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Some remarks on rheology and fluid migration in the Paleozoic eastern Midcontinent of North America from regional calcite twinning patterns

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ABSTRACT

Mechanical twins in calcite from carbonates of the Paleozoic cover sequence of eastern North America preserve a record of far-field paleostress and strain transmission that is associated with late Paleozoic ("Alleghenian") activity at the Laurentian plate margin. Calcite twinning analysis permits the determination of regional differential paleostress (σ_D) and finite strain (e) patterns that are combined to obtain rheologic properties of the cover rocks. The combination of strain vs. distance and stress vs. distance relationships produces a stress-strain relationship of the form: $e = 10^{-5} \cdot \sigma_D^2$. Modeling of linear viscous rheologies by others supports the observation of far-field effects transmitted from this convergent margin if the convergence vector between the Laurentian and Gondwanan plates is at a high angle to the margin. Using differential paleostress data from calcite twinning at the orogenic front, high fluid pressure is calculated ($\lambda = 0.65$). Moreover, the occurrence of twinning in the carbonate cover changes its permeability, perhaps permitting fluids to migrate along evolving grain boundaries in rocks that otherwise have low porosities.

INTRODUCTION

In his landmark paper, Oliver (1986) proposed that Appalachian tectonics at the margin of eastern North America was responsible for a variety of geologic features that occur well inboard from that active margin. In particular, Oliver emphasized the role of fluids that were expelled from the evolving thrust belt by loading of sedimentary cover (Fig. 1). Much of the subsequent work has focused on the evidence for the presence of this fluid and the nature of its migration (e.g., Bethke and Marshak, 1990, and references therein). Some have argued, based in part on the basis of thermal considerations, that a fluid must have migrated in essentially a single pulse, while others favor more long-lasting fluid migration. Major fluid migration was proposed during the late Paleozoic Alleghenian orogenic event that is prominent in the southern and central portion of the Appalachians as well as in the Ouachitas of the southern United States. In addition, physical evidence that includes large wavelength folds, cleavage, deformed fossils, and jointing indicates that large tracts of the cratonic cover sequence have undergone penetrative deformation that is related to late Paleozoic activity at the plate margin (e.g., Rodgers, 1963; Nickelsen, 1966; Engelder and Engelder, 1977; Geiser and Engelder, 1983; Anderson, 1988).

Craddock and van der Pluijm (1989) and Craddock et al. (1993) collected samples across the eastern interior of North America (Fig. 2) and showed that calcite of the cratonic cover preserves a record of regionally consistent differential paleostress and strain patterns associated with late Appalachian convergent activity. They concluded that lateral transmission of orogenic stresses away from the evolving margin produced these twins in

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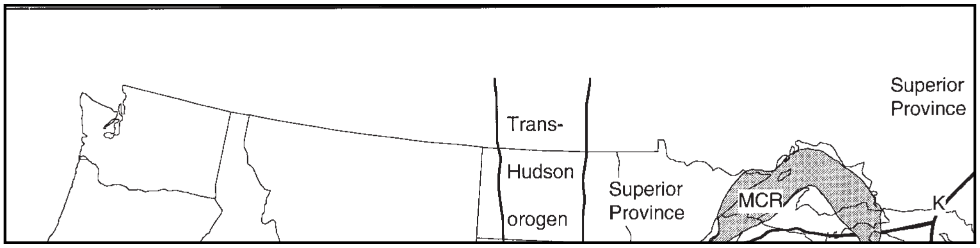

Figure 1. Proposed scenario of fluid expulsion from an evolving mountain belt and associated geologic phenomena (redrawn after Oliver, 1986).

