Curving cross joints and the lithospheric stress field in eastern North America

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ABSTRACT

Cross joints are late-formed nonsystematic fractures that extend across intervals between systematic joints. Traces of such cross joints are seen on bedding-plane surfaces of Devonian Catskill clastic sedimentary rocks of the Appalachian Plateau of western New York State, where the maximum horizontal principal stress (S_H) is oriented ~N65°E, as indicated by in situ stress measurements. Between pairs of closely spaced systematic joints, traces of cross joints are commonly planar and orthogonal to the preexisting joints. However, in the mid-region between some widely spaced systematic joints in western New York, cross joints strike parallel to the S_H of the present lithospheric stress field, but then curve to abut the preexisting joints at right angles. A curving trace reflects a local perturbation of the regional stress field in the vicinity of preexisting joints, and the perpendicular termination indicates that the preexisting joints were open. Depending on their age, the strike of the mid-region of curving cross joints denotes the orientation of either the neotectonic stress field or its Tertiary predecessor in the North American lithosphere.

INTRODUCTION

We suggest here that the orientation of some late-formed curving cross joints on the Appalachian Plateau was controlled by either the neotectonic lithospheric stress field or by a Tertiary predecessor. If this is so, the outcrop trace of these curving cross joints should be added to the inventory of brittle structures; this permits mapping of the lithospheric stress field in lieu of more expensive in situ stress measurements (e.g., Engelder, 1982). That inventory of brittle structures already includes late-formed joints found in central Pennsylvania (Hancock and Engelder, 1989) and the linear segments of the Niagara Escarpment, New York (Gross and Engelder, 1991).

Nonsystematic cross joints propagate between preexisting systematic joints to generate a pattern resembling rungs on a ladder, particularly if the former are planar and orthogonal to the latter (Gross, 1993). Pavement surfaces of Devonian clastic rocks on the Appalachian Plateau commonly display such a simple pattern (Engelder and Geiser, 1980). Because they are mode I cracks, cross joints propagate normal to the least principal stress, σ_3, an effective tensile stress at the time of propagation. If the local stress field is inhomogeneous, cross joints will curve in response to that stress configuration.

Cross joints consistently terminate at right angles to preexisting systematic joints. Such terminations occur when the latter joints are open, as is the case in near-surface rocks. Open joints are like mechanical layer boundaries, and the distance between adjacent open joints constitutes a joint-controlled mechanical layer thickness (Gross, 1993). In the vicinity of open joints, the orientation of a far-field stress is perturbed, causing the local principal stresses to rotate to orthogonality with the preexisting joints. If a cross joint begins to form under influence of a regional stress field and propagates toward a preexisting joint, the perturbed, inhomogeneous stress field will cause the cross joint to curve either parallel or perpendicular to the preexisting joint, depending on the orientation of the far-field stress and the stress ratio (Dyer, 1988).

CROSS JOINTS IN CLASTIC ROCKS OF THE DEVONIAN CATSKILL DELTA

Cross joints in clastic rocks of the Devonian Catskill Delta are seen best on large pavement surfaces, a relatively rare type of outcrop. Two particularly striking examples of nonsystematic joints are found in some fine-grained sandstones of the Canadaway Group in the Genesee River bed at Belmont, New York, and in some organic-rich shale beds of the West Falls Group within a stream bed passing through Stony Brook State Park, New York (Fig. 1). The pavement surface at Belmont displays three joint sets, including a strike-perpendicular systematic set reflecting the orientation of S_H (320°) during the Alleghanian orogeny (e.g., Engelder and Geiser, 1980), an east-west systematic set (085°) of unknown origin, and a set of late-formed cross joints (Fig. 2A). Abutting relations demonstrate that the east-west systematic set postdates the strike-perpendicular joints associated with the Alleghanian orogeny. Spacing of the strike-perpendicular joint set varies from

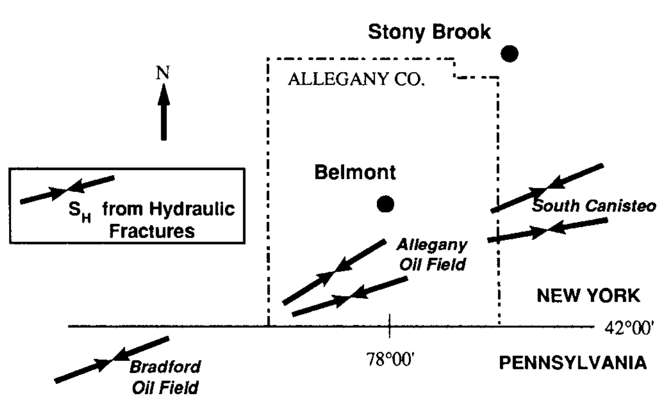


Figure 1. Outcrop locations at Belmont (Canadaway Group) and Stony Brook (West Falls Group), New York. Hydraulic fracture orientations include those within Allegany and Bradford oil fields (Overby and Rough, 1968; Haimson and Stahl, 1969) and South Canisteo (Evans et al., 1989).

