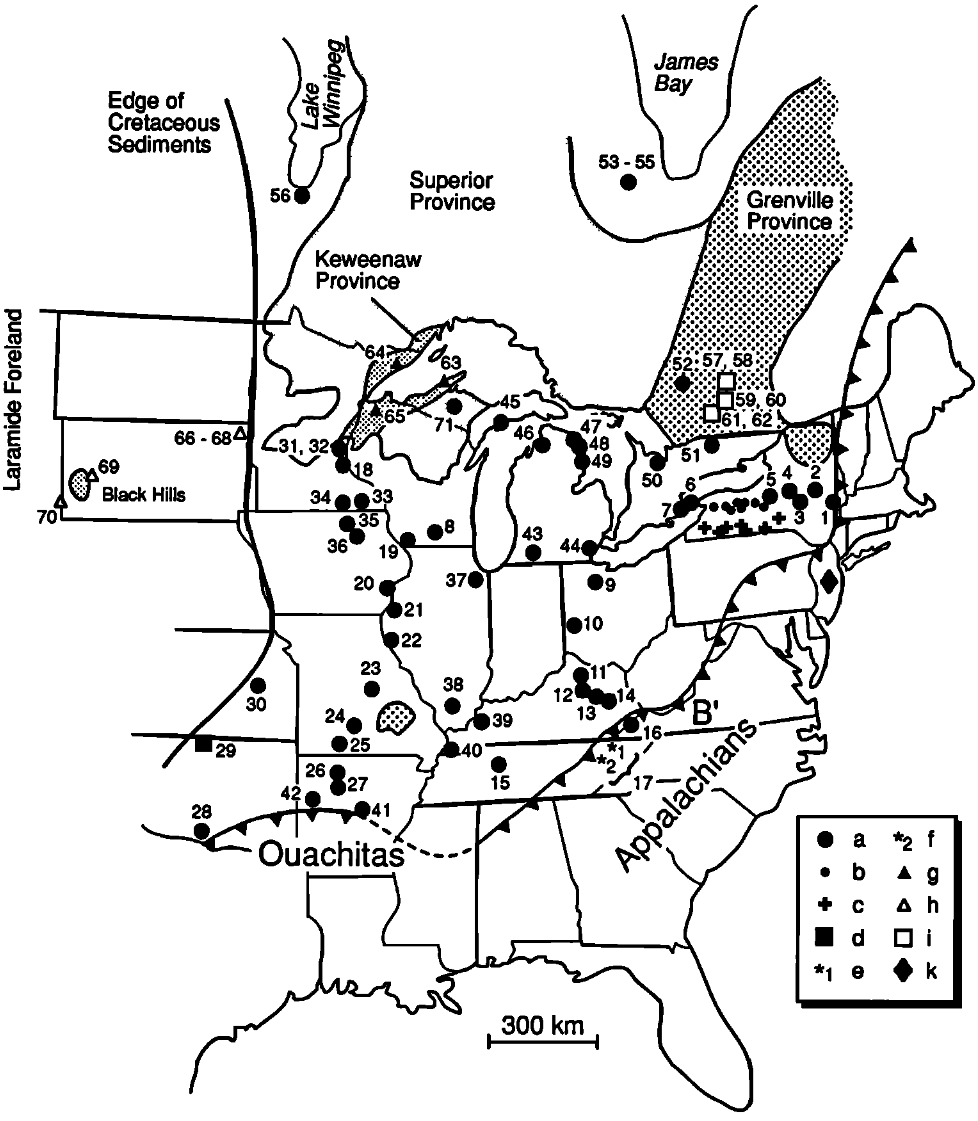

Fig. 1. Sample location map including tectonic provinces adjacent to the Appalachian-Ouachita foreland. Sample information: a (large circle), this study; b (small circle), Engelder [1979a]; c (cross); Engelder [1979b]; d (solid square), Gasteiger, [1980] e (asterisk), Wiltschko et al. [1985]; f (asterisk), Kilsdonk and Wiltschko [1988]; g (solid triangle), this study/Keweenaw province; h (open triangle), this study/Black Hills; i (open square), this study/Grenville province; k (solid diamond), Lomando and Engelder [1984].