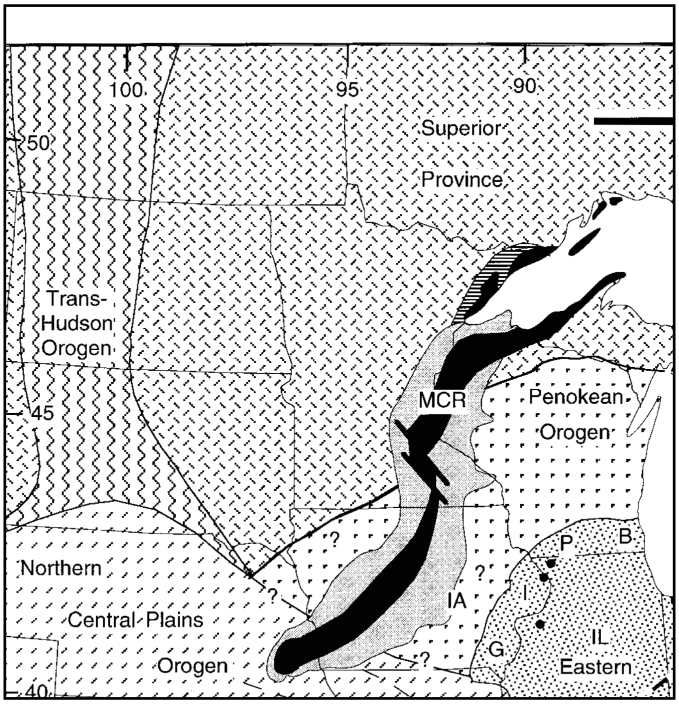

Figure 2. North American sampling sites for calcite twinning analysis. Numbers refer to data listed in Table 1 (modified from Craddock et al., 1993).

coarse-grained carbonates. These patterns were not generally overprinted by younger activity (such as Atlantic rifting) in the eastern part of the continent, except in localized regions (e.g., Triassic basins; Craddock et al., 1993). The aim of this short chapter is to briefly review the underlying theory of calcite twinning analysis, but in particular to speculate on the significance of these data for rheologic and fluid migration properties of the Paleozoic cover sequence of eastern North America.

CALCITE TWINNING ANALYSIS

At low temperatures (<300 °C), calcite deforms plastically by twinning in response to a minimum applied stress (Turner, 1953; Fig. 3a). A surface imperfection separates two regions of a twinned crystal that are mirror images of each other (Fig. 3b); in other words, the twin boundary is a mirror plane with a specific crystallographic orientation. Mechanical twins are produced when the critical resolved shear stress (CRSS) acting on the future twin boundary is exceeded. During twinning the crystal lattice rotates in the direction that produces the shortest movement of atoms, with a unique rotation angle. As such, mechanical twinning has similarities with dislocation glide, but differs in two respects. First, atoms are not moved an integral atomic distance as in dislocation glide, but rather some fraction; consequently, twinning involves partial dislocations (e.g., Hull, 1975). Second, the twinned portion of a grain is a mirror image of the original lattice, whereas the slipped portion of a grain has the same crystallographic orientation as the unslipped portion.

That twinning takes place along distinct crystallographic planes in a calcite crystal and that rotation occurs over a specific angle and in a specific sense allow us to use twinning as a measure of finite strain (Groshong, 1972; Groshong et al., 1984). For low-temperature twinning we only consider e-twins ({1018} ⟨4041⟩) with a rotation angle for the c-axis of 52.5°, and a CRSS of 10 MPa (Wenk et al., 1983). Twinning in calcite is illustrated in Figure 3, showing the rotation angle of the crystallographic c-axis, which is perpendicular to the planes containing the CO_3 groups, and that of the crystal face. In Figure 4a, a deformed grain A′B′CD with one twin is schematically shown. The original grain outline is ABCD with its sides parallel to calcite crystal planes. In the twinned grain the shear strain is given by:

$$\gamma = \tan\Psi = q/T. \quad (1)$$

For one twin, $q = p$, so

$$\gamma = \left[2t\ \tan(\phi/2)\right]/T, \quad (2)$$

where T is the grain thickness and t is the twin thickness. For a grain containing several twins (Fig. 4b) the shear strain is obtained simply by adding the strain due to each twin:

$$\gamma = \frac{2}{T}\sum_{i=1}^{n} ti\ \ \tan(\phi/2), \quad (3)$$

where n is the number of twins in the grain. Given that the angle ϕ is constant for calcite (≈38°; Fig. 3b), this simplifies to:

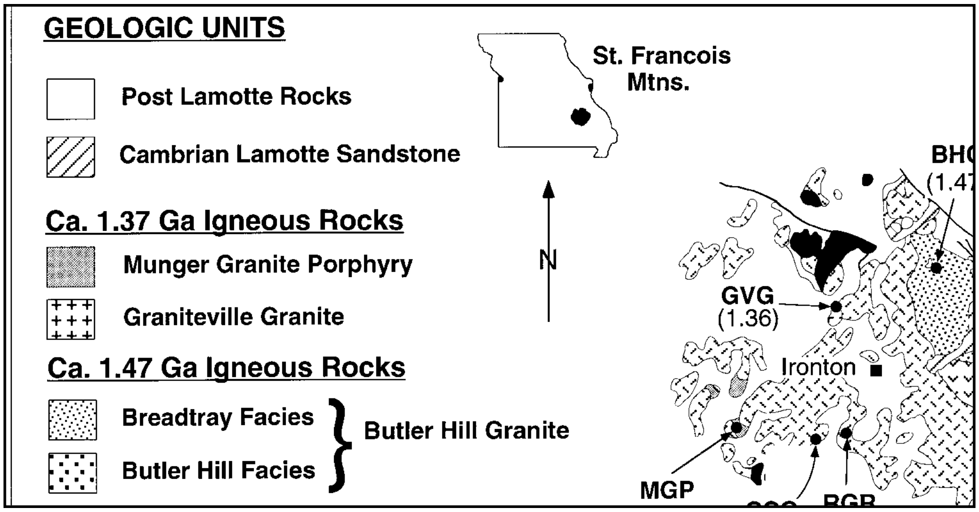

Figure 3. Atomic model of calcite twinning showing the untwinned calcite structure (a) and the configuration of the same atoms after twinning along *e* (b). Closed circles are Ca atoms, open circles are O that surround C atoms (small closed circles); C and T are the compression and tension axes, respectively. Twinning results in a ~52° rotation of the crystallographic c-axis.

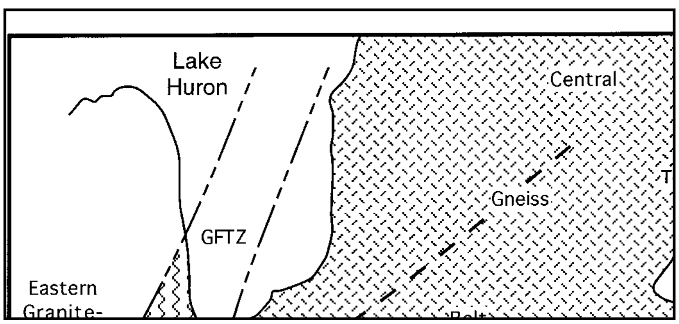

Figure 4. The principle of strain determination from twinned grains; (a) single twin, (b) multiple twins (modified from Groshong, 1972). See text for discussion.

$$\gamma = \frac{0.7}{T}\sum_{i=1}^{n} ti\,. \qquad (4)$$

So, measuring the total width of twins and the grain size perpendicular to the twin plane gives the total shear strain for a single twinned grain. In an aggregate of grains, the shear strains will vary as a function of crystallographic orientation of individual gains relative to the bulk strain ellipsoid, which we use to determine the orientation of the principal strain axes by determining the orientations for which the shear strains are zero and maximum. The details of the method were described in Groshong (1972), and a computer routine is normally used for the analysis (see Evans and Groshong, 1994). Note that maximum shear strain occurs when the entire grain is twinned; i.e., if $t = T$ (Fig. 4), with $\gamma_{max} = 0.7$ or $X/Z \approx 2$. In practice, this means that only relatively small strains on the order of 10% or less can be measured with this method.

Using the Groshong method, the strain ellipsoid is calculated for each thin section (or group of thin sections for each sample), and compression axes (Turner, 1953) are contoured in lower hemisphere projections. In weakly deformed rocks such as these cover carbonates, the maximum shortening axis and the maximum of contoured compression axes generally are approximately parallel. Determination of the magnitude of the differential stress, σ_D, is computed using the method devised by Jamison and Spang (1976). This twin density counting method is most reliable in weakly deformed rocks where grains generally contain only one twin set. Rocks with multiple, non-coaxial deformation histories allow for determination of the bulk differential stress, but the stress field magnitudes for each twinning deformation cannot be resolved. Twinning occurs at stresses greater than 10 MPa and the differential stress, σ_D, is obtained from:

$$\sigma_D = 10/S_1, \qquad (5)$$

where S_1 is a value ranging from 0 to 0.5 for many to few twins, respectively. The particular value of S_1 is read off a graph that plots the percentage of grains twinned as a function of S_1 (Jamison and Spang, 1976). In practice, one counts the percentage of grains with one, two, and three twin sets in a thin section, and then that value is plotted to get S_1. Using equation 5 gives an approximate value for the differential stress. Both strain and differential stress methods have been applied to the samples from the Midcontinent region. An excellent review of these applications of calcite twinning, and descriptions of several field examples can be found in Burkhard (1993).

