Tracking the burial and tectonic history of Devonian shale of the Appalachian Basin by analysis of joint intersection style

Gary G. Lash[†]
Department of Geosciences, State University of New York–College at Fredonia, Fredonia, New York 14063, USA

Terry Engelder*
Department of Geosciences, Pennsylvania State University, University Park, Pennsylvania 16802, USA

ABSTRACT

The most pervasive systematic joints hosted by Devonian black shale of the Appalachian Plateau include east-northeast joints and younger northwest-striking cross-fold joints. Both sets were driven exclusively by fluid pressure generated as a consequence of hydrocarbon-related maturation supplemented by subsequent tectonic compaction during the Alleghanian tectonic cycle. In the more deeply buried, proximal region of the Catskill Delta, joints of both sets crosscut. However, in stratigraphically equivalent black shale of the distal, shallower region of the delta to the west, ~25% of the joint intersections are crosscutting whereas ~75% of the intersections are defined by east-northeast joints curving into and abutting cross-fold joints. East-northeast joints in the distal shale propagated early but were neither as long nor as pervasive as similarly oriented joints in the more deeply buried proximal delta deposits. However, these same joints are much better developed (more closely spaced) stratigraphically lower in the distal shale succession, where essentially all intersections are crosscutting. It is likely that relatively high contact stress, an effective stress on east-northeast joints, in the more deeply buried parts of the delta enabled the unimpeded transmission of elastic stress concentration at the tip of cross-fold joints across the older joints. In the distal delta, exhumation of the Devonian shale sequence following establishment of the contemporary stress field in middle Tertiary time to within ~1 km of the Earth's surface resulted in renewed propagation of east-northeast joints. The propagation path of the reactivated joints curved into and terminated against cross-fold joints at angles of 60°–90°. The curving-to-termination intersection style is a manifestation of crack-tip stress-field blunting as a consequence of slippage along the interface of cross-fold joints enabled by exhumation-induced relaxation of contact stress on these latter joints. It is noteworthy that the orientation of the densely formed east-northeast joints parallel to the maximum horizontal stress direction of the contemporary lithospheric stress field likely imparts a meaningful permeability anisotropy to these hydrocarbon source rocks.

Keywords: joints, Appalachian Basin, joint intersection, black shale, exhumation, contact stress.

INTRODUCTION

As the global production of hydrocarbons nears its peak, the search for new reserves is rapidly expanding to the exploration of unconventional reservoirs. In the Appalachian Basin, as elsewhere in the world, industry is focusing its attention on Devonian black shale as a relatively untapped reservoir for the production of natural gas. Production from black shale relies, in part, on the successful stimulation of natural fractures by massive hydraulic fracture treatments within vertical wells or by horizontal drilling. Accessing matrix porosity may, in turn, depend on the extent to which natural fractures are interconnected. Accurate assessment of both fracture permeability and porosity requires an understanding of the different styles of natural fracture intersection and how these styles can vary on a regional basis within the black shale basin.

An understanding of the mechanics of joint intersection starts with analysis of the stress concentration at the tip of a joint, the crack-tip stress field (Pollard and Aydin, 1988). The two-dimensional crack-tip stress field is calculated using familiar equations of linear elastic fracture mechanics (Lawn, 1993). In a mechanically isotropic and homogeneous rock the stresses near the tip of a joint are approximated by the following expression:

$$\begin{Bmatrix} \sigma_{xx} \\ \sigma_{yy} \\ \sigma_{xy} \end{Bmatrix} = \left\{ \frac{K_I}{\sqrt{2\pi r}} \right\} \begin{Bmatrix} \cos\frac{\theta}{2}\left[1-\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \\ \cos\frac{\theta}{2}\left[1+\sin\frac{\theta}{2}\sin\frac{3\theta}{2}\right] \\ \sin\frac{\theta}{2}\cos\frac{\theta}{2}\cos\frac{3\theta}{2} \end{Bmatrix}, \quad (1)$$

in which r and θ are polar coordinates with the origin at the joint tip, and K_I is the opening mode stress intensity factor (Fig. 1). The angular distribution of crack-tip stresses yields a characteristic pattern best represented by a contour map of normal stress, σ_{yy}, near the joint tip where σ_{yy} is symmetrical about the projection of the plane of the joint with a maximum σ_{yy} at $\theta \approx 70°$ (Figs. 1 and 2). The angular variation of shear stress, σ_{xy}, is the crucial determinant of joint intersection style.

In-plane propagation of a joint follows a crack-tip stress field that projects symmetrically ahead of the joint tip a distance proportional to K_I. A symmetric crack-tip stress field is maintained as long as joint propagation takes place in a macroscopically homogeneous, isotropic rock subject to a rectilinear stress field (e.g., Whitaker and Engelder, 2005). However, the presence of a shear traction on a preexisting joint will cause the crack-tip stress field of the propagating joint to project asymmetrically about the tip. In this case, joint propagation is out-of-plane with the joint curving toward the larger lobe of the crack-tip stress field, bearing in mind that the larger lobe is truncated at the slipped joint (Fig. 2; Brace and Bombolakis, 1963; Ingraffea, 1987). Propagation terminates when the crack-tip stress field fails to project forward, even if

[†]E-mail: lash@fredonia.edu
*E-mail: engelder@geosc.psu.edu

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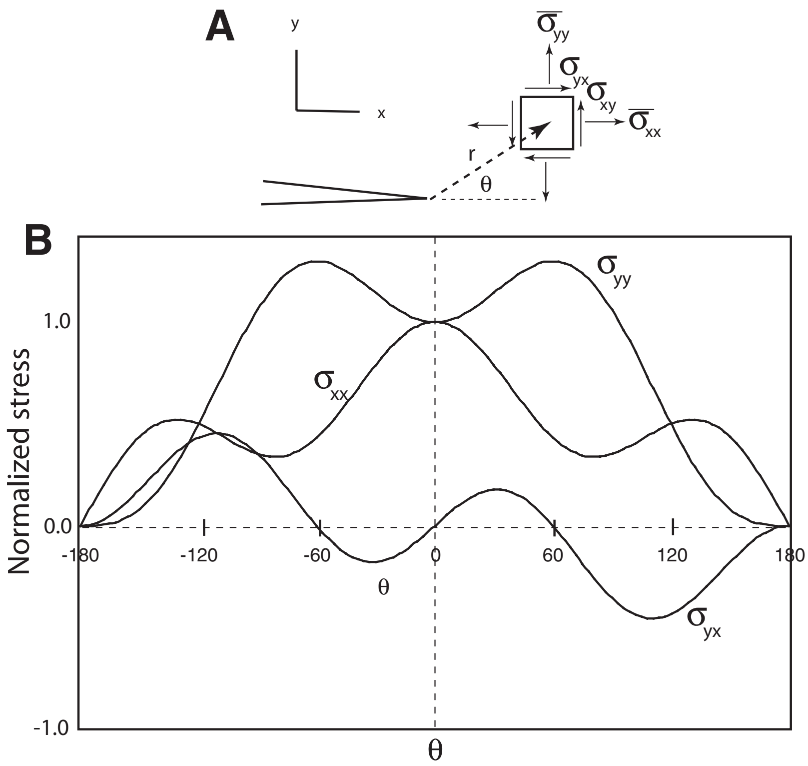

Figure 1. Stresses in the vicinity of a crack tip (tensile stress is positive): (A) Frame of reference with positive θ measured counterclockwise from the plane of the joint; *r*—radial crack-tip distance normalized to half the length of a joint. (B) Angular distribution of crack-tip stresses for mode I (opening mode) loading in the vicinity of a crack tip normalized by $K_I/(2\pi r)^{1/2}$.