TABLE 1. Calcite Twinning Data: Cratonic Appalachian Foreland

Sample*	Age	NEV, percent	Error, percent	e1, percent	e1 Trend, degrees
1	D	12	0.23	-0.56	85
2	D	0	0.27	-0.70	167
3	D	0	0.07	-0.67	1
4	D	5	0.17	-0.18	30
5	D	0	0.04	-0.16	38
6	D	12	0.33	-0.45	160
7	D	10	0.21	-0.22	160
SYR(1)	S,D	32	0.42	-2.16	172
OAK(1)	S,D	25	0.57	-1.35	170
HON(1)	S,D	40	1.81	-5.34	28
LRY(1)	S,D	43	0.24	-0.66	143
AVN(1)	S,D	45	0.06	-0.22	147
STA(1)	S,D	37	0.08	-0.59	169
LAN(1)	S,D	20	0.04	-0.18	4
EVS(1)	S,D	29	0.05	-0.11	13
TRI(2)	S,D	9	0.35	-1.27	17
SMB(2)	S,D	6	0.26	-1.58	176
ADI(2)	S,D	47	1.41	-5.32	167
CAM(2)	S,D	34	2.62	-7.37	168
AND(2)	S,D	20	1.37	-5.88	152
VAN1(2)	S,D	23	0.62	-1.32	134
RAW(6)	S,D	40	0.76	-1.63	140
8	O	10	0.10	-2.52	152
9(6)	D	0	0.06	-0.48	152
10(6)	O	0	0.09	-3.88	167
11	D	12	0.19	-0.46	166
12	D	6	0.20	-0.49	162
13	M	6	0.06	-1.84	149
14	M	0	0.09	-2.21	152
15	M	21	0.75	-3.51	161
16(3)	M	14	0.98	-3.80	150
17(4)	C to P	7	1.21	-3 to -5	140-170
20	M	3	0.07	-0.31	170
21	M	6	0.11	-0.38	163
22	M	12	0.09	-0.51	172
25	M	8	0.07	-1.31	3
26	M	6	0.03	-1.71	9
27	M	0	0.08	-2.38	172
28	M	13	0.61	-3.60	158
29(5)	P	23	0.06	-0.29	117
31	O	0	0.07	-4.2	149
32	O	22	0.12	-2.8	178
33	D	12	0.09	-1.6	154
34	D	8	0.11	-2.2	186
35	D	36	0.14	-0.93	177
36	D	0	0.03	-0.45	178
42	M	12	0.17	-10.8	152
43	D	29	0.78	-1.60	168
44	D	38	0.17	-1.21	175
45	O	14	0.13	-1.80	152
46	D	27	0.21	-1.51	102
47(6)	D	16	0.52	-3.14	90
48	D	15	0.06	-0.40	110
49	M	16	0.16	-0.83	120
53	D	25	0.01	-0.21	184
54	D	15	0.08	-0.28	180
55	D	12	0.05	-0.37	176
56	O	25	0.12	-2.9	179
Grenville Marbles					
57	PC	5	0.13	-10.80	176
58	PC	22	0.90	-18.0	46
59	PC	10	0.16	-4.20	155
60	PC	25	0.11	-14.1	60
61	PC	9	0.07	-4.9	138
62	PC	24	0.04	-6.4	179
Keweenawan Rift					
63	PC	10	0.05	-9.8	55
64	PC	12	0.12	-3.5	42
65	PC	20	0.02	-5.2	50
Laramide Foreland					
66	K	30	0.02	-2.7	81
67	K	2	0.13	-1.1	67
68	K	0	0.07	-3.5	130
69	D	13	0.08	-2.30	131
70	M	34	0.03	-1.10	120
Early Proterozoic Michigamme Formation at Eric's Crossing, Michigan					
71	PC	12	0.04	-5.93	164
Newark Basin [Lomando and Engelder, 1984]+					
72	Tr	33	1.19	-3.47	23,61
73	Tr	28	0.57	-2.10	97,42
74	Tr	27	0.44	-0.83	195,7
75	Tr	20	0.44	-1.57	321,43
76	Tr	47	0.28	-0.42	56,20
77	Tr	41	0.24	-0.40	183,39
78	Tr	19	0.73	-1.01	328,39
79	Tr	0	1.24	-1.38	6,38
80	Tr	10	0.46	-0.57	343,27
81	Tr	8	0.32	-0.76	11,37