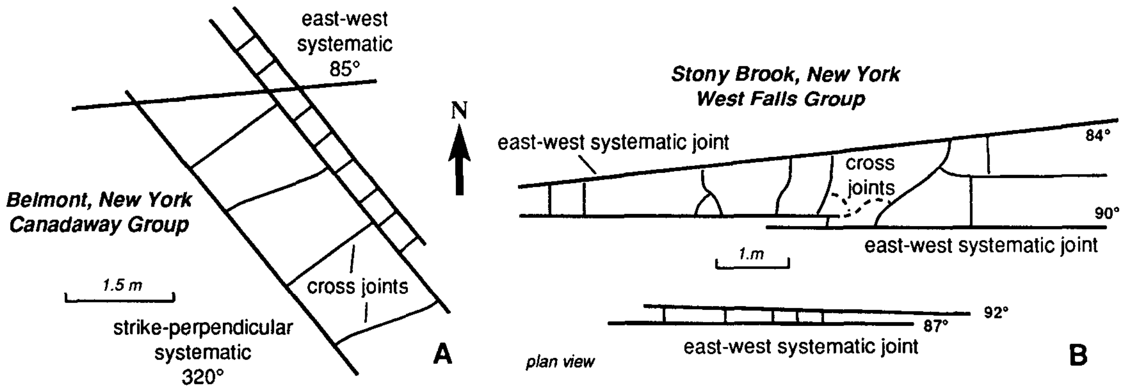


Figure 2. A: Schematic diagram showing three joint sets that cut Canadaway Group siltstones in Genesee River bed at Belmont, New York. Relative ages of three sets are indicated from oldest (1) to youngest (3). Note alternating curving and planar cross joints, implying sequential infilling process for cross-joint propagation. B: Sketch of outcrop showing joints that cut West Falls Group organic-rich shales at Stony Brook State Park, New York.

about 24 cm to 1.79 m, whereas spacing of the east-west set exceeds 4 m. At Stony Brook the east-west systematic set is more closely spaced, and the intervening space is filled by cross joints (Fig. 2B). The east-west systematic set is best developed within metre-thick organic-rich black shale layers, which are separated by up to 5 m of gray shale. Whereas strike-perpendicular joints are seen within the gray shale, they are absent on the pavement surface of black shale described here.

The orientation of cross joints was measured at five points along their trace length between adjacent systematic joints (Fig. 3). At Belmont, as many as 15 cross joints were measured between six pairs of systematic joints (Fig. 4). Cross joints were numbered in sequential order from north to south between each pair of systematic joints. At Stony Brook, cross-joint data were collected sequentially from west to east between one systematic joint pair. For a given cross joint in Figures 4 and 5, a tight cluster of orientation data indicates a straight trace, and presumably a planar joint, whereas a wider range of orientation data indicates a curving cross-joint trace.

The pavement surface at Belmont is characterized by strike-perpendicular joints most commonly spaced more than 1 m apart and connected by nonsystematic cross joints of two types, both of which terminate against systematic joints at 90° ±2°. One is characterized by a straight trace striking 50° ±2° and oriented roughly perpendicular to 320° systematic joints. When closely spaced (~24 cm), the systematic joint pairs are always infilled by straight cross-joint traces, as indicated by clustered orientation data (Fig. 4A). The other cross-joint type propagates along a curved trajectory. Systematic joint pairs spaced at 0.79 m or more are infilled with a combination of curving and planar cross joints (Fig. 4, B–F). As a general rule, the planar joints are most common between closely spaced systematic joint pairs, whereas the curving cross joints are most common between the more widely spaced systematic joint pairs. The outcrop trace of the mid-region of many curving cross joints has a trend close to 65°, which is approximately the orientation of S_H of the lithospheric stress field in the Appalachian basin (Plumb and Cox, 1987).