RESULTS

The results of dynamic twinning analysis of 48 cratonic samples are listed in Table 1 and the shortening directions as well as magnitudes are plotted in Figure 5. In Craddock and van der Pluijm (1989), the possible origins of these twinning patterns were discussed, and they concluded that the twins were formed in response to the inland transmission of orogenic stresses from the active Appalachian margin. Additional work reported in Craddock et al. (1993) lends further support to this interpretation and also showed that discrete patterns are associated with specific geologic provinces. The extent of the twinning patterns indicates that stress transmission may have occurred well over 1000 km away from the convergent margin. However, local perturbations, such as preexisting faults, affected the stress field and may be responsible for observed local complexities. In fact, such perturbations may allow us to identify important faults within the cratonic interior. One example is the orientation of the field in northern Ohio around the area of the Bowling Green Fault (Onasch and Kahle, 1991), where the shortening direction is perpendicular to the regional pattern.

DISCUSSION

The present data base is sufficiently robust to make some inferences of these paleostress and strain patterns for rheological properties of the cratonic interior. However, because the data do not enable us to determine strain rate, we are limited to stress-strain correlations. The relations between distance from the orogenic front and differential stress (D versus σ_D), and distance and finite strain (D versus e) are plotted in Figure 6, a and b, respectively. These stress and strain versus distance diagrams show an overall nonlinear decrease away from the orogenic front, which will be discussed in the next section.

Simple rheologic properties of the cover sequence

For an examination of the rheologic properties of the cover sequence based on the calcite twinning data, we arbitrarily limit the data set to results from distances within ~700 km of the orogenic front in order to reduce the influence of noise and local perturbations, especially for the fluctuating finite strain data at greater distances (dashed lines in Fig. 6). Curves were fitted in log-log space, and the corresponding relations and their correlation coefficients, R, are:

$$\sigma_D = 10^{2.67} \bullet D^{-0.47} \left(R^2 = 0.81\right), \qquad (6)$$

and

$$e = 10^{0.17} \bullet D^{-0.90} \left(R^2 = 0.76\right). \qquad (7)$$

TABLE 1. CALCITE TWINNING DATA: APPALACHIAN FORELAND

Sample*	Age†	NEV§ (%)	Error** (%)	e_1‡ (10^2)	e_1 trend‡ (°)	σ_D (MPa)
1	D	12	0.23	-0.56	085	
2	D	0	0.27	-0.70	167	
3	D	0	0.07	-0.67	001	
4	D	5	0.17	-0.18	030	
5	D	0	0.04	-0.16	038	
6	D	12	0.33	-0.45	160	
7	D	10	0.21	-0.22	160	
SYR[a]	S,D	32	0.42	-2.16	172	
OAK[a]	S,D	25	0.57	-1.35	170	
HON[a]	S,D	40	1.81	-5.34	028	
LRY[a]	S,D	43	0.24	-0.66	143	
AVN[a]	S,D	45	0.06	-0.22	147	
STA[a]	S,D	37	0.08	-0.59	169	
LAN[a]	S,D	20	0.04	-0.18	004	
EVS[a]	S,D	29	0.05	-0.11	013	
TRI[b]	S,D	9	0.35	-1.27	017	
SMB[b]	S,D	6	0.26	-1.58	176	
ADI[b]	S,D	47	1.41	-5.32	167	
CAM[b]	S,D	34	2.62	-7.37	168	
AND[b]	S,D	20	1.37	-5.88	152	
VAN[b]	S,D	23	0.62	-1.32	134	
RAW[b]	S,D	40	0.76	-1.63	140	
8	O	10	0.10	-2.52	152	42
9[f]	D	0	0.06	-0.48	152	
10[f]	O	0	0.09	-3.88	167	
11	D	12	0.19	-0.46	166	32
12	D	6	0.20	-0.49	162	29
13	M	6	0.06	-1.84	149	25
14	M	0	0.09	-2.21	152	38
15	M	21	0.75	-3.51	161	41
16[c]	M	14	0.98	-3.80	150	102
17[d]	C to P	7	1.21	-3 to -5	140-170	
20	M	3	0.07	-0.31	170	24
21	M	6	0.11	-0.38	163	23
22	M	12	0.09	-0.51	172	24
25	M	8	0.07	-1.31	0.03	52
26	M	6	0.03	-1.71	0.09	57
27	M	0	0.08	-2.38	172	71
28	M	13	0.61	-3.60	158	84
29[e]	P	23	0.06	-0.29	117	
31	O	0	0.07	-4.2	149	6
32	O	22	0.12	-2.8	178	6
33	D	12	0.09	-1.6	154	20
34	D	8	0.11	-2.2	186	20
35	D	36	0.14	-0.93	177	40
36	D	0	0.03	-0.45	178	39
42	M	12	0.17	-10.8	152	80
43	D	29	0.78	-1.60	168	
44	D	38	0.17	-1.21	175	
45	O	14	0.13	-1.80	152	20
46	D	27	0.21	-1.51	102	
47	D	16	0.52	-3.14	090	
48	D	15	0.06	-0.40	110	
49	M	16	0.16	-0.83	120	
53	D	25	0.01	-0.21	184	20
54	D	15	0.08	-0.28	180	20
55	D	12	0.05	-0.37	176	19
56	O	25	0.12	-2.9	179	17