Ages are PC, Precambrian; C, Cambrian; O, Ordovician; S, Silurian; D, Devonian; M, Mississippian; P, Pennsylvanian; and K, Cretaceous. NEV is negative expected value. Error is nominal error: 1/2(SE(X) + SE(Y)) x 100 [Groshong et al., 1984]. e1 is principal shortening axis.

*Numbered samples are from Craddock and van der Pluijm [1989]. Numbers in parentheses indicate 1, Engelder [1979a]; 2, Engelder [1979b]; 3, thrust belt sample; 4, Wiltschko et al. [1985] and Kilsdonk and Wiltschko [1988] (25 samples); 5, Gasteiger [1980] [nine samples); and 6, non-thrust transport-parallel fabric.

+Non-layer-parallel shortening samples with trend and plunge listed.

layer-parallel calcite shortening strain fabric (Figure 2 and Table 1). The discrepancy between the number of samples and strain analyses results from the unsuitability of samples (too micritic, dolomitic, etc.) for twin analysis, or because we have plotted multiple strain results as one sample site (Figure 1, e.g, site 29) and one averaged strain result (Figure 2; e.g., site 29). All the samples indicate a simple coaxial deformation history based on relatively low NEV percentages, low nominal errors, and the presence of only one twin lamellae set in most grains. All the data have low el shortening strain values (<6%), which are highest in the thrust belt and decrease exponentially to approximately 1700 km from the orogenic front where the last erosional remnants of the Paleozoic sediments exist (e.g., Selkirk, Manitoba; Moosonee, Ontario). As shown in Figure 2, the layer-parallel shortening strain fabric is present everywhere and is parallel to the inferred thrust-transport direction except in three samples (Table 1; samples 9, 10,and 47).

We have used twinned calcite to infer the magnitude of the differential stress responsible for the twinning deformation following the method of Jamison and Spang [1976]. This straightforward twin lamellae set/crystal/thin section counting technique documents that differential stress magnitudes were highest (90 MPa) at the orogenic front and