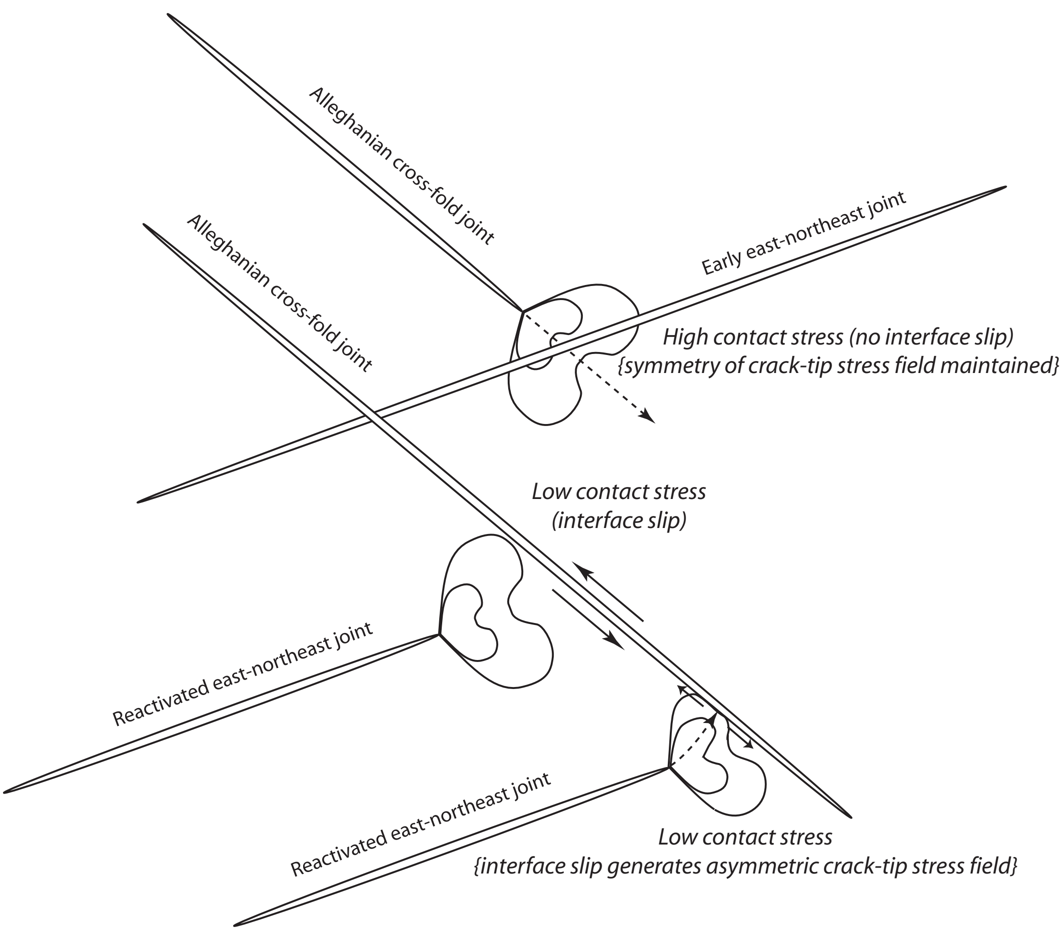

Figure 2. Schematic of hypothesized crack-tip stress fields, showing contours of normal stress, σ_{yy}. Large arrows on the cross-fold joint represent the sense of shear induced by the regional stress field under which east-northeast joints were reactivated. Crosscutting joints maintain symmetry of the crack-tip stress field. However, abutting joint interactions arise when a joint approaches a preexisting joint along which the effective contact stress is minimal (i.e., an open joint). Oppositely directed interface slip along the preexisting joint (indicated by the smaller arrows in the crack-tip stress-field lobe in contact with the cross-fold joint) disturbs the crack-tip stress field of the approaching joint, resulting in truncation of the stress field lobe and termination of the joint.

the crack-tip stress intensity remains high up to termination (Fig. 2).

Projection of a crack-tip stress field may be limited by development of a crack-tip process zone, which causes the crack-tip stress field to become blunted (Friedman et al., 1972). Extreme blunting of a crack-tip stress field may occur when a propagating joint encounters an open older joint (Fig. 2; Dyer, 1988; Gross, 1993). Elastic deformation ahead of a joint propagating toward an unwelded interface causes the interface to slip (Fig. 2). If the propagating joint drives toward the unwelded interface at an oblique angle, stress relaxation accompanying slip produces an asymmetric crack-tip stress field, which, in turn, drives propagation along a curved path toward the earlier joint. Ultimately, slip can reduce the crack-tip stress, causing the propagating joint to terminate (Keer and Chen, 1981). Termination can also occur if the interface is welded but the rock across the interface is stiffer (Helgeson and Aydin, 1991; McConaughy and Engelder, 1999). In this case the younger joints terminate because insufficient elastic strain energy is transmitted across the interface. Coincident initiation of joints yields intersections that may look like termination (Renshaw and Pollard, 1995). However, the propagation direction of the younger joint is away from, rather than toward, the existing joint.

The presence of crosscutting joints (e.g., Renshaw and Pollard, 1995) indicates that interfacial slip caused by elastic deformation in the crack-tip stress field is not a universal outcome of joint intersection. The most frequently cited explanation for crosscutting joints holds that the welding of an existing joint interface by mineralization enables the uninterrupted transmission of the crack-tip stress field of the younger joint across an older filled joint or vein (e.g., Laubach et al., 2004; de Joussineau et al., 2005). Alternatively, contact stress (i.e., the joint-normal effective stress) may be sufficient to generate a frictional contact strong enough to prevent joint-parallel slip and concomitant blunting of the approaching crack-tip stress field. In this mechanism, known as compressional crossing (Renshaw and Pollard, 1995), the crack-tip stress field of the propagating joint maintains its symmetry, and crack-tip deformation projects uninterrupted across the preexisting joint (Fig. 2).

Joint propagation across an unbonded frictional interface may take place by either continuous or discontinuous propagation (Renshaw and Pollard, 1995). The small step-over observed in composite joints is a manifestation of compressional crossing where reinitiation of joint propagation on the opposite side of a bedding interface occurs at a small asperity or notch along the interface (Helgeson and Aydin, 1991). Although discontinuous propagation of this type is believed to be common to the propagation of hydraulic fractures (e.g., Lam and Cleary, 1984), continuous propagation is the more likely outcome where the interface is a joint across which there are no changes in material properties. This paper describes field examples of the continuous propagation of joints across frictional interfaces in Devonian black shale of the Appalachian Basin.

Gravitationally induced overburden loading constitutes the major component of both vertical and horizontal normal stress in the upper crust. It is, therefore, reasonable to hypothesize that joint termination by abutting interaction reflects conditions of low joint-normal contact stress resulting from either a lower effective normal stress or joint propagation at shallow depth. On the other hand, compressional crossing of joints reflects conditions of higher contact stress, suggestive of either a higher effective normal stress and/or a greater depth of propagation. To the best of our knowledge, the relationship between contact stress and joint intersection style has yet to be documented in rocks of a basin that has passed through a complete burial-exhumation cycle. This paper documents changes in intersection style as a function of overburden-induced joint-normal contact stress in Devonian black shale of the Appalachian Basin. Our interpretations reflect a marriage of field observations and the mechanics of fracture intersection (e.g., Renshaw and Pollard, 1995).

CATSKILL DELTA, APPALACHIAN BASIN

Assessment of the role of contact stress on unmineralized joints in the generation of crosscutting joints relies upon the study of a sequence of rocks in which joint welding by mineralization did not occur. The Catskill Delta of the Appalachian Basin, especially its numerous black shale units, hosts several systematic joint sets that provide a record of a remote stress field that changed orientation throughout the Alleghanian orogeny, a necessary condition for crosscutting joints (Engelder and Geiser, 1980; Younes and Engelder, 1999). Preferential jointing of organic-rich shale suggests that joints were driven as a consequence of the transformation of organic matter to hydrocarbons upon burial to the oil window (Lash et al., 2004). Indeed, plumose structures decorating joint surfaces evince growth by incremental propagation, as is typical of fluid loading during natural hydraulic fracturing (Lacazette and Engelder, 1992; Lash et al., 2004). Joints that propagated in plane around carbonate concretions in black shale provide further evidence for an incremental growth history typical of natural hydraulic fracturing (McConaughy and Engelder, 1999; Lash and Engelder, 2007). Joints of the Appalachian Plateau in New York show no evidence of mineralization of any kind, suggesting that the driving fluid was methane, which displaced other fluids that might have allowed mineralization (Lacazette and Engelder, 1992). Similarly, Evans (1994, 1995) observed few mineralized joints in cores of the Middle Devonian shale interval of western Pennsylvania and eastern Ohio. However, Evans noted that the frequency of mineralized joints increases eastward toward the folded region of the Appalachian Plateau and in association with décollement tectonics. Indeed, rocks of the Catskill Delta that host mineralized joints crop out 100–150 km south-southeast of the outcrops reported on in this paper.

Consideration of the role of normal-stress-induced frictional contacts as a determinant of joint intersection style provides solutions to other unresolved questions of joint chronology in the Appalachian Basin. One of the more intriguing issues concerns the mechanism(s) responsible for the apparent ca. 300 Ma propagation history of the east-northeast (060°–075°)–trending joint set that formed over much of the Appalachian Mountain chain (Engelder and Whitaker, 2006). East-northeast joints in Middle and Upper Devonian black shale of the more proximal region of the Catskill Delta (Fig. 3) formed as a prelude to the Alleghanian orogeny and prior to propagation of cross-fold (315°–345°) joints that vary in strike across the plateau, maintaining an orientation roughly normal to Alleghanian fold axes (Engelder et al., 2001; Engelder and Whitaker, 2006). To the west in the more distal region of the Catskill Delta (Fig. 3), east-northeast joints abut correlative cross-fold joints, suggesting that the former joints are the younger structures (Lash et al., 2004). Thus, different styles of joint intersections (i.e., abutting versus crosscutting) argue against a simple temporal correlation of similarly oriented east-northeast joints in black shale from the proximal to the distal region of the delta. This paper revisits the longstanding problem of dating east-northeast joint propagation (e.g., Engelder, 1982) by considering intersections of nonmineralized joints in Middle Devonian black shale that crops out in the distal delta of western New York (Fig. 3).