*Numbered samples are from Craddock and van der Pluijm, 1989; others are from: (a) = Engelder, 1979a; (b) = Engelder, 1979b; (c) = Thrust belt sample; (d) = Wiltschko et al., 1985, Kilsdonk and Wiltschko, 1988 (25 samples); (e) = Gasteiger, 1980 (9 samples; (f) = Nonlayer-parallel shortening fabric.
†Ages are: C = Cambrian; O = Ordovician; S = Silurian; D = Devonian; M = Mississipian; P = Pennsylvanian.
§NEV = negative expected value.
**Error = nominal error 1/2[SE(X) + SE(Y)] ˇ 100 (Groshong et al, 1984).
‡e_1 = principal shoretning axis.

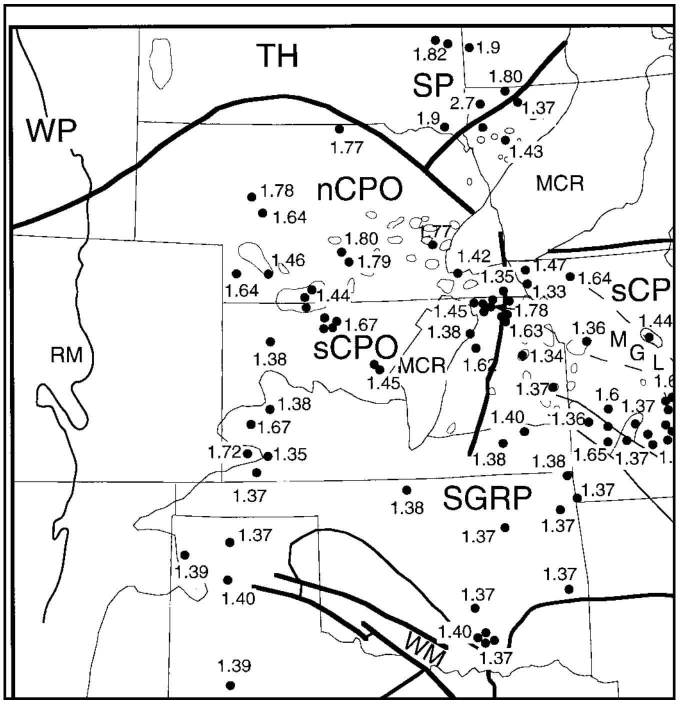

Figure 5. Orientation and magnitude of the maximum shortening strain based on calcite twinning analysis at the localities shown in Figure 2.

By combining equations 6 and 7, we determine a stress-strain relation:

$$e = 10^{-4.96} \bullet \sigma_D^{\,1.9}. \qquad (8)$$

Thus, we obtain a power-law relationship between stress and strain, in which the power *n* is on the order of 2. Linear stress-strain relations characterize elastic behavior (e.g., Twiss and Moores, 1992, p. 361); thus, an elastic rheology is not representative of the calcite cratonic cover sequence. Rather, this simple analysis indicates that even this uppermost layer of the lithosphere may be adequately modeled by using linear viscous or Newtonian properties. Note that equation 8 nonlinearly relates strain with stress, but that viscous behavior equates strain rate with stress (e.g., Twiss and Moores, 1992, p. 362). This discrepancy can be resolved by integrating finite strain over a particular time interval. However, reliable time estimates for stress transmission are not available to our knowledge; consequently, the calculated stress exponent (n) assumes that time is a constant.