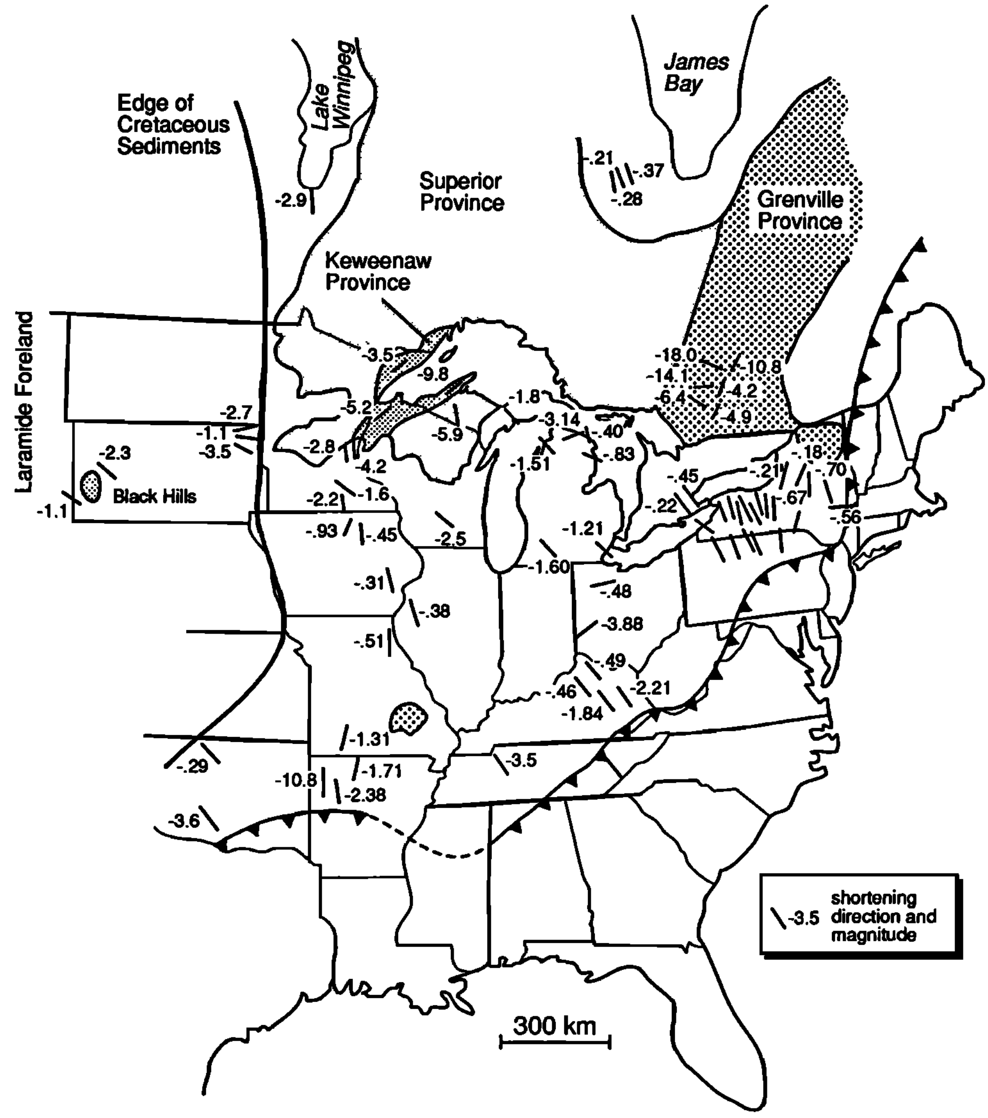

Fig. 2. Eastern North America, showing the Appalachian-Ouachita thrust front (line with teeth) and the isolated basement exposures (stippled; Ozark Mountains and Black Hills). Regional tectonic provinces are labeled and stippled differently (Superior, Grenville, and Keweenaw provinces). Data presented are the orientation and magnitude (shortening is negative) of the layer-parallel shortening axis as preserved by twinned calcite, all of which are subparallel to bedding in the Appalachian-Ouachita, Laramide, and Proterozoic limestone suites and subhorizontal in the Grenville and Keweenaw suites. The Newark Basin sediments do not contain a layer-parallel shortening strain and are not shown here. See Table 1 for details.

decrease exponentially into the extended footwall until the minimum stress level for twinning is reached (~10 MPa; Figure 3). Moreover, the orientation of the maximum paleostress was also subhorizontal and parallel to the inferred Appalachian-Ouachita thrust transport direction.

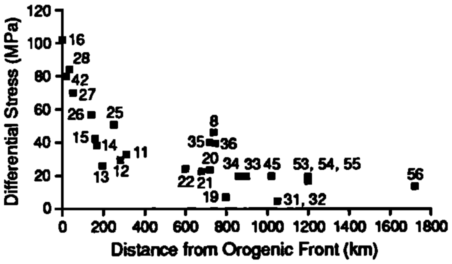

Fig. 3. Plot of inferred differential stresses [Jamison and Spang, 1976] and distance of the sample site from the orogenic front for the Appalachian-Ouachita sample suite. Sample site numbers plotted here correspond to locations on Figure 1.