JOINT INTERSECTION STYLES IN MIDDLE AND UPPER DEVONIAN BLACK SHALE

Most outcrops of Middle and Upper Devonian Catskill Delta rocks on the Appalachian Plateau of western New York host at least one systematic joint set; however, systematic joints are especially

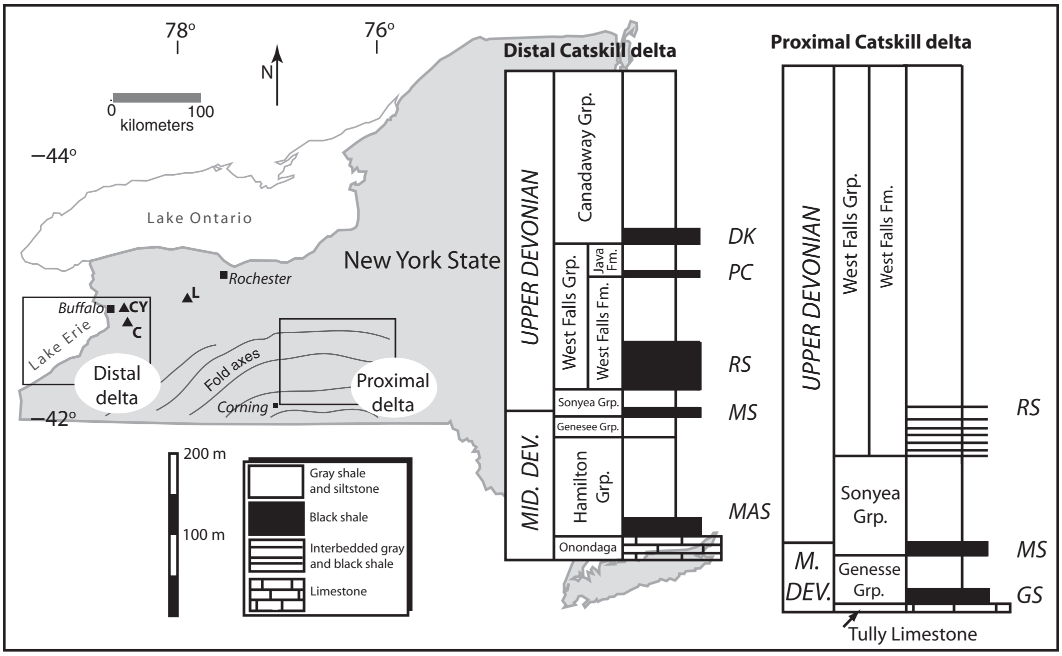

Figure 3. Map of New York State, showing locations of proximal and distal delta regions. Triangles denote locations mentioned in the text. CY—Cayuga Creek exposure of the Marcellus Shale; C—Cazenovia Creek exposures of the Middlesex Shale and younger black shale units; L—LeRoy exposure of the Marcellus Shale on Oatka Creek. Columns present generalized stratigraphy of both the distal and proximal delta regions (from Lindberg, 1985); DK—Dunkirk Shale; PC—Pipe Creek Shale; RS—Rhinestreet Shale; MS—Middlesex Shale; MAS—Marcellus Shale; GS—Geneseo Shale.

well developed (i.e., most closely spaced) in black shale, where as many as three sets may be present (Sheldon, 1912; Parker, 1942; Engelder and Geiser, 1980; Lash et al., 2004). Most exposures of Devonian black shale across the delta carry east-northeast and cross-fold joints (i.e., the J_1 and J_2 joint sets, respectively, of Engelder, 2004), yet the nature of joint intersections varies systematically from the proximal, more deeply buried rocks westward into the distal delta deposits. One exception to this rule is seen in the most deeply buried black shale of the distal region, the Middle Devonian Marcellus Shale, in which the style of joint intersection is invariant from proximal to distal outcrops.

Distal Delta Deposits

Almost all exposures of Upper Devonian black shale in the distal delta (Fig. 3), that region of the Appalachian Plateau that was affected by a slight amount of Alleghanian shortening, carry cross-fold and east-northeast joints. Joints of both sets formed preferentially in the Middlesex, Rhinestreet, Pipe Creek, and Dunkirk black shales (Fig. 4; Lash et al., 2004; Lash and Blood, 2006). Of the two joint sets, however, east-northeast joints are more closely spaced at a given exposure (Fig. 4; Lash et al., 2004; Lash and Blood, 2006).

Approximately 73% of east-northeast joints in Upper Devonian black shale of the distal delta abut cross-fold joints, the most typical geometry being a curving-(near)perpendicular intersection (e.g., Engelder and Gross, 1993) (Table 1; Figs. 5 and 6A). However, and perhaps more importantly, 25% of the joint intersections are crosscutting (Table 1; Fig. 6B). There appears to be some degree of variation in frequency of abutting intersections among the four Upper Devonian black shale units of the distal delta with the stratigraphically lowest unit, the Middlesex Shale, containing the greatest percentage of crosscutting intersections (Table 1). This is the first hint that burial depth may have played some role in determining the style of joint intersections in black shale. Nevertheless, the dominance of abutting joint intersections in the distal region of the Catskill Delta suggests that cross-fold joints formed first, followed by propagation of east-northeast–trending joints (Lash et al., 2004).

Not all abutting intersections describe right angles, a manifestation of a joint propagating toward a free surface (Dyer, 1988). The average strike of east-northeast joints in the distal delta is 071°, whereas the strike of cross-fold joints is 312°. Thus, the typical east-northeast joint would have to deviate from in-plane propagation by 29° to intersect a cross-fold joint at 90°. In a data set of more than 100 measurements, the intersection angle of east-northeast and cross-fold joints varies from 60° to 90° with more than half of the intersections <80° (Fig. 7A). Angular deviation from in-plane propagation varies between 0° and 42° (Fig. 7B). The five data that exceed a deviation of 32° reflect a natural variation in orientation of both the east-northeast and cross-fold joints, as is common with all joint sets in nature (Whitaker and Engelder, 2005).

Proximal Delta Deposits

East-northeast–trending joints carried by black shale of the distal delta align with their similarly oriented counterparts in Middle and Upper Devonian black shale units of the proximal, more deeply buried region of the delta, where the Alleghanian orogeny is manifested by as much as 10% layer-parallel shortening (Lash et al., 2004). However, the east-northeast joints show no consistent geometric relationship to Alleghanian fold axes (Engelder, 1982). The Middle and Upper Devonian succession of the proximal delta is also host to multiple cross-fold joint sets that remain approximately normal to Alleghanian fold axes (Engelder and Geiser, 1980). These proximal cross-fold joints correlate with cross-fold joints of the distal delta, both of which record the orientation of the maximum horizontal principal stress, S_H, of an Alleghanian remote stress field as it makes its way around the oroclinal bend of the central Appalachian foreland (Lash et al., 2004).

As in the distal delta, east-northeast and cross-fold joints of the proximal region are most densely formed in black shale units, notably the Middlesex and Geneseo Shales (Figs. 3 and 4). Moreover, east-northeast joints are more closely spaced than are cross-fold joints (Fig. 4; Sheldon, 1912). Unlike in the distal delta, east-northeast joints of the Middlesex and Geneseo black shales never abut cross-fold joints. In fact, crosscutting intersections of east-northeast and cross-fold joints in rocks of the more proximal region of the delta makes

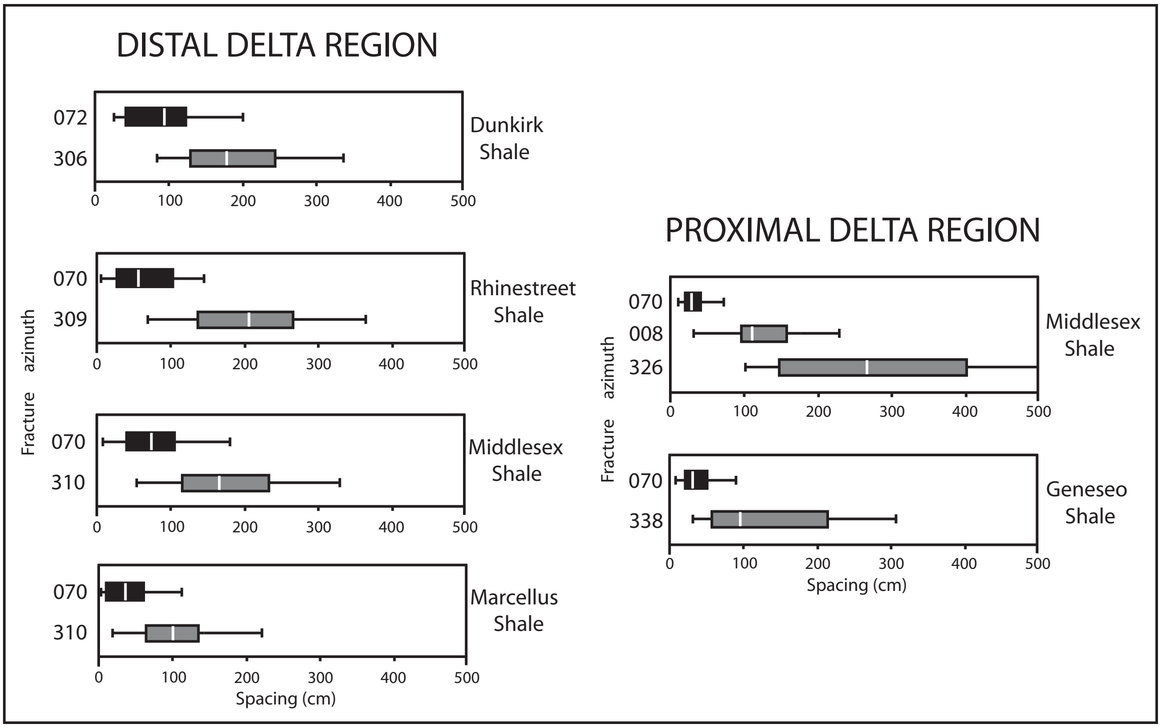

Figure 4. Representative box-and-whisker plots, showing joint density (orthogonal spacing) of east-northeast (070°) and cross-fold (008°, 310°, 326°, 338°) at the bases of black shale units of the distal and proximal delta regions (rocks of the proximal delta carry multiple cross-fold joint sets). The box encloses the interquartile range of the data set population; bounded on the left by the 25th percentile (lower quartile) and on the right by the 75th percentile (upper quartile). The vertical line through the box is the median value, and the "whiskers" represent the extremes of the sample range. In the distal scanlines the spacing on east-northeast joints reflects the late-stage reactivation of those joints.