Calculations of thin sheet, linear viscous behavior to continental dynamics have demonstrated that the ratio of the length of the active margin divided by the margin-perpendicular distance over which deformation is significant (i.e., the length scale) is primarily a function of the exponent n and the orientation of the convergence vector between the two plates (e.g., England et al., 1985). On the basis of these theoretical arguments and the observed regional extent of deformation in the North American cratonic interior, we can speculate that the convergence vector between Laurentia and Gondwana must have been oriented at a relatively high angle to the margin, regardless of the position of the lithospheric far-field stress guide.

Implications for fluid flow

The results from dynamic twinning analysis also place constraints on the fluid pressure in the evolving Appalachian-Ouachita thrust belt and offer a possible mechanism for long-distance fluid transport. To determine the fluid pressure in the mountain belt, we assume that the Appalachian thrust belt is a critically stressed Coulomb wedge (Davis et al., 1983), and we use an estimate of 6 km overburden at the exposed orogenic front (sample 16). The contribution of other ductile deformation mechanisms, such as pressure solution, is excluded. In this case the mechanical behavior of the wedge is governed by the Coulomb failure criterion (e.g., Twiss and Moores, 1992, p. 169):

$$1/2\ \ \sigma_D = \sigma_0 + \mu\left(\sigma_n - P_f\right). \qquad (9)$$

Given a cohesive shear strength (σ_0) of ~20 MPa, a coefficient of internal friction (μ) of 0.6, a load stress from 6 km overburden

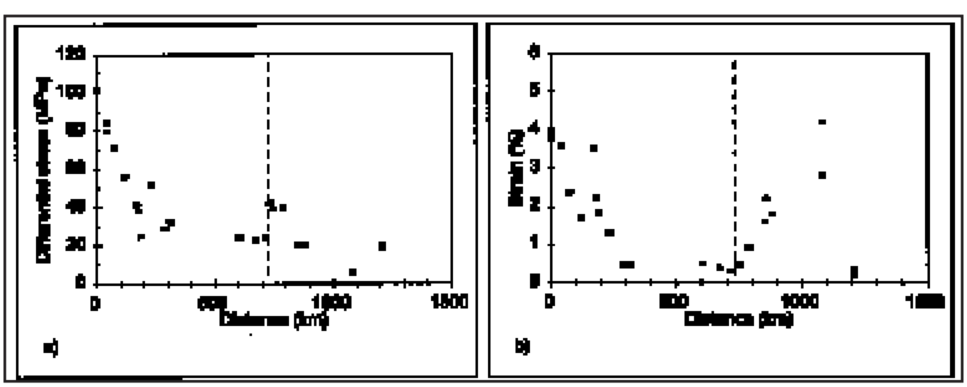

Figure 6. Plots of distance vs. differential stress (a) and distance versus strain (b) from the data in Table 1. Only data within ~700 km of the orogenic front (dashed line) are used for the calculations in this chapter.

(σ_n) of ~140 MPa, the measured differential stress at the orogenic front of ~100 MPa (Fig. 6), gives a fluid pressure of ~100 MPa that corresponds to a Hubbert-Rubey ratio λ (=P_f/σ_n) of 0.65 at the orogenic front.

Finally, twinning may also have played an important role in the lateral movement of fluid away from the evolving thrust belt. The porosity of carbonate at several kilometers depth is very low (<10%; Schmoker and Halley, 1982), severely limiting the ability for fluid flow that is required in most models (e.g., Oliver, 1986). However, when twinning occurs, the relative positions of grain boundaries change, and such an evolving microstructure may permit fluid to move along these transient boundaries until cementation occurs. Moreover, if these pores remain open for geologically significant times or if twinning continues to modify the grain boundaries, this secondary porosity may permit large volumes of fluid to pass along these boundaries, which may ultimately have been responsible for such varied phenomena as hydrocarbon and Mississippi Valley type deposits, and paleomagnetic remagnetization in the Midcontinent region.

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