Adjacent Tectonic Provinces

Grenville province. Paleozoic carbonates once covered much of the Grenville province in Ontario as evidenced by their presence to the north and south of these Proterozoic metamorphic rocks (Figure 1). Marble mylonites were sampled at 17 sites (three sites and six strain results shown here) within three northeast-southwest trending zones in the Central Metasedimentary Belt [Craddock et al., 1991]. The marbles preserve two regional subhorizontal shortening fabrics, one that is oriented NW-SE (thrusting) and a second that is oriented NE-SW (strike-slip motion), both of which are distinct from the twinning strains preserved in the adjacent and overlying Paleozoic carbonates (Figure 2 and Table 1).

Keweenawan Rift Province. The Keweenawan rift was active as an extrusive, divergent plate boundary at about 1.1 Ga but later closed along thrust faults (Douglas and Keweenawan) of opposite dip and displacement on opposing sides of the rift [e.g., Dickas, 1986]. The timing of rift closure along these thrust faults is debated; the Proterozoic(?) Jacobsville Sandstone is offset along the Keweenawan fault, as are Devonian sediments along the southern extension of this fault. This time span probably indicates multiple episodes of displacement [Craddock, 1972]. The rift is filled with a thick sequence of basalts, many of which are amygdaloidal and fractured. Both the fractures and vesicles are commonly filled with calcite, which is everywhere twinned. Our strain analysis (three sites and three strain results shown here) discovered a subhorizontal shortening strain that is parallel or slightly oblique to the rift axis (NE-SW; Figure 2 and Table 1). This strain fabric is again distinct from the twinning strain pattern preserved in the adjacent (Upper Peninsula, Michigan) or overlying (southern Minnesota and Iowa) Paleozoic carbonates and probably reflects local stress conditions associated with vein formation rather than a regional stress pattern [e.g., Craddock and van der Pluijm, 1988].

Laramide Thrust Belt and Foreland. Similar results as described above for the Appalachian-Ouachita foreland are now emerging for the Laramide-aged tectonic activity associated with the Cordilleran thin- and thick-skinned deformation across Wyoming and South Dakota, between the Idaho-Wyoming fold-and-thrust belt (west) and western Minnesota (east; three sample sites and five strain analyses shown here). Calcite strain results in the Idaho-Wyoming thrust belt preserve a layer-parallel, thrust transport-parallel (e.g., E-W) twinning fabric [Craddock et al., 1988; Craddock, 1992] that is also found in the Bighorn Mountains [Hennings, 1986], and in the Black Hills, South Dakota, in Paleozoic and Mesozoic carbonates (Figure 2). The Cretaceous Greenhorn Limestone also hosts a bedding-parallel, thrust transport-parallel calcite strain fabric again suggesting that the deformed foreland of the Cordilleran mountain belt extended at least 1200 km from the eastern boundary of the Idaho-Wyoming thrust belt (Figure 2 and Table 1). The Cretaceous Cedar Valley Formation in southeastern Minnesota is also host to an iron-rich MVT-type deposit [Bleifuss, 1972], suggesting post-depositional, cratonward migration of Cordilleran orogenic fluids. Moreover, Cretaceous-aged chemical remagnetizations that coincide with periods of thrusting are preserved within the Idaho-Wyoming thrust belt [McWhinnie et al., 1989].

Newark Basin. Triassic clastic sediments fill the Newark Basin, which is generally thought to have formed as a post-Appalachian rift basin associated with the opening of the Atlantic Ocean. Calcite is present in the Triassic Brunswick Formation as cement, and thin section study has revealed that it is everywhere mechanically twinned. Lomando and Engelder [1984] found a northerly shortening strain within the basin with strain axes that plunge from 7 to 61 for 10 strain results from 10 sites (Figure 1 and Table 1). This non-lps twinning fabric is attributed to strike-slip motions on faults within the Newark Basin. This calcite strain fabric is again distinct from the Appalachian-Ouachita foreland strain pattern described earlier.