TABLE 1. RELATIVE ABUNDANCES OF DIFFERENT TYPES OF JOINT INTERACTIONS IN MIDDLE AND UPPER DEVONIAN BLACK SHALE UNITS OF THE DISTAL DELTA REGION

Black shale unit	No. of observations	East-northeast joints abut cross-fold joints (%)	Cross-fold joints abut east-northeast joints (%)	Crosscutting east-northeast and cross-fold joints (%)
Dunkirk Shale	343	71	2	27
Pipe Creek Shale	68	68	3	29
Rhinestreet Shale	421	77	2	21
Middlesex Shale	104	66	0	34
All Upper Devonian data	936	73	2	25
Middle Devonian Marcellus Shale	78	4	0	96

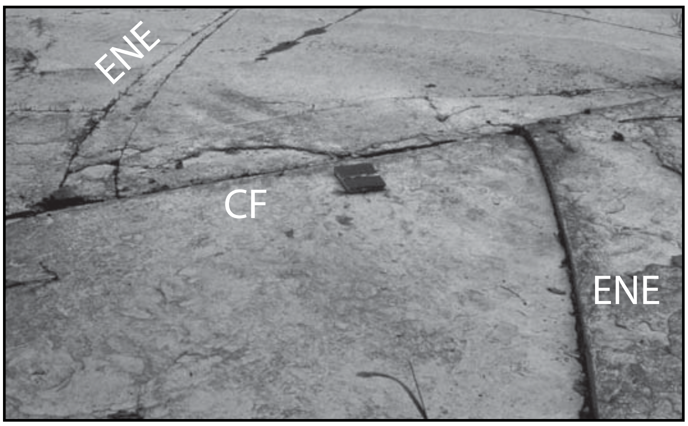

Figure 5. Field photograph of east-northeast (ENE) joints abutting a cross-fold joint (CF) in the Upper Devonian Dunkirk Shale of the distal delta region (notebook is 13 cm wide).

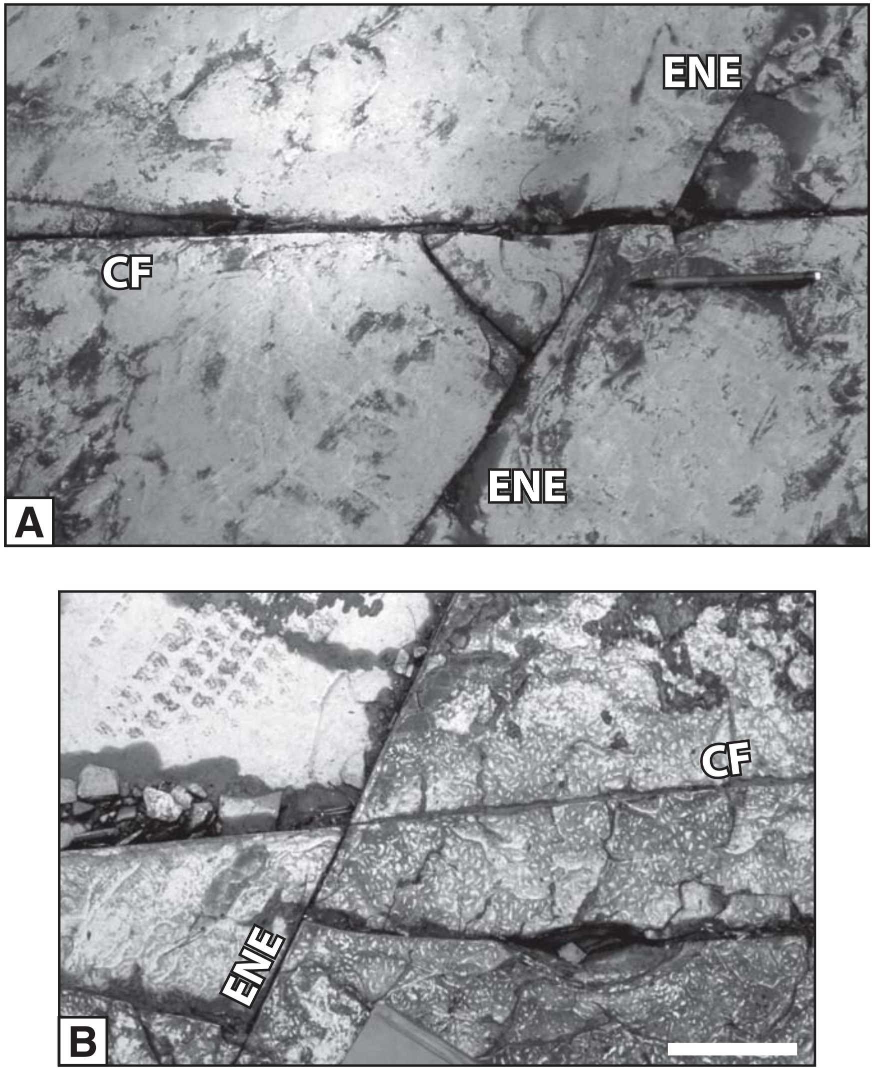

Figure 6. Field photographs of joint interactions in the Upper Devonian Middlesex Shale of the distal delta region. (A) Curving perpendicular east-northeast joint (ENE) abutting a cross-fold joint (CF) (pen is 15 cm). (B) Mutually crosscutting east-northeast (ENE) and cross-fold joints (CF) (white bar is 13 cm).

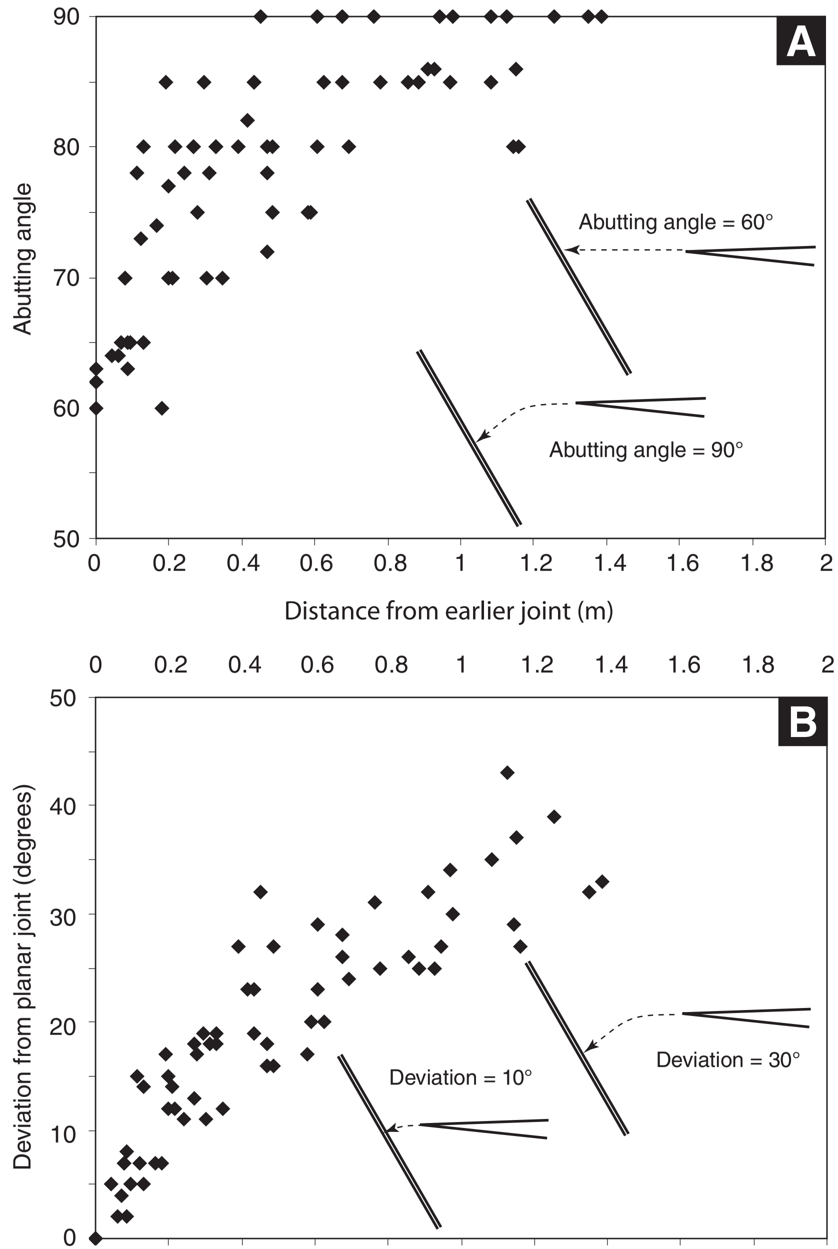

Figure 7. Joint intersections in the Rhinestreet black shale of the distal region of the Catskill Delta. (A) Intersection angle as a function of distance from the point of deviation from in-plane propagation of the east-northeast joint to the cross-fold joint, *r*. (B) Deviation angle as a function of distance from the point of deviation from in-plane propagation of the east-northeast joint to the cross-fold joint, *r*.

interpretation of the relative timing of these sets difficult. However, as much as 8 cm of horizontal offset of east-northeast joints along some cross-fold joints indicates that the former predates the latter (Engelder et al., 2001).