To understand cross-joint propagation at Belmont, four other observations are relevant. First, as systematic joint spacing increases, so does the number of cross joints with mid-region strikes of ~65° (Fig. 4). Second, cross-joint traces are generally straight (cross joints 10 and 12 in Fig. 4D) adjacent to the earlier crosscutting joints striking at 85° (joint 11 in Fig. 4D). Third, adjacent cross joints tend to alternate between curving (cross joints 1, 3, and 5 in Fig. 4D) and straight (cross joints 2 and 4 in Fig. 4D) traces; only the wider spaced systematic joints are infilled by adjacent curving cross joints (Fig. 4, E and F). Fourth, the spacing of the cross joints increases with the spacing of the systematic set.

The correlation between systematic joint spacing and curving cross joints is also apparent at Stony Brook, where the systematic joint set is the same 85° set seen at Belmont. At Stony Brook, joints of the 85° set are infilled with nonsystematic cross joints, some of which curve in an irregular or haphazard manner. The most interesting preexisting joint pair consists of nonparallel members; one joint strikes 84°, whereas the other strikes at 90° (Fig. 2B). As the distance between this pair increases, cross joints change from planar to curving, as demonstrated by an increasing range in orientations measured along the trace length of each cross joint (Fig. 5B). With increasing systematic joint spacing, the mid-region trace of cross joints curves toward alignment with S_H and away from an orthogonal orientation next to the preexisting joints. The similarity among cross joints at Belmont and Stony Brook is that their mid-region traces strike

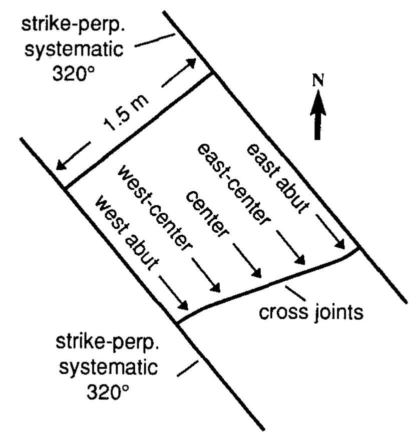


Figure 3. Orientation data were collected at five points along each cross joint. Measurements were made near either end of cross joint where it abuts systematic set. Other measurements were made at center point and at 25% and 75% of distance between systematic joints.

within 5° of each other. The difference is that the trace of the longest of the cross joints at Stony Brook curves up to 60°, whereas it is 15° at Belmont.

DISCUSSION

On the Appalachian Plateau cross joints are thought to have propagated in response to layer-parallel stretching during Tertiary uplift and erosion. Curving cross joints develop if spacing between systematic joints is relatively large and if the lithospheric stress, a far-field stress, is nonorthogonal to the early systematic joint set. At a distance of less than half the height of the early joint, a stress perturbation by the open joint suppresses the influence of the far-field stress on controlling cross-joint propagation. In this case, the stress perturbation causes curved stress trajectories and curved cross joints in the vicinity of an early joint (Fig. 6). Planar cross joints develop orthogonal to early systematic joints if the latter are closely spaced. In this case the stress perturbation near the early joints completely controls joint propagation. At Belmont the suppression of the far-field stress is also indicated by the straight cross-joint traces next to the preexisting 85° joints and the alternation between curving and straight cross-joint traces (Fig. 4D).

If the mid-region trace of curving cross joints is consistently oriented on the outcrop scale as well as between outcrops, the trace records the orientation of a lithospheric stress field at the time of uplift and erosion. The trace of the mid-region of cross joints at Belmont and Stony Brook is toward 65° and 60°, respectively. Furthermore, the orientations of traces of the mid-region are similar despite differences in orientation and origin of the associated systematic joint pair (320° at Belmont vs. 85° Stony Brook). The orientation of the eastern North American lithospheric stress field is 60° to 65°, as indicated by local hydraulic fracture measurements (Fig. 1). Because arguments based on plate tectonics suggest that the orientation of the lithospheric stress field in eastern North America has not changed appreciably since at least the middle Tertiary, the orientations of the present lithospheric stress field and either the neotectonic stress field or its Tertiary predecessor are one and the same (Zoback and Zoback, 1991). We are unaware of any pre-Tertiary tectonic event that is consistent with N65°E cross joints. For example, in mapping dikes in New England, McHone (1978) identified three sets, none of which shows S_H parallel to the present lithospheric stress field. Therefore, curving cross joints indicate the orientation of the neotectonic lithospheric stress field or its Tertiary predecessor, provided that the cross joints propagated between systematic joint pairs whose spacing is equal to or greater than their height (Gross, 1993).

Curving cross joints may permit mapping of the recent lithospheric stress field in lieu of more expensive in situ stress measurements. However, this technique has several requirements: good pavement surfaces, well-developed systematic joints, interbedded rocks, and nonorthogonality between systematic joints in the lithospheric stress field.