Proterozoic Limestone, Eric Falls, Michigan. Kalliokoski and Lynott [1987] have described a paleoregolith deposit containing quartzite, limestone, conglomerates, and some cherty iron formation resting on Archean granite-greenstone belt rocks. The unconformable surface is horizontal and apparently correlates with the upper part of the early Proterozoic Michigamme Formation of the Baraga Group. The Eric Falls outcrop is north of the Penokean orogenic suture, the Niagara fault, and these rocks are unmetamorphosed. The limestone exposed along the river here is quite sparry in places and produced a calcite strain result (one site, one strain result) different from the adjacent Ordovician limestones and Keweenawan vesicle fillings (Figure 2 and Table 1).

DISCUSSION

Tectonic Deformation and Wedge Dimensions

Deformation of the foreland sedimentary rocks of the Appalachian-Ouachita fold-and-thrust belt of eastern North America is characterized by mechanically twinned calcite, jointing, solution cleavages, and gentle folds which on the Appalachian plateau are cored by evaporites. All of these structural phenomena are localized near the frontal parts of the thrust belt and disappear within a hundred kilometers or so. However, the sensitivity of the calcite strain technique has shown that small strains from orogenic deformation can be found at least 1700 km into the Appalachian-Ouachita foreland (Figure 2).

The possible geologic and man-made causes for this twinning fabric, such as sample preparation, sample location problems (e.g., roadcuts with dynamite), glacial overburden, opening of the Atlantic Ocean, and loading of the margin and transmission of compressive orogenic stresses have been evaluated by Craddock and van der Pluijm (1989), who eliminated all of the explanations except the latter. The additional data clearly support this conclusion. The timing of the measured lps twinning strain cannot be determined directly, but the fabrics have a kinematic affinity with the initial, prethrusting stress and strain fields within sediments that eventualy became incorporated in the deformed sedimentary wedge. The lps twinning strain is found in the same carbonates in both the allochthonous thrust belt and the autochthonous foreland. Mesozoic carbonates, on the other hand, do not show these strain patterns. Moreover, strain analyses in the thrust belt reveal the presence of synthrusting, non-lps twinning strains in both the country rock and younger calcite veins [Kilsdonk and Wiltschko, 1988; Craddock, 1992]. Collectively, this indicates that thrust-transport-parallel strain is a early orogenic fabric that extends up to 1700 km from the margin of the present-day thrust belt, of which parts are transported passively within the thrust sheets as the thrust belt develops. This observation alters the dimensions of the initially stressed sedimentary wedge [e.g., Davis et al., 1983] by including the extended foreland. The dimensions of the wedge now include +1700 km of the footwall (foreland) and the balanced and restored fold-and-thrust belt width (400 km [Woodward et al., 1989] for a total of +2100 km. The sedimentary wedge, through which compressive orogenic stresses are transmitted, is now an arcuate wedge that spans nearly 15 of Earth curvature in cross section.

Collisional Orogenic Stresses

Recent studies on present-day stress fields, for example, the San Andreas system [Mount and Suppe, 1987], have documented the orientation of the maximum principal stress axis (ENE-WSW and horizontal) which remains in that orientation up to 2500 km away in the center of cratonic North America [Zoback and Zoback, 1980; Zoback et al., 1987]. Similar studies in the Himalayas indicate that a consistent stress field exists 1000 km into central Asia [Tapponier et al., 1986]. The collision of Africa into North America perhaps represents a similar orogenic style [Hatcher, 1987]. The effect of continental deformation decays exponentially away from the active plate margin where the dimension of continental deformation is related to the dimension of the compressive margin [England et al., 1985]. All of these results correspond with the quantitative pattern from our regional calcite strain data, which show an exponentially decaying stress field into the cratonic interior from a high of ~90 MPa to a low of ~10 MPa (Figure 3). Engelder [1982] has reported Alleghanian stresses as low as 6 MPa in the Appalachian plateau.