Middle Devonian Marcellus Shale—The Most Deeply Buried Black Shale in the Distal Delta

The Middle Devonian Marcellus black shale of the distal shale was studied in exposures along Cayuga Creek in the village of Lancaster, New York, and on Oatka Creek in LeRoy, New York, ~50 km to the east (Fig. 3). As is the case for other Devonian black shales of the Appalachian Plateau, east-northeast joints of the Marcellus Shale are more densely formed than are cross-fold joints (Fig. 4). Moreover, joints of both sets in the Marcellus Shale are longer and more closely spaced than in stratigraphically higher black shale units of the distal region of the delta (Fig. 4).

There is a critical difference in intersection style between the Marcellus Shale and overlying Upper Devonian black shales of the distal delta; only 1 in 25 joint intersections displayed by the Marcellus Shale shows an east-northeast joint abutting a cross-fold joint (Fig. 8; Table 1). This observation is especially relevant, because stratigraphically higher black shale units of the distal delta carry mostly terminating intersections (Table 1). Indeed, the Marcellus Shale at Lancaster is ~130 m below the Middlesex Shale, exposed on nearby Cazenovia Creek (Fig. 3), where most east-northeast joints terminate against cross-fold joints (Table 1). The pervasive crosscutting of joints in the Marcellus Shale of the distal delta is reminiscent of crosscutting intersections described from Middle and Upper Devonian black shale of the more deeply buried proximal delta, where east-northeast joints propagated first.

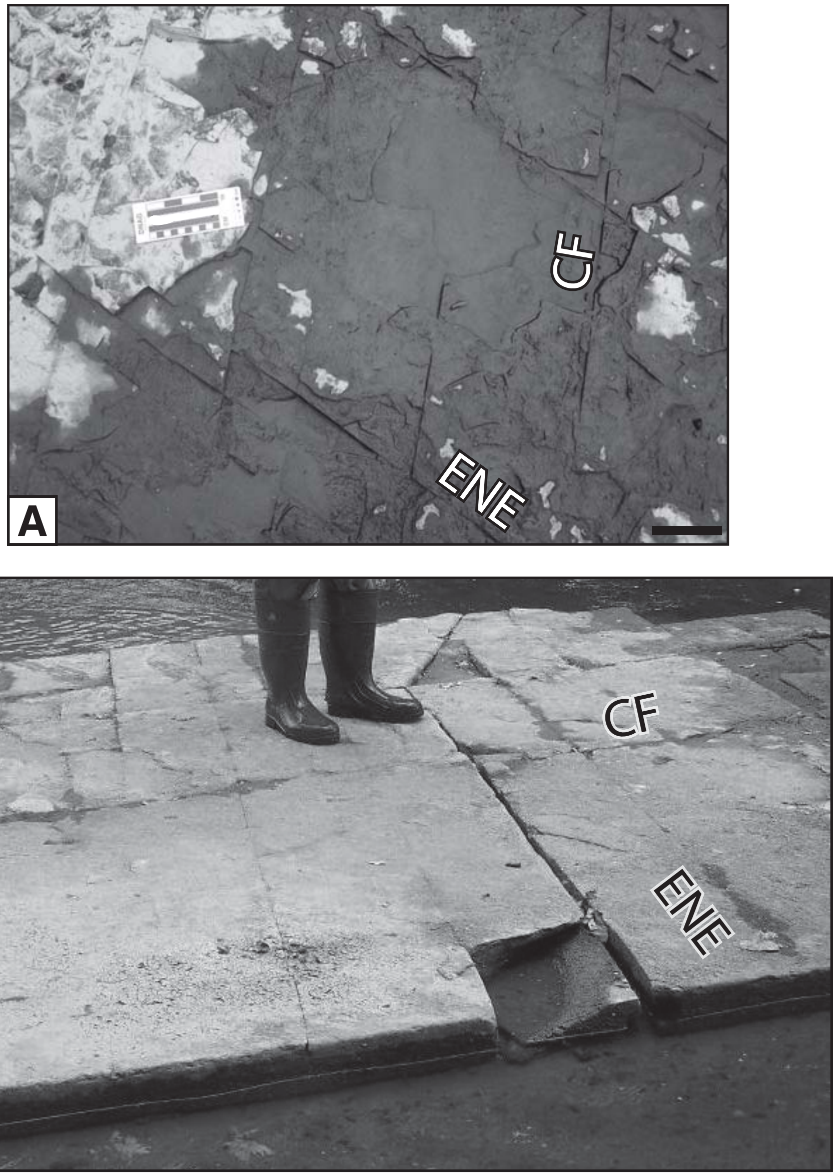

Figure 8. Field photographs of joint interactions in the Middle Devonian Marcellus Shale. (A) Cayuga Creek, Lancaster, New York (black bar is 10 cm). (B) Oatka Creek, LeRoy, New York. Note the close spacing of joints of both sets, especially the east-northeast set. ENE—east-northeast joints; CF—cross-fold joints.

DISCUSSION

Mechanism and Timing of Early Joint Propagation

Transformation of organic matter to hydrocarbons in Middle and Upper Devonian black shale of the proximal delta produced the high fluid pressure that drove both east-northeast and subsequent cross-fold joints close to or at peak burial depth, perhaps >4.5 km (Lash and Engelder, 2005). The most compelling evidence for fluid-driven joints includes incremental propagation, as expected of natural hydraulic fractures driven by fluid decompression, and joint-concretion interactions (Lacazette and Engelder, 1992; Engelder and Fischer, 1996; McConaughy and Engelder, 1999). The result of this early propagation event was a high density of maturation-related east-northeast joints in black shale (Fig. 4). The east-northeast joints propagated within a remote stress field that affected much of the southeastern edge of Laurentia early in the Alleghanian orogeny (Engelder and Whitaker, 2006). Lithospheric S_H at this time was derived from east-northeast (modern coordinates) oblique convergence of Gondwana against Laurentia and the subsequent dextral slip between these continents (Hatcher, 2002; Engelder and Whitaker, 2006).

Cross-fold joints in rocks of the Catskill Delta formed subsequent to east-northeast joints in a stress field associated with the transport of detachments driven by basement thrusts in the Blue Ridge and Piedmont regions of the Appalachian orogen upon closure of Gondwana against Laurentia (Hatcher, 2002; Wise, 2004). The catagenesis-related driving stress for cross-fold joints that propagated in the proximal delta deposits may have been supplemented by a component of pressure generated as a consequence of tectonic compaction (e.g., Oertel et al., 1989). By this time the Upper Devonian succession of the distal delta was close to or at its maximum burial depth of ~3 km (Lash et al., 2004). These deposits resided in the oil window long enough that cross-fold joints formed preferentially in all black shales of the distal delta under the same maturation-related, high-pressure fluid-drive mechanism responsible for east-northeast joint propagation in the proximal delta (Lash and Blood, 2006). Layer-parallel shortening in the distal delta was so low (~1%; Engelder, 1979) that it is likely to have played little role in the pressure buildup that resulted in the generation of cross-fold joints in these rocks.

Joint Intersection Style as a Function of Burial Depth

Variation in joint intersection style, both vertically in the distal delta and regionally across the delta, leads to the interpretation that east-northeast joints propagated during two distinct stages of the Appalachian Basin burial-exhumation cycle rather than solely under an early fluid-drive event. Confirmation of the two phases of east-northeast joint propagation requires validation of the early propagation of east-northeast joints extending from the proximal to the distal regions of the Catskill Delta. Evidence for the early generation of east-northeast joints in the distal delta can be found in the Middle Devonian Marcellus Shale where ≈96% of the studied joint intersections are of the compressional crossing type (Fig. 8). Subsidence of the Devonian clastic succession carried the Marcellus Shale through a depth threshold early enough in the Alleghanian orogeny that the orientation of fluid-driven joint propagation was controlled by the stress field associated with oblique convergence and dextral slip of Gondwana relative to Laurentia. Thermal maturation of these more deeply buried organic-rich rocks of the distal delta resulted in the generation of a well-developed (closely spaced) array of the long east-northeast–trending joints in the Marcellus Shale (Fig. 8). Subsequent cross-fold joints cut east-northeast joints in the form of the observed compressional crossing intersections (Fig. 8; Table 1). The wider spacing of cross-fold joints in black shale across the delta (Fig. 4) suggests that gas generation was waning by the time they propagated or that gas pressure was relieved by joints driving upward into overlying gray shale and siltstone.

The critical role that burial depth played in joint behavior in the Catskill Delta is manifested by the change in joint intersection style from Middle to Upper Devonian strata of the distal delta. Intersection style in the Upper Devonian Middlesex Shale, the only black shale unit that can be traced in outcrop from the proximal to the distal region of the Catskill Delta, varies as a function of its position in the delta, and hence its depth of burial at the time of maturation. Cross-fold joints in the Middlesex Shale of the proximal delta crosscut east-northeast joints (i.e., Engelder et al., 2001); to the west in the distal delta, however, most east-northeast joints terminate against cross-fold joints (Table 1). Propagation of cross-fold joints in the Middlesex Shale throughout the delta occurred during a limited time interval in the Permian (Engelder and Whitaker, 2006) and thus serves as a common time event. However, because burial of the Middlesex Shale of the distal region lagged behind its burial in the proximal delta, earlier maturation-related east-northeast joints are less pervasive and more widely spaced in the Middlesex of the distal delta in comparison with the proximal delta (Fig. 4; Lash et al., 2004).