The shape of the curving propagation path of cross joints is a function of the orientation of the far-field stress, the elastic properties of the host rock, the height of the systematic joints, and the differential stress, $\sigma_d = S_H - S_h$ (Dyer, 1988). If the orientation of the far-field stress is known, then the shape of the outcrop trace of cross joints can be used to predict the σ_d at the time of cross-joint propagation, if elastic properties and systematic joint height are assumed. We

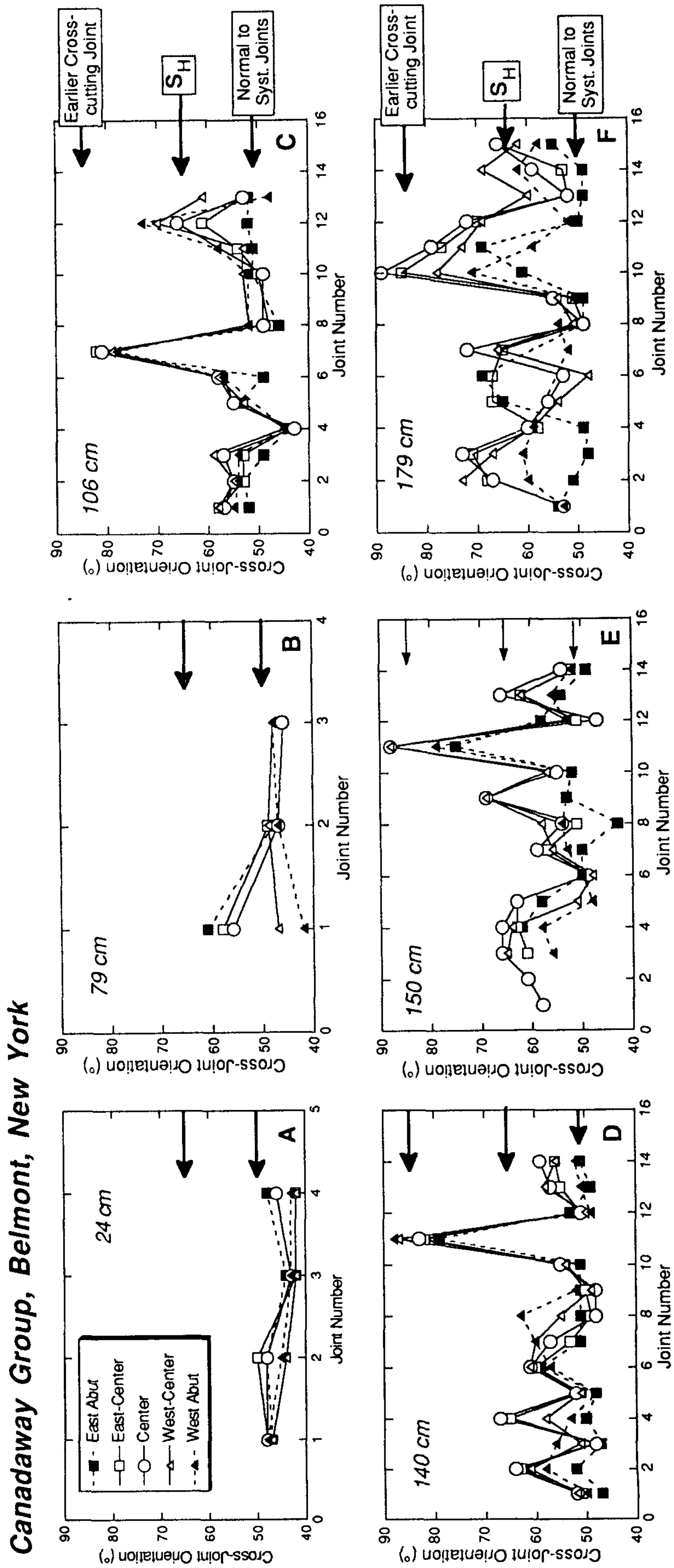


Figure 4. Cross-joint orientation data for various pairs of systematic joints at Belmont, New York, as indicated by spacing between systematic joints (24 to 179 cm). Joint number indicates order of cross joints in outcrop from northwest to southeast. Solid symbols indicate orientation of cross-joint traces at their termination against systematic joints; open symbols indicate mid-region orientation of cross-joint traces; *measurement location is specified in Figure 3. Arrows indicate strike of earlier crosscutting joint* (85°), orientation of maximum horizontal lithospheric stress (S_H), and normal to strike-perpendicular (systematic) joint set.