The calcite strain gauge technique derives a unique strain ellipsoid (orientation and magnitude) for each sample, and Turner [1953] compression axes are also plotted; these axes represent the orientation of the paleo-stress which resulted in the mechanical twinning of the calcite. The magnitude of this paleo-stress is inferred from the density of twin lamellae sets per grain (three sets are possible in calcite) averaged over the thin sections for each sample [Jamison and Spang, 1976]. The modest accuracy of this technique is a function of the sample purity (grainstone versus wackestone), grain size, degree of dolomitization, and sorting. In our cratonic samples, only one twin lamellae set was ever observed in any calcite crystal; this indicates a simple, coaxial stress and strain history. The exponential decay of the inferred differential stress magnitudes, which caused the lps twinning strains in the foreland, also can be explained by facies changes within stratigraphic horizons across the study area, as well as by the variety of carbonates sampled (Table 1; Ordovician through Permian). Principal shortening strain magnitudes [Craddock and van der Pluijm, 1989] show the same trend: highest lps strains near the thrust front, lowest at 1700 km from the thrust front. Strain magnitudes are also a function of sample lithology and clay content [see Marshak and Engelder, 1985].

Contemporaneous Stress Fields in the Appalachian Foreland

Three of our samples (9, 10, and 47) preserve a lps twinning strain that is oriented nearly perpendicular to the general NW-SE lps fabric in the remainder of our cratonic data set. This horizontal, NE-SW orientation is parallel to the principal compressive stress (S_{Hmax}) of today's stress field [McGarr and Gay, 1978; Richardson et al., 1979; Zoback and Zoback, 1980]. One interpretation of the strains in these three samples could be that they existed in a stress shadow during the Appalachian-Ouachita orogeny and were untwinned until the present. Studies of in situ stress in the eastern midcontinent region demonstrate an increasingly compressive stress gradient with depth (~26 MPa/km) where S_{Hmax} is high enough in basement crystalline rocks to twin calcite [Haimson and Doe, 1983; Baumgartner and Zoback, 1989] but is too low to twin calcite in sedimentary rocks of the Appalachian Basin [Evans, 1989]. The Wolf River pluton (1.45 Ga) in north central Wisconsin preserves a set of healed microfractures that are subhorizontal and strike NW-SE [Jang et al., 1989] and could be interpreted as related to either the Grenville or Appalachian orogens. The absence of any overprint in the calcite strain results (e.g., a high percentage of NEVs) by the contemporaneous stress field indicates how well calcite strain hardens once it twins along one glide plane (Teufel, 1980), how consistent the Appalachian-Ouachita stress field was in orientation, and how low any post-Appalachian stress fields were in magnitude. Alternatively, rocks buried deeply enough to have experienced these younger, higher-magnitude stresses and preserve a more complex twinning strain history may not yet be exposed at the surface. A comparative study of foreland twinning strains and magnetic anisotropy fabrics for the Laramide belt and its foreland in in progress (J.P. Craddock et al.,manuscript in preparation, 1992; sample sites 66-70).

CONCLUSIONS

Bedding-parallel, subhorizontal shortening strains, as preserved by twinned calcite in Paleozoic carbonates that cover cratonic eastern North America are perpendicular to the orogenic fronts of the Appalachian and Ouachita mountains. These thrust-parallel fabrics extend up to 1700 km into the foreland and perhaps farther, but no samples are available beyond this distance. The calcite twinning was caused by the transmission of subhorizontal compressive Paleozoic orogenic stresses into the craton. The magnitudes of both the twinning strains and paleostresses decrease exponentially away from the active plate margin. Comparisons of twinning strain patterns in adjacent tectonic provinces reveal that these geologic provinces contain mechanical twinning fabrics that are distinct and unrelated to the Paleozoic pattern associated with the Appalachian-Ouachita orogenic event.

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J. P. Craddock, Geology Department, Macalester College, St. Paul, MN 55105.

M. Jackson, Department of Geology and Geophysics, University of Minnesota, Minneapolis, MN 55445.

B. van der Pluijm, Department of Geological Sciences, University of Michigan, Ann Arbor, MI 48109.

R. Versical, Department of Geology, Western Michigan University, Kalamazoo, MI 49008.

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