The timing of thermal maturation is critical to the hypothesized role of burial depth on joint intersection style. The older (Marcellus Shale) and more deeply buried (proximal) black shale of the delta complex generated hydrocarbons and consequent high fluid pressure before distal Upper Devonian black shales had passed deeply enough into the oil window to produce sufficient hydrocarbons necessary for extensive joint development. Thus, the Marcellus Shale and proximal black shales host long, close-spaced east-northeast joints. The less deeply buried Middlesex Shale and younger black shale units of the distal delta also generated east-northeast joints, but these joints did not undergo enough propagation events related to pore fluid pressure buildup to become either long or pervasive (Fig. 9A). Compressional crosscutting of east-northeast joints by cross-fold joints in Upper Devonian black shale is presumed to have been synchronous with crosscutting in the underlying Marcellus Shale. However, cross-fold joints propagating through Upper Devonian black shale encountered only relatively widely spaced east-northeast–trending joints induced by the lower level of thermal stress experienced by these rocks (Fig. 9B). Thus, compressional crossing of joints constitutes only one in four joint intersections described from the Upper Devonian succession of the distal delta, the balance being terminations (Fig. 9B). The boundary in degree of east-northeast joint development cuts up-section toward the proximal delta, where pervasive, thermally driven east-northeast joints were produced in the Middlesex Shale, a reflection of westward progradation of the Catskill Delta and increasing depth of burial to the east.

In summary, the generation of east-northeast joints was dependent upon the timing of burial to the oil window. The frequency of compressional crossing intersections is lower in Upper Devonian black shales of the distal portion of the Catskill Delta, largely because early east-northeast joints were not generated as densely in these rocks as they were in the proximal, more deeply buried region of the delta. Thus, there were fewer targets for cross-fold joints driven by maturation-related high fluid pressure later in the Alleghanian tectonic cycle, resulting in the low number of compressional crossing intersections documented from Upper Devonian deposits of the distal delta (Table 1).

Reactivation of East-Northeast Joints in the Contemporary Tectonic Stress Field

Joint terminations occur when an open joint perturbs the symmetrical crack-tip stress field of a younger propagating joint. The consequent asymmetric stress field guides the younger joint along a curving path into the preexisting open joint at a right angle (Dyer, 1988; Engelder and Gross, 1993). Termination occurs because the crack-tip stress field is not transmitted across the slipping interface. Thus, the common abutting relationships documented from the Middlesex Shale and younger black shale units of the distal delta (Table 1) indicate that propagating east-northeast joints in these rocks intersected cross-fold joints that were either open or had slipped, thereby partially blunting the crack-tip stress field of the approaching joint. In this context, "open" means that the contact stress was low enough to allow interface slippage in response to elastic crack-tip deformation. This phenomenon has been described from gray shale and siltstone of the proximal region of the Catskill Delta in the form of curving cross joints (Engelder and Gross, 1993). It is noteworthy that open joints are characteristic of a near-surface environment but could also exist under conditions of low effective normal stress, such as in the presence of very high pore pressure.

The common joint terminations in the Middlesex Shale and younger deposits of the distal delta likely resulted from the reactivation of east-northeast joints during post-Alleghanian exhumation of the Appalachian Plateau. The driving mechanism for exhumation-related reactivation may have involved some combination of thermal contraction, Poisson contraction, and lateral strain accompanying uplift (Price, 1966). The timing of this event is equivocal, although the orientation of these late-stage joints indicates that they were reactivated within the contemporary lithospheric stress field of eastern North America (Zoback and Zoback, 1991). In this scenario the propagation direction of the reactivated east-northeast joints was controlled by the contemporary lithospheric S_H, which is oriented 072° ± 6° in western New York (Plumb and Cox, 1987). Moreover, thermal modeling and analysis of apatite fission tracks convinced Blackmer et al. (1994) that rapid exhumation of the Appalachian Basin was initiated in the Miocene, continuing to the present. Thus, it is reasonable to postulate that exhumation of the Appalachian Plateau since the Miocene relaxed contact stress on cross-fold joints to such a point that reactivated east-northeast joints terminated against open cross-fold joints. Such terminating intersections are not present in black shale of the proximal region of the delta or in the Marcellus Shale of the distal delta because east-northeast joints that had formed early in the Alleghanian orogeny, having saturated these more deeply buried rocks, simply opened with little further growth during exhumation. Nevertheless, the alignment of the Alleghanian east-northeast joints with the contemporary lithospheric S_H remains one of the most striking geological coincidences described within the Appalachian Mountains (Engelder and Whitaker, 2006).

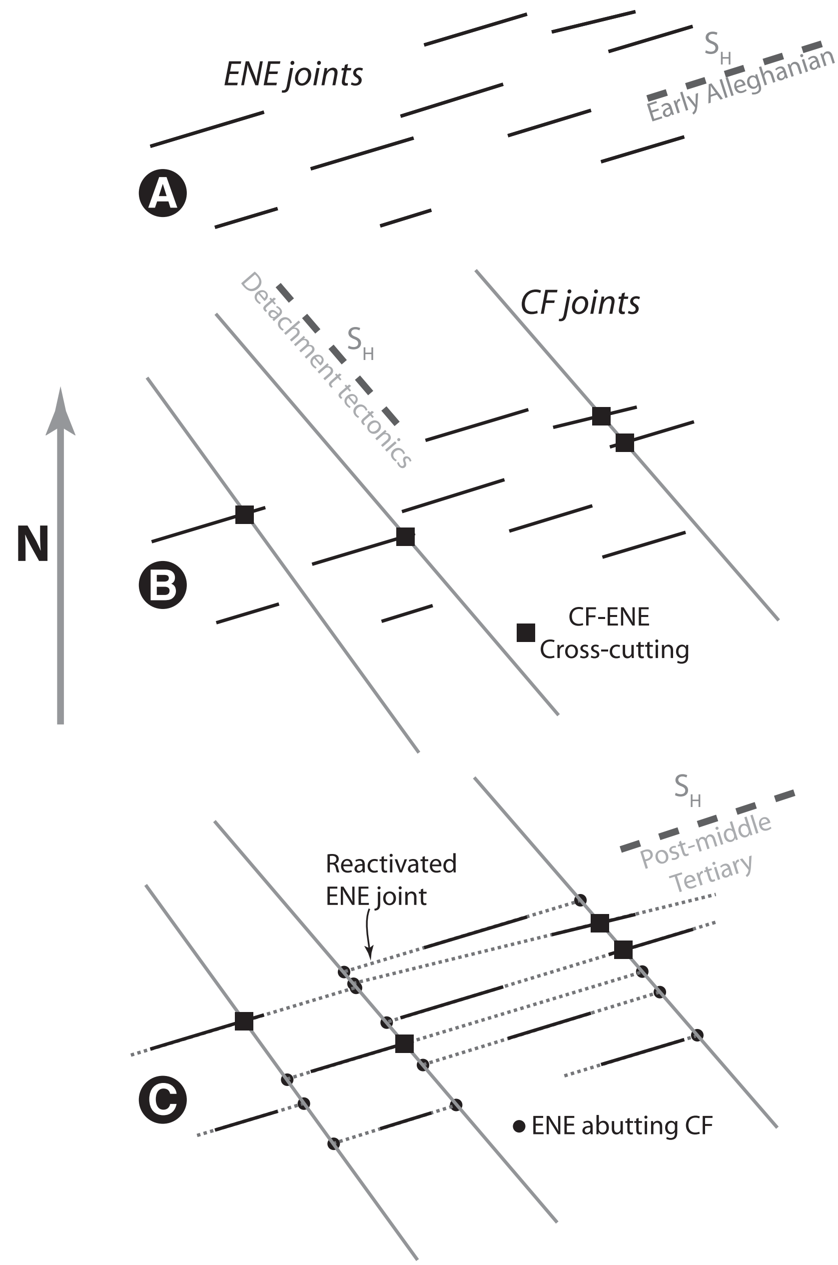

Figure 9. Cartoon illustrating the proposed chronology of joints and joint interactions in the Middlesex Shale and younger black shale units of the distal delta region. S_H—maximum horizontal stress. Refer to text for discussion.

Role of Effective Normal Stress

Elevated pore pressure in deeply buried rocks can greatly reduce effective normal stress and lead to a relatively low contact stress across joints. Development of abnormal fluid pressure during thermal maturation and later tectonic compaction in the Late Carboniferous–Early Permian history of the Catskill Delta is indicated by natural hydraulic fracturing in the Middle and Upper Devonian succession of the Appalachian Plateau (Lacazette and Engelder, 1992; Engelder and Fischer, 1996; McConaughy and Engelder, 1999). Abnormal pressure persisted along east-northeast joints as fluid-driven cross-fold joints propagated through the sedimentary succession of the proximal delta. Further, abnormal fluid pressure working on east-northeast joints could have reduced contact stress to such a point that interface slip blunted the crack-tip stress field of cross-fold joints, leading to their termination against the older joints (Figs. 2 and 10). However, the dearth of this type of intersection (Table 1) reflects a level of stress anisotropy in the horizontal plane high enough to maintain sufficient contact stress across the older joints capable of suppressing interface slip and concomitant crack-tip blunting (Fig. 2). Such horizontal stress anisotropy attended layer-parallel shortening that accompanied northwest-directed detachment of the Appalachian Plateau thrust sheet (Engelder and Engelder, 1977).