Figure 5. A: Systematic joint spacing vs. cross-joint orientation for pavement surface of Canadaway Group at Belmont, New York. Cross-joint orientation data from Belmont outcrop are average of up to 15 measurements for each systematic pair of joints as given in Figure 4. Symbols as in Figure 4. B: Systematic joint spacing vs. cross-joint orientation for one systematic pair on pavement surface of West Falls Group at Stony Brook.

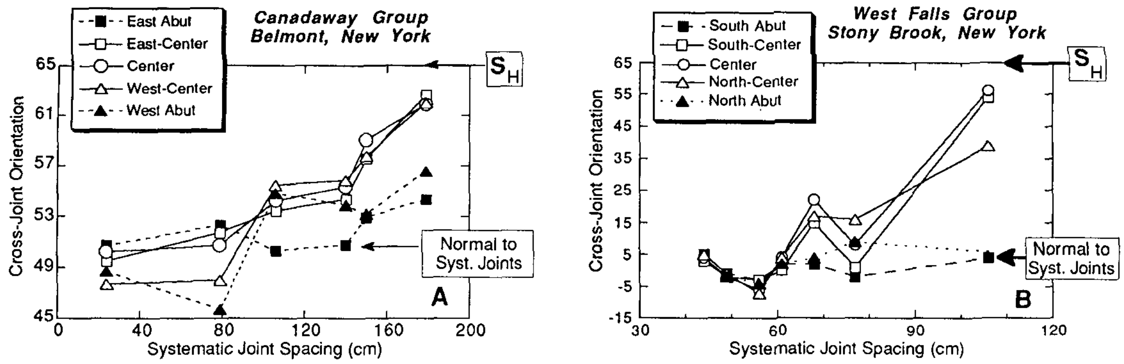
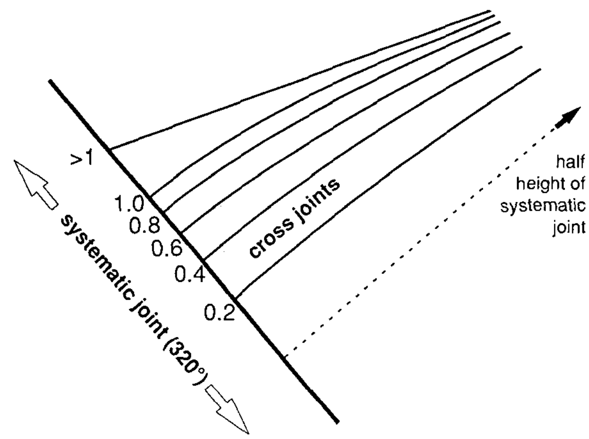


Figure 6. Dyer's (1988) analysis of joint interaction to determine paleostress. Shape of curving cross joint depends on differential stress, σ_d, at time of propagation. Analysis used Dyer's equations for both open joint when joint-normal stress is tensile (σ_d = 0.2, 0.4, 0.6, 0.8, and 1), and locked joint when joint-normal stress is compressive (σ_d > 1). Orientation of cross joint for locked systematic joint is parallel to inferred orientation of S_H for neotectonic or Tertiary stress field. All curving cross joints parallel "locked" cross joint at distances greater than half height of systematic joint. Dashed line indicates distance of half height of systematic joint. For case of open joint, Dyer's equation 13 was modified by dropping −2.



modeled the trace of the cross joint using Dyer's (1988) technique, which solves for a local stress field near a single throughgoing joint. Dyer's technique assumes that the presence of a curving cross joint does not alter the stress perturbation that arises from the systematic joint. If this is so, then the local S_H stress trajectory is the propagation path for a curving cross joint in the vicinity of a preexisting joint. Stress is normalized by setting S_h ($= -1 = \sigma_3$) equal to the tensile strength of the host rock. We calculated several propagation paths for increasing σ_d starting at 0.2, which is 20% of the tensile strength of the rock (Fig. 6). The width of the perturbation zone decreases with increasing σ_d, but when σ_d exceeds 1.0, a value equal to the tensile strength of the rock, the preexisting joint closes, thus muting the stress perturbation. Assuming the systematic joint becomes locked, the cross joints will not curve. Curving cross joints at Belmont more closely resemble those models with higher σ_d but, of course, not models where σ_d is so high that the systematic joint locks.

CONCLUSIONS

In some outcrops of clastic rocks on the Appalachian Plateau, curving cross joints develop between preexisting systematic joints. The mid-region trace of these curving cross joints strikes parallel to S_H of the present lithospheric stress field. Because of the correlation between the trace of curving cross joints and S_H, we conclude that the trace of curving cross joints in flat-lying rocks records the orientation of the neotectonic stress field or its Tertiary predecessor in eastern North America.

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