An isolated natural hydraulic fracture is driven incrementally by recharging from local matrix permeability (Fig. 10; Lacazette and Engelder, 1992). Cross-fold joints that had intersected east-northeast joints may have been further recharged by the older joints, which, despite their frictional contacts, would have been far more permeable than the unfractured shale matrix (e.g., Kranz et al., 1979). Draining of east-northeast joints into cross-fold joints would have, in turn, increased contact stress on the older joints, further suppressing crack-tip blunting by interface slip (Fig. 10).

Estimate of Burial Depth for Terminating Intersections

Arguments presented in this paper rely on two important assertions: (1) Frictional strength dictates unmineralized joint intersection style, and (2) the style of intersecting joints is a first-order measure of contact stress on the earlier

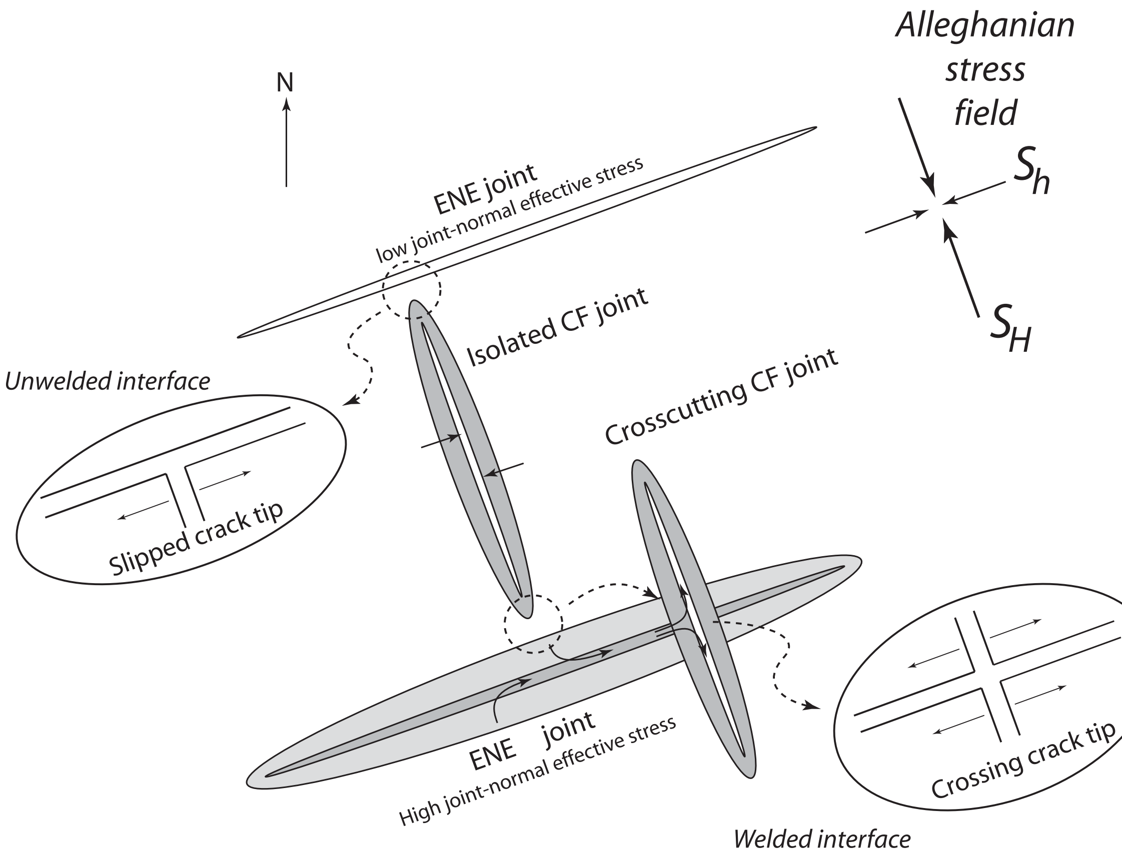

Figure 10. Crosscutting of an east-northeast (ENE) joint by a cross-fold (CF) joint. Shaded areas around joints represent a zone of reduced pore pressure as fluid drains into propagating cross-fold joints. Where the cross-fold joint crosscuts the east-northeast joint, pore fluid drains from the rock matrix and from along the east-northeast joint into the cross-fold joint, further increasing contact stress on the east-northeast joint. S_h—minimum horizontal stress; S_H—maximum horizontal stress.

joint at the time the later joint propagated. Contact stress is an effective normal stress that appears to be a first-order proxy for burial depth of Catskill Delta deposits. Joint intersection style provides evidence for two stages of east-northeast joint propagation within the Catskill Delta at very different burial depths and phases in the burial-exhumation cycle. These phases are distinguished by the role that stress-induced frictional contacts played in (1) enabling the compressional crossing of east-northeast joints by subsequent cross-fold joints early in the jointing history of the Devonian shale succession and (2) the termination of east-northeast joints against cross-fold joints during a late-stage propagation event.

Field observations do not permit an estimate of threshold contact stress for compressional crossing during joint propagation. However, application of linear elastic fracture mechanics following Renshaw and Pollard (1995) provides some degree of insight into this question. A criterion for compressional crossing is based on the premise that if the contact stress, $\bar{\sigma}_{xx}$, an effective normal stress across an interface, is high enough, the frictional strength of the interface will prevent interfacial slip and concomitant crack-tip stress field blunting. Slip along the interface will occur whenever

$$\left|\sigma_{xy}\right| > \mu\bar{\sigma}_{xx} \quad (2)$$

where σ_{xy} is the shear stress parallel to the interface and μ is the coefficient of friction of the interface, in this case a joint. In the case of a preexisting joint that is oblique to an approaching joint, the shear stress, σ'_{xy}, on the oblique joint is obtained by the familiar transformation equation

$$\sigma'_{ij} = \alpha_{ik}\alpha_{jl}\sigma_{kl} \quad (3)$$

where σ_{kl} are components of the crack-tip stress field obtained using Equation 1, and a_{ij} are direction cosines relating the coordinate system of the oblique joint to that of the propagating joint (Fig. 11A). K_I, the opening mode stress intensity factor, is set equal to the joint propagation criterion

$$K_I \geq K_{Ic} \quad (4)$$

where K_{Ic} is the fracture toughness of a Devonian black shale, which is ~1 Mpa $\sqrt{m}$ (Scott et al., 1992). The transformation equation is used to obtain σ'_{xy} along a joint interface oriented at, for example, 90°, 80°, 70°, and 60° from the plane of the approaching joint (Fig. 12).

Compressional crossing in black shale takes place without the visible offset expected for discontinuous propagation. Because there is no stress singularity at a frictional contact (e.g., Dollar and Steif, 1989), we assume that reinitiation takes place where the approaching joint is very close to, but not touching, the interface. This distance, r, is ~0.005 m. At this distance the maximum σ_{xy} on the existing joint normal to the oncoming joint is 2.51 MPa (Fig. 11A). Frictional properties of joints in Devonian black

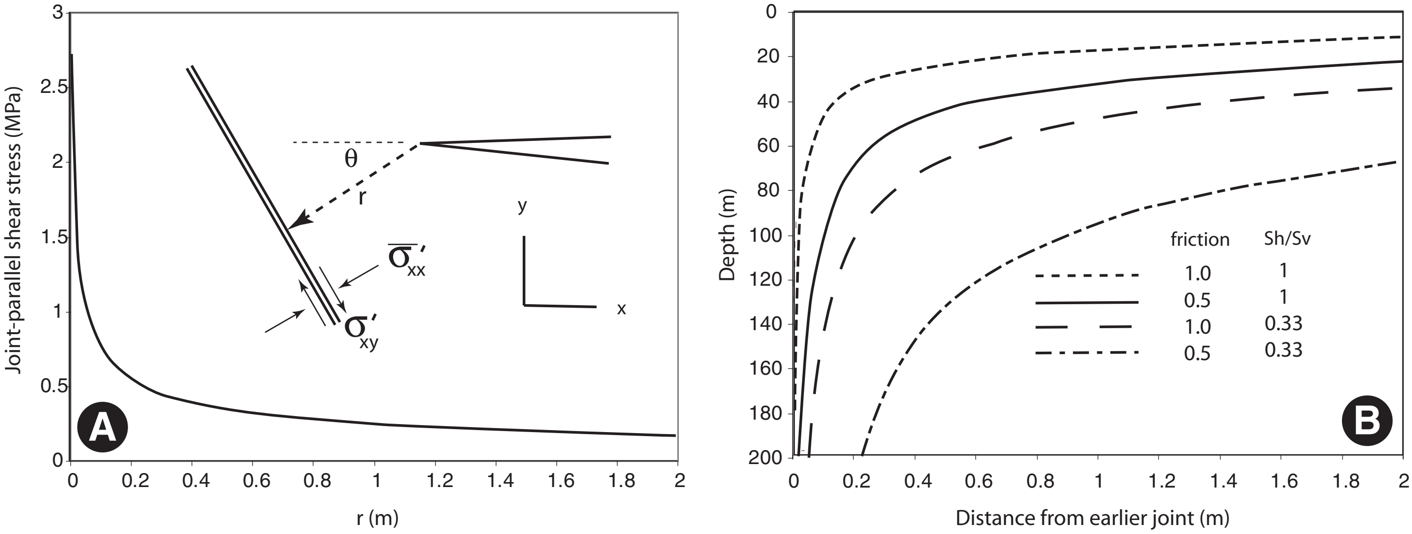

Figure 11. (A) Joint-parallel shear stress as a function of cross-fold joint, *r*, assuming an opening mode stress intensity factor of 1 Mpa $\sqrt{m}$ and θ = 33°. B. Depth below which shear stress does not exceed the frictional strength of a joint in Devonian black shale as a function of *r*, where the opening mode stress intensity factor on the joint is 1 Mpa $\sqrt{m}$ and θ = 33°.

shale are not well known but are likely to fall within the range of $0.5 < \mu < 1.0$. Hence, the contact stress on a joint necessary to prevent interface slippage and related blunting of the crack-tip stress field ranges from 2.51 to 5.02 MPa. Under hydrostatic conditions, and in the absence of a component of tectonic stress, the maximum depth for crack-tip stress-field blunting might be ~1000 m, depending on how effectively overburden stress is transformed to a horizontal contact stress. Even a small contribution (i.e., 1–2 MPa) of tectonic stress will greatly reduce the maximum depth for interface slippage in a crack-tip stress field. Likewise, the greater shear stresses on joints oriented <90° to the propagating joint would also ensure that the maximum depth of interface slip and crack-tip stress-field blunting is less than if the propagating joint is normal to the existing joint (Fig. 11).

It can be argued that when propagating joints approach an interface at 90°, symmetrical shear stresses of opposite sign cancel any tendency for interface slippage. This behavior appears to describe the situation that existed in the Geneseo and Middlesex black shales of the proximal delta during propagation of cross-fold joints against east-northeast joints (Fig. 12). However, most propagating cross-fold joints in shallower black shales of the distal delta approached existing east-northeast joints at oblique angles of 70° or less, resulting in a relatively higher shear stress along the cross-fold joints. Nevertheless, the fact that cross-fold joints crosscut almost all east-northeast joints in the Marcellus Shale, and one in four east-northeast joints in younger black shales, indicates that Alleghanian contact

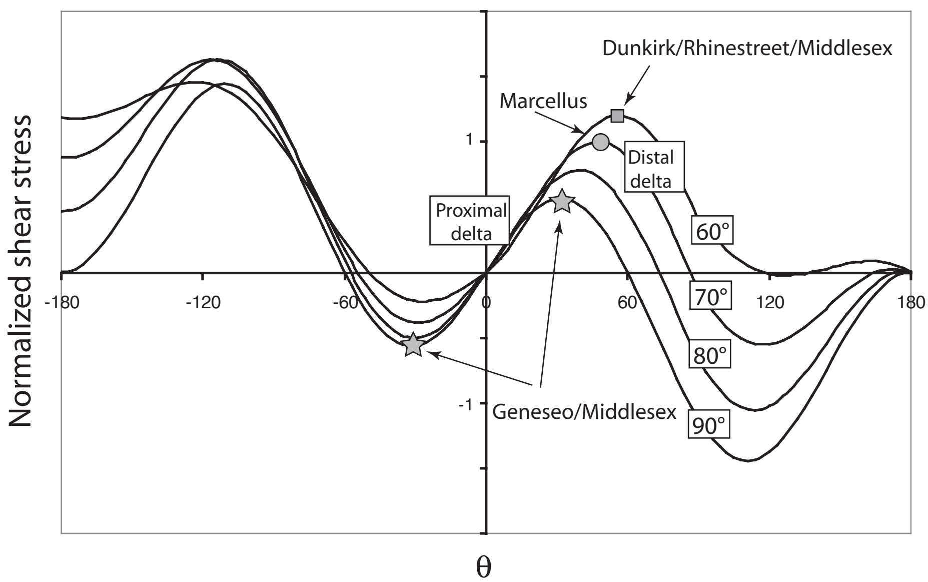

Figure 12. Angular distribution of crack-tip stresses for mode I (opening mode), loading in the vicinity of a crack tip normalized by $K_I/(2\pi r)^{1/2}$. The four curves permit the identification of the maximum shear stress that would be exerted on existing east-northeast joints oriented at 90° (proximal delta: Geneseo-Middlesex Shale), 80°, 70° (distal delta: Marcellus Shale), and 60° (distal delta: Dunkirk-Rhinestreet-Middlesex Shale) to an approaching cross-fold joint propagating in-plane and subject to mode I loading. Stresses are normalized (unitless).

stress in the distal delta was high enough to prevent frictional slip on early east-northeast joints (Fig. 12).

The curving of east-northeast joints before termination (Figs. 5 and 6) provides information regarding the level of contact stress on cross-fold joints and, by proxy, the reactivation depth of the east-northeast joints. The arguments presented here presume that the distance between the initiation of curving propagation and the nearby interface (cross-fold joint), *r*, yields a means of calculating the contact stress on the cross-fold joint at the onset of out-of-plane propagation of the reactivated east-northeast joint. Some east-northeast joints in black shale began curving a meter or more from the nearby interface (Fig. 5). East-northeast joints departed in-plane propagation when shear stress on the cross-fold joint exceeded its coefficient of friction. Slip on the interface modified the crack-tip stress field of the approaching reactivated east-northeast joint initiating curving propagation toward the larger but truncated lobe of the crack-tip stress field (Fig. 2). Assuming a cross-fold joint with a lower coefficient of friction (i.e., $\mu = 0.5$), east-northeast joints that deviated from in-plane propagation 1 m from the cross-fold joint were reactivated at depths of <100 m even when the overburden-induced contact stress was relatively low ($S_h/S_v = 0.33$; Fig. 11B). Further, east-northeast joints that approached cross-fold joints defined by a higher coefficient of friction ($\mu = 1.0$) may have departed in-plane propagation within ~200 m of the Earth's surface (Fig. 11B). It is important to note that the superposition of a right lateral sense of shear (interface slip) on the open cross-fold joint on the regional left lateral shear (Fig. 2) yields an overestimated depth of departure from in-plane propagation.

Interface slip does not imply a total stress drop along the oblique joint. A total stress drop is most likely to occur at a free interface where an approaching joint curves to meet the slipped interface at 90°. Less than 10% of the joint terminations in the distal delta are 90° intersections (Fig. 7A). Thus, despite modification of the crack-tip stress field by interface slippage, the maintenance of some degree of frictional contact resulted in intersection angles <90°. A comparison of data shown in Figure 7 with the curves in Figure 11B reveals that a complete stress drop on cross-fold joints reflects east-northeast joints reactivated in the contemporary tectonic stress field at depths of <150 m and probably much closer to the Earth's surface. Even a partial stress drop by frictional slip in the crack-tip stress field of a reactivated east-northeast joint (<90° intersection) is most likely restricted to within 200 m of the surface during exhumation. Given the exhumation rate typical of midcontinents, late stage activation of east-northeast joints could date to 20–30 Ma.

CONCLUSIONS

The style of joint intersections in Devonian black shale of the Appalachian Plateau of New York varies as a function of effective normal stress at the time of propagation. Relatively early propagation of joints yields compressional crosscutting intersections with preexisting joints, whereas late propagation leads to termination against older joints. The parameter that dictates intersection style is contact stress, an effective normal stress generated by burial, tectonic compaction, or relaxation during exhumation. Early crosscutting occurred when pore pressure was sufficiently high to generate east-northeast–striking natural hydraulic fractures. Subsequent Alleghanian detachment tectonics resulted in a significant horizontal stress anisotropy that attended the formation of cross-fold joints when the rocks were close to or at maximum burial depth. The associated increase in contact stress enabled propagating cross-fold joints in the deeper, proximal region of the Catskill Delta as well as more deeply buried Middle Devonian deposits of the distal delta to cut across a preexisting saturated array of long east-northeast joints that had formed early in the Alleghanian tectonic cycle. However, the fact that no more than one of four joint intersections in Upper Devonian deposits of the distal delta is crosscutting indicates that only a small number of short east-northeast joints had formed in the less deeply buried region of the basin. Rapid exhumation of the Appalachian Basin starting in the Miocene caused the reactivation of the short east-northeast joints in the distal delta succession in the North American lithospheric stress field and relieved contact stress on existing cross-fold joints (Engelder, 1982; Hancock and Engelder, 1989). Reactivated east-northeast joints were driven along curving paths into abutting contacts with cross-fold joints under low contact stress. Exhumation-related curving is a manifestation of slip on cross-fold joints under relatively low contact stress following Miocene reactivation of short east-northeast joints.

Results of this investigation have bearing on hydrocarbon exploration strategies of Devonian black shale units of the Appalachian Basin, principally the Marcellus Shale. The fact that both east-northeast and cross-fold joints formed close to or at peak burial depth means that the joints are carried by these rocks in the subsurface. Moreover, the higher average density of the east-northeast joint set relative to that of the cross-fold joint set and the parallelism of the former with the maximum horizontal stress direction of the contemporary lithospheric stress field likely impart a stress-induced permeability anisotropy that could enhance productivity of hydraulically stimulated north-northwest–directed horizontal wells